J Ambient Intell Human Comput (2016) 7:763–775
DOI 10.1007/s12652-015-0317-4

ORIGINAL RESEARCH

Effects of depth perception cues and display types on presence and cybersickness in the elderly within a 3D virtual store

Cheng-Li Liu[1] · Shiaw-Tsyr Uang[2]

Received: 3 January 2015 / Accepted: 31 August 2015 / Published online: 19 September 2015

Abstract As the population ages, home computers with an Internet connection can provide the elderly with a new way to access information and services and manage Internet shopping tasks. One of the primary advantages of virtual environment (VE) technology for online shopping is its ability to provide a three-dimensional (3D) perspective to customers for a more realistic sense of the goods and the shopping environment. A sense of presence is one of the critical components required for an effective VE. However, side effects such as cybersickness may be caused by the display medium. When the quality of depth perception cues is poor, will the elderly's experience of cybersickness influence their feeling of presence and performance of goods searching during exposure within a 3D virtual store with 3D displays? An experiment addressed associations among presence, cybersickness, and performance in a 3D virtual store with autostereoscopic, stereoscopic and monocular displays with good and poor depth perception cues in an elderly sample. The results showed that the virtual store with an autostereoscopic display with high-quality depth perception cues will produce good sense and realism in stereopsis to allow the elderly to experience presence within a virtual store. However, if the depth perception cues are poor, 3D displays, and especially stereoscopic displays, are not recommended; elderly users may lose interest in a 3D virtual store due to even more serious cybersickness than that experienced with a monocular display.

Keywords 3D virtual store · Elderly · Presence · Cybersickness · Depth perception cues · 3D displays

1 Introduction

1.1 General introduction

With the rapid development of the Internet, online shopping has become a way of connecting oneself within today's culture based on what people purchase and how they use their purchases; indeed, online shopping has been popular since its inception. Many of the members of the increasing elderly population (i.e., the "silver tsunami" generation) have problems performing daily tasks due to restricted mobility, lack of transportation, inconvenience, and/or fear of crime (Czaja and Lee 2003). Home computers with an Internet connection can provide this relatively immobile population with a new way to access information and services, including the ability to shop. However, traditional websites introduce commodities with two-dimensional (2D) pictures and descriptive catalogues, thereby falling short in terms of reality and actual interaction with goods. Due to its limitations, type of design may negatively influence a customer's online shopping experience, minimizing the customer's desire to make purchases online. The elderly may find that these barriers prevent effective communication and, therefore, bar them from completing shopping transactions (Johnson and Kent 2007). In today's technological society, however, such problems can be solved using virtual environments (VEs). One of the primary advantages of using VE technology in

✉ Cheng-Li Liu
johnny@vnu.edu.tw

1 Department of Industrial Management, Vanung University, Taoyuan, Taiwan

2 Department of Industrial Engineering and Management, Minghsin University of Science and Technology, Xinfeng, Taiwan

online stores is its ability to provide a three-dimensional (3D) perspective, providing customers a more realistic sense of the products that they are viewing and the actual shopping environment. As the worldwide elderly population is rapidly increasing (Jones and Fox 2009), the combination of VEs and the Internet could introduce a new mode of online shopping to this population. Therefore, we are confident that 3D virtual web stores will become increasingly popular in the future and that the elderly will become an increasingly important demographic for the online shopping industry.

1.2 Presence and depth perception cues of 3D displays

A 3D virtual store differs from a common website store, and it is expected that viewing goods in 3D may be especially attractive to the elderly. Therefore, it is important for VE designers to create the illusion of being "present" in a VE (Sylaiou et al. 2008). Several researchers have found that presence is generally regarded as a vital component of VEs, as users must experience and interact with the VE in real time (Nichols et al. 2000; Sheridan, 1992). Presence has been identified as the defining characteristic, a design goal or a desirable outcome of VE participation (Wilson 1997; Steuer 1992). Witmer and Singer (1998) defined presence as the subjective experience of being in one place or environment even when one is physically situated in a different location. Freeman et al. (1999) described presence as the observer's subjective sensation of being in a remote environment. As presence increases, the observer becomes more aware of and engaged by the mediated environment, and less aware of the environment in which he or she is physically located. Therefore, although it will be a challenge for online retailers and programmers (Mikropoulos and Strouboulis 2004) to create the sensation of presence for online shoppers by designing 3D virtual stores that will immerse the user in the shopping experience, it is important for them to do so.

Certain factors influence the degree of presence within a VE. For example, depth perception is a primary factor in self-inclusion (Sadowski and Stanney 2003). Wickens et al. (1989)proposed that people can use a variety of depth perceptions to sense the shapes and distances of objects within a 3D environment. Depth perception is the result of a variety of depth perception cues that are typically classified into visual depth perception cues, which can be further categorized into monocular and binocular cues, and oculomotor depth perception cues. Monocular cues are subdivided into pictorial depth perception cues and motion cues. Images can provide static depth perception cues, including interposition, linear perspective, relative and known sizes, texture gradients, heights in the picture plane, light and shadow distributions, and aerial perspectives. Motion cues involve shifts in the retinal image and are induced by relative movements between the observer and the object. Among these cues are motion parallax, kinetic depth effect, and dynamic occlusion. Binocular cues, by contrast, take advantage of both eyes by allowing each eye to receive slightly offset views of the same visual scene and include stereopsis, which is the perception of depth from binocular vision through the exploitation of parallax. Stereopsis is the process that leads to the perception of depth from two slightly different projections of the world onto the retinas of the two eyes. The difference in the two retinal images is called retinal disparity or binocular disparity. Parallax is an apparent displacement or difference in the apparent position of an object that is viewed along two different lines of sight, and parallax is measured by the angle or semi-angle of inclination between those two lines (Steinman and Garzia 2000). Nearby objects have a larger parallax than more distant objects when observed from different positions, and parallax can thus be used to determine distances. Other depth perception cues include oculomotor depth perception cues, which occur via accommodation and convergence and involve combining visual and proprioceptive information from the eye to derive information that is related to distance. In a generally accepted view, the mutual interplay between accommodation and convergence is modeled as two dual and parallel feedback control systems that are connected via cross-links. Both feedback control systems receive the same physical input, that is, fixation on a point or region that differs in distance from a previously fixated object (Lambooij et al. 2009). In an artificial display, 3D displays could provide an enhanced perception of depth and are, therefore, thought to represent an important contribution to increasing the sensation of presence (Ijsselsteijn et al. 1998).

A 3D display is any display device that is capable of conveying a stereoscopic perception of 3D depth to the viewer. A variety of technologies for visualizing 3D scenes on displays have been developed and refined. For optimum visual comfort, all depth perception cues that are delivered by a 3D display must be both mutually linked and consistent with natural viewing, and they must present offset images that are displayed separately to the left and right eyes. The most common types of 3D displays are stereoscopic and autostereoscopic. Stereoscopic displays utilize the conventional stereo principle; that is, they deliver two views of the same scene to the viewer's left and right eyes. Only one set of images is presented per frame. Binocular separation of the views is created by multiplexing methods that utilize space/direction-division, time-division, polarization-division or various combinations thereof. Eyewear is needed to present binocular scenes; LCD shutter glasses create active 3D visualizations, and anaglyph- or polarization-based glasses produce passive 3D scenes (Benzie et al. 2007; Lambooij et al. 2009). To clarify, shutter glasses are designed to show one image to one eye at time one and a different image to the other eye at time two. In contrast to the stereoscopic view, autostereoscopic displays yield more natural 3D images without glasses. This type of display is realized by creating a fixed viewing zone for each eye (parallax-barrier or lenticular). In a more advanced approach, the parallax-barrier or lenticular viewing zones are combined with tracking for eye detection and viewing zone movement (shifting barriers or lenticulars, steerable backlight). Only binocular parallax, however, is provided as a depth cue. In contrast to the traditional autostereoscope, multi-view autostereoscopic displays create a discrete set of perspectives per frame and distribute the views across the viewing field. These views are generally classified as spatial- or time-multiplexed displays. Spatial-multiplexed displays, however, tend to have lower resolution and poor alignment. Thus, time-multiplexed displays without alignment issues or reduced resolution have been proposed (Toyooka 2001; Cornelissen et al. 1999). The light that is emitted by these displays is redirected to the viewer's eyes by sequentially switching the light source. A new time-multiplexed display with a dual-directional light-guide and a micro-grooved structure is patterned to restrict the viewing cones and display a uniform image (Chu et al. 2005). Holography is a diffraction-based coherent imaging technique in which a 3D scene can be reproduced from a flat, 2D screen with a complex amplitude transparency (amplitude and phase values). Holographic displays reconstruct the wave field of a 3D scene in space by modulating coherent light, for example, with a spatial light modulator. Because of its superior capabilities, real-time holography is commonly considered to be the ideal 3D technique. However, real-time holographic displays are expensive, new, and rare. Although they have the only 3D display technology that provides extremely realistic imagery, their cost must be justified. Each specific computer graphics application dictates whether holovideo is a necessity or an extravagant expense. Furthermore, holovideo is much more complicated than other methods, requires a high control voltage, and provides a limited viewing angle. Therefore, this study focuses on the effects of presence within stereoscopic and autostereoscopic displays compared to monocular displays within a 3D virtual store.

1.3 Cybersickness and depth perception cues

Some users exhibit symptoms that parallel the symptoms of classic motion sickness both during and after a VE experience. Referred to as cybersickness, it is likely caused by a sensory conflict between the three major spatial senses: the visual system, the vestibular system, and the non-vestibular or proprioception system (Spek 2007; LaViola 2000). The main symptoms of cybersickness are eye strain, disorientation and nausea (Stanney 2002; Lathan 2001). Several researchers have found that 80–95 % of all users will experience some level of disturbance or cybersickness during exposure to a VE, with between 5 and 30 % experiencing symptoms that are severe enough to discontinue exposure (Stanney et al. 1998).

The primary sensory conflict factor that causes cybersickness is attributed to the observer's perception of self-motion without actual motion (Kennedy et al. 1997); that is, the illusory sensation of self-motion induced by viewing optical flow patterns such as virtual scene movement and rotation (Lo and So 2001; Hettinger et al. 1990). Additionally, some researchers have found that visual displays induce cybersickness. For example, Howarth (1996) found that exposure to stereoscopic displays increases symptoms of cybersickness, such as eye strain and blurred vision, because mismatched oculomotor cues create an oculomotor disturbance. Furthermore, individuals with low stereovision may be unable to completely fuse the images together when presented with two different visual scenes, which can also lead to increased oculomotor disturbances (Hale and Stanney 2006). These studies found that the factors that contribute to cybersickness include not only sensory conflict or postural instability but also depth perception cues within the VE. However, few studies have been performed on the effect of the quality of depth perception cues on cybersickness in the elderly or the relationship between the sense of presence and display types with respect to the elderly.

1.4 Objectives

VE technology's ability to provide immersive VE experiences has greatly improved. Through a combination of hardware and software features, computer graphics systems can create 3D VEs that not only appear notably realistic but also improve specific spatial task performance with good 3D image quality. Although depth perception cues improve with good 3D image quality and 3D displays, the normal aging process can trigger decreases in visual acuity and cognition as well as physical impairments that, in turn, impact depth perception, particularly in the presence of serious sensory conflicts. Cybersickness, especially among the elderly, is easily induced by poor-quality depth perception cues and may influence individuals' sense of presence and overall shopping experience during exposure to a 3D virtual store. Therefore, the purpose of this study is to clearly understand the effects of the quality of depth perception cues in different display types (i.e., autostereoscopic, stereoscopic, monocular displays) on presence and cybersickness in the elderly within a 3D virtual store.

2 Method

2.1 Participants

We selected sixty people with an average age of 65.3 years to participate in the experiment. All participants had normal vision or corrected-to-normal (i.e., they scored between 0.83 and 1.11 in a visual acuity test, no cataract and had normal color vision). Each participant was paid a nominal NTD1000 as compensation for his/her time. All participants were fully informed and signed a consent form. Some researchers found that repeated exposure to the same VE with a separation of <7 days significantly affected levels of cybersickness, inducing disorientation and nausea (Stanney 2002; Lathan 2001). Therefore, the participants in the current study were not exposed to the experimental VEs for at least 2 weeks prior to the experiment.

2.2 Apparatus and the VE

The experimental environment was constructed by developing software and presenting the images on three types of displays: a 46-in. stereoscopic display with active LCD shutter glasses and two fields of 1080-line interleaved vertical resolution lines of 1920 horizontal pixels each to simultaneously show two 3D images with polarization at a 2000:1 contrast ratio; a 46-in. autostereoscopic LCD display with a free lenticular lens, designed with 1920 × 1080 resolution and a 1200:1 contrast ratio; and a 42-in. monocular TFT-LCD display. This study focused on the effect of autostereoscopic and stereoscopic displays on the sense of presence and symptoms of cybersickness in the elderly when 3D scenes were visualized through common, commercial 3D display types. The monocular displays were commonly used to show VEs in the past; however, in this study, a 2D display with monocular cues was designed as a control to compare the differences between the effects of 2D and 3D displays on the sense of presence and symptoms of cybersickness. The VE scene for our study was a retail store containing four categories of merchandise, stationery, hand-held tools, cleaning products and toiletries, as shown in Fig. 1. Stationery and hand-held tools included eighteen objects that were exhibited in the center of the retail store. Cleaning products and toiletries included twenty-seven objects that were exhibited throughout the retail store. In addition, the scene was designed with two different display conditions, which contained high-level or low-level depth perception cues. The high-level depth perception cues are designed with 3D stereo pictures to exhibit good shape and depth for people feeling good-quality depth perception. On the contrary, the low-level depth perception cues are just shown with 2D

Fig. 1 A scene of the experimental 3D retail store

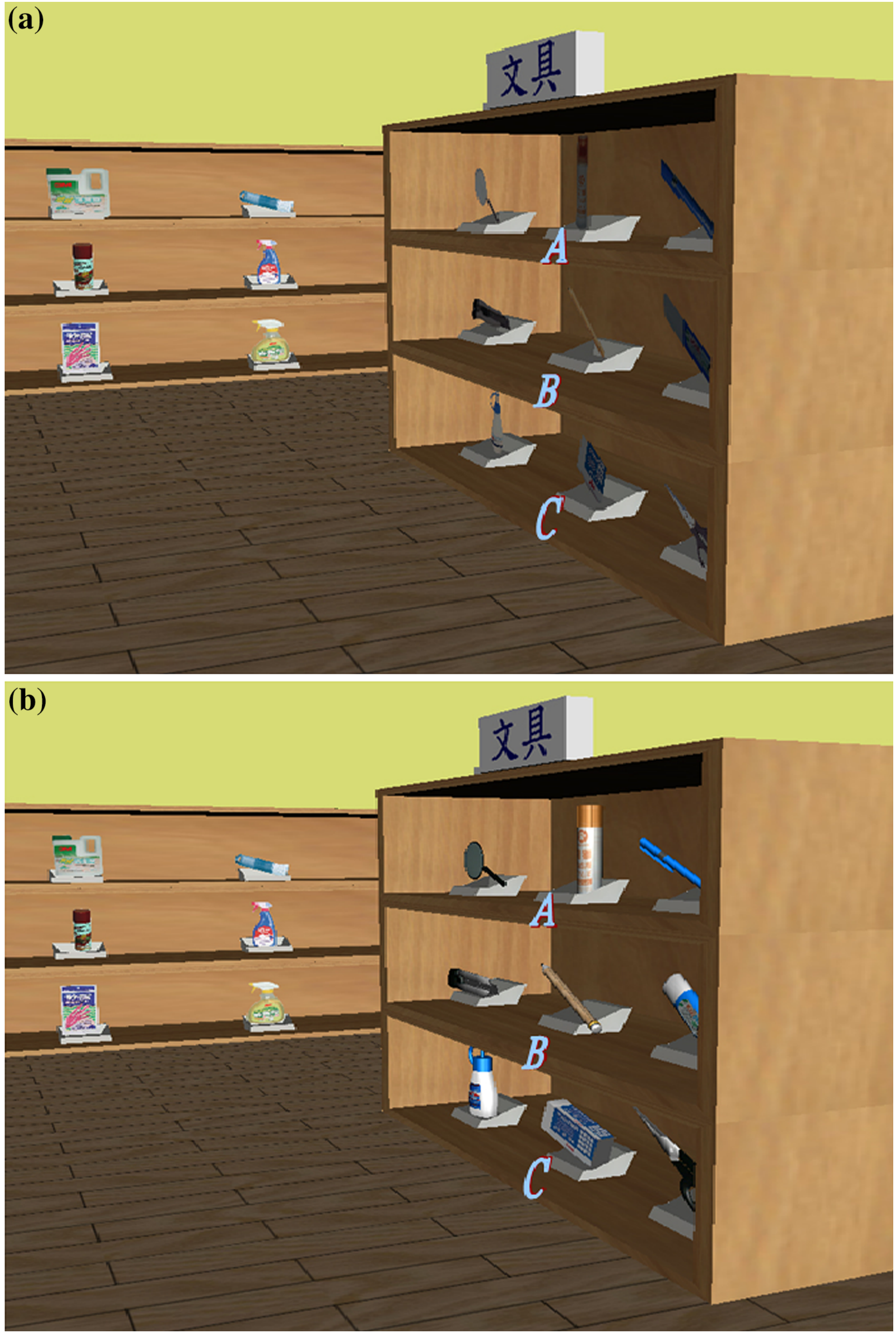

Fig. 2 A scene of: **a** low level depth perception cues with 2D images; **b** high level depth perception cues with 3D stereo pictures

pictures. Figure 2a shows a scene with low-level depth perception cues. Figure 2b shows a scene with high-level depth perception cues.

Additionally, the tasks in this study were designed as movement-based tasks to examine participants' performance with respect to object manipulation, object identification, and response time. To evaluate response time in different experimental situations, participants were asked to search for and confirm certain objects in the store. For object manipulation, participants interacted with objects using the computer mouse and cursor. In the scene with high-level depth perception cues, participants could rotate an object along pitch and yaw axes to see multiple viewpoints, as shown in Fig. 3.

2.3 Experimental design and procedures

The study involved a 2 (level of depth perception cues: low and high) × 3 (type of display: autostereoscopic, stereoscopic and monocular displays) between-subjects experiment, resulting in a full-factorial design with six treatment conditions. Ten participants were randomly assigned to each of the six treatment conditions to complete the product-searching task.

During the exposure period, each participant was required to search for eight target objects. However, only six of these objects were exhibited in the showroom. When the target object was found, participants moved the cursor over the object and push the left button on the control device to identify the object. If the object was the target, the system beeped once to notify the participant. At the same time, the participant recorded the correct position on the check sheet (i.e., each showcase was numbered). If the participant determined that a particular target object was not exhibited in the showroom, the participant marked "X" in the corresponding column.

Before exposure, participants were asked to complete the Simulator Sickness Questionnaire (SSQ) to document the level of severity with which they experienced 16 sickness symptoms. There were three subscales in SSQ, oculomotor, nausea and disorientation, which were computed by adding the ratings of all symptoms and multiplying this value by the appropriate weight (Kennedy et al. 1993). The weights were 7.58 for oculomotor, 9.54 for nausea and 13.92 for disorientation. The total severity of cybersickness was computed by adding the sums of the oculomotor, nausea and disorientation symptom ratings and multiplying the resulting value by 3.7. The SSQ is the most popular subjective measure of both simulator sickness and side effects experienced in VEs. According to the study by Kennedy et al. (1993), nausea seldom occurs when the SSQ score is <7.5. Therefore, if a participant reported any moderate symptom of discomfort or sickness in the pre-exposure SSQ (i.e., the SSQ score was >7.5), the participant was asked to rest for 10 min and then complete a second pre-exposure SSQ. If the second pre-exposure SSQ score was >7.5, the participant was withdrawn from the study. In addition, participants received training and time to familiarize themselves with the input device and maneuvering within the VE. Participants were asked to complete one lap of the 3D store to ensure that they understood the basics of functioning within the VE. When the participant finished the training, a simple test would be held. He/she was required to search for a target object within 5 min. If he/she did not accomplish this task, the training will be repeated. During the exposure, participants could freely involve themselves in the VE by manipulating the mouse button and rotating the scene around the vertical or lateral axes. They could also zoom in using the SHIFT key and zoom out using the CTRL key. When all six target objects were found, and the other two objects were confirmed to not be present in the showroom, the experiment was concluded. Finally, participants were asked to complete a Presence Questionnaire (PQ) and the SSQ. The PQ was designed to measure user presence within a VE on a 7-point scale and consisted of 4 categories (control factors, sensory factors, distraction factors and realism factors) with 32 questions regarding user interaction (Witmer and Singer 1998). The PQ aimed to identify the respondent's degree of involvement in the virtual experience and the effects of different aspects of the environment on that experience. Because much of the information that the participants received in this study typically came through visual channels (e.g., recognition of objects and identification of position) and because the connectedness or continuity of the stimuli being experienced are important within a virtual store, sensory factors and realism factors will be discussed further. In addition, the PQ is a statistically validated tool that allows some powerful subscale statistics to be performed, such as examinations of involvement/control and natural resolution subscales. The involvement/control subscale was applied to evaluate the degree to which the participant felt able to control events in the virtual store, the degree of responsive of the VE and the degree to which the participant felt involved in the virtual experience. Thus, the involvement/control subscale will be discussed further.

3 Results

The data set (sense of presence scores and cybersickness scores with independent variables in different levels) was analyzed using the Shapiro–Wilk test to determine the distribution of the sample. The results showed that the data set for each cell was consistent with a normal distribution with a P value >0.05 on the Shapiro–Wilk Test. Based on the results, an ANOVA on the sense of presence scores and the cybersickness scores was performed. Based on the ANOVA results shown in Tables 1 and 5, it is apparent that the effects of depth perception cues and display types are significant factors affecting the sense of presence and cybersickness in the elderly.

3.1 Sense of presence measures

Table 1 shows that high-quality depth perception cues (i.e., 3D stereo pictures for multiple viewpoints) provided participants with a sense of presence that was significantly higher than that they experienced with low-quality cues (i.e., 2D images). This result suggests that 3D stereo

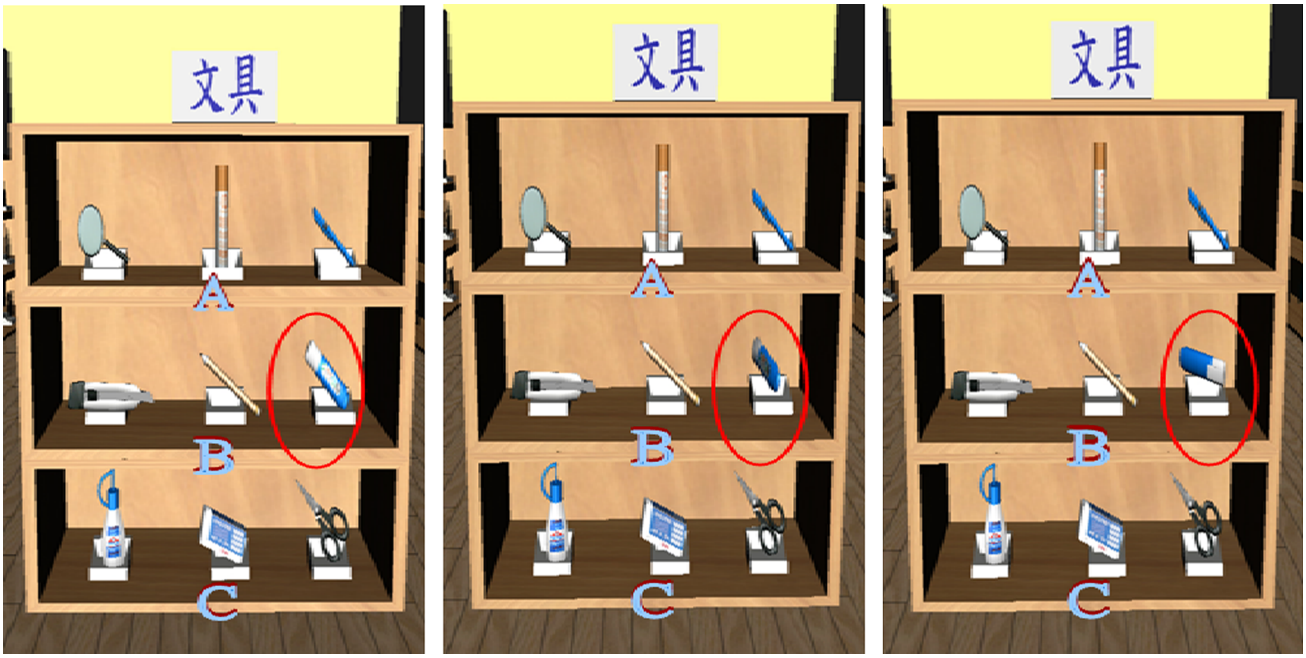

Fig. 3 The objects can be rotated along pitch and yaw axis in high level depth perception cues environment

Table 1 ANOVA analysis of the effects of depth perception cues and display types on presence scores

Sources	Mean	SS	df	MS	F	P value
Depth cues						
Low quality	84.1	14,539.267	1	14,539.267	77.907	0.000*
High quality	115.3					
Display types						
Auto-stereoscopic display	111.9	12,759.600	2	6379.800	34.186	0.000*
Stereoscopic display	108.0					
Monocular display	79.2					
Interaction		90.133	2	45.067	0.241	0.786
Error		10,077.600	54	186.622		
Total		37,466.600	59			

* $P < 0.05$ significance level

images may provide sufficient stereopsis and stereo acuity for users to identify objects, examine those objects from multiple viewpoints and interact with those objects, thereby allowing participants to experience a stronger sense of presence than they did with the 2D images of objects in the virtual store. In addition, there were significant differences across display types. Therefore, there is a need for further investigation into the effects of different display types on the sense of presence. Tukey's post hoc test was used for a pair-wise comparison of display types, and the results are shown in Table 2. The results showed that the sense of presence was stronger for 3D displays than for monocular displays. Furthermore, we assessed the participants' feelings of presence, realism and involvement with the virtual store to understand the influences of depth perception cues and display types. Tables 3 and 4 show the sub-factor scores for the sense of presence in the sensory category. Questions that assessed the participants' sense of presence as objects moved through space, the participants' sense of moving around inside the virtual environment and how well the participants were able to examine objects from multiple viewpoints were used in this category. Within the realism category, the participants were asked if their experiences in the virtual environment seemed consistent with real-world experiences and if they were able to actively survey or search the environment visually. For the involvement/control sub-scale, participants evaluated the degree to which they felt able to control events in the virtual store, the responsiveness of the VE and how involved they felt in the virtual experience based on the

Table 2 Turkey's post hoc tests for the effects of display types on presence

(I) Display types	(J) Display types	Mean difference (I–J)	Std. error	P value
Auto-stereoscopic	Stereoscopic	3.900	4.320	0.371
	Monocular	32.700*	4.320	0.000
Stereoscopic	Auto-stereoscopic	−3.900	4.320	0.371
	Monocular	28.800*	4.320	0.000
Monocular	Auto-stereoscopic	−32.700*	4.320	0.000
	Stereoscopic	−28.800*	4.320	0.000

* $P < 0.05$ significance level

Table 3 Sub-factor and sub-scale scores of presence for depth cues levels

Depth cues	Sensory	Realism	Involvement/control
Low quality			
Mean	21.07	13.00	34.57
SD	8.48	4.43	7.51
High quality			
Mean	30.10	16.63	50.20
SD	7.03	3.60	8.41

Table 4 Sub-factor and sub-scale scores of presence for display types

Display types	Sensory	Realism	Involvement/control
Autostereoscopic display			
Mean	32.85	17.50	49.20
SD	5.00	2.50	9.11
Stereoscopic display			
Mean	27.65	15.75	42.85
SD	6.04	4.00	11.68
Monocular display			
Mean	16.25	11.20	35.10
SD	6.03	3.94	7.89

various depth perception cues and display types. Testing the differences between the two depth perception cue levels with these three rating factors demonstrated that participants perceived stronger feelings of presence, realism and involvement/control when experiencing high-quality depth perception cues [sensory: high-quality depth perception cues are better than low-quality cues ($t(29) = 14.222$, $p < 0.000$); realism: high-quality depth perception cues are better than low-quality cues ($t(29) = 6.634$, $p < 0.000$); involvement/control: high-quality depth perception cues are better than low-quality cues ($t(29) = 16.093$, $p < 0.000$)].

Additionally, a test of differences across display types with these three rating factors showed that participants felt that the sensory, realism and involvement/control aspects

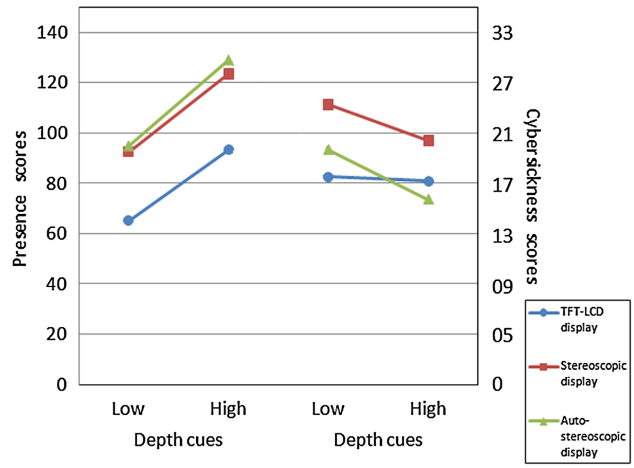

Fig. 4 Plots of mean scores of presence and cybersickness on depth perception cues for display types (2D monocular display, 3D stereoscopic display and 3D autostereoscopic display)

were strongest in autostereoscopic displays and weakest in monocular displays [sensory: autostereoscopic displays are better than stereoscopic displays ($t(19) = 7.839$, $p < 0.000$) and monocular displays ($t(19) = 20.433$, $p < 0.000$); stereoscopic displays are better than monocular displays ($t(19) = 15.163$, $p < 0.000$); realism: autostereoscopic displays are better than stereoscopic displays ($t(19) = 3.018$, $p = 0.004$) and monocular displays ($t(19) = 8.391$, $p < 0.000$); stereoscopic displays are better than monocular displays ($t(19) = 8.132$, $p < 0.000$); involvement/control: autostereoscopic displays are better than stereoscopic displays ($t(19) = 6.094$, $p = 0.004$) and monocular displays ($t(19) = 13.227$, $p < 0.000$); stereoscopic displays are better than monocular displays ($t(19) = 5.488$, $p < 0.000$)].

If 3D displays, especially autostereoscopic displays, are combined with high-quality depth perception cues, as shown in Fig. 4 (left side), the phenomenon of stereopsis can easily be created and the participants' sense of presence is at its highest level. The results indicated that when users browsed the 3D virtual store with high-quality depth perception cues on a 3D display, the objects appeared to have better shapes and depths and to be more natural, and participants became more involved and immersed in the experience to the extent that they perceived themselves to be surrounded by or interacting with the virtual store. Although the average presence scores for autostereoscopic displays were higher than those for the stereoscopic displays, the difference in the scores was not significant. This result suggests that a 3D display, regardless of whether it is autostereoscopic or stereoscopic, provides participants with binocular disparity cues and allows them to make quick and accurate relative-distance judgments. However, the participants' sense of presence, realism and involvement is better in autostereoscopic displays than in stereoscopic displays.

3.2 Association between cybersickness and sense of presence

Symptoms of cybersickness were evaluated using the SSQ after exposure. Table 5 shows that the effect of the depth perception cues was nonsignificant but that the effect of the display type was significant. Tukey's post hoc test was used for the pair-wise comparison of display types, as shown in Table 6. The stereoscopic display seemed to induce cybersickness more easily than other display types. As a result, our question became which category of sickness was the most easily induced. Table 7 shows SSQ subscores for the different display types. Oculomotor disturbances (i.e., nausea and disorientation) appeared to be more common than the other categories, especially in 3D displays. The cause of these disturbances may be the conflict between the fixed focal depth of the image plane and the depth perception cues provided within a 3D display. These conflicting stimuli would promote an inappropriate ocular response when viewing a virtual environment. In addition, the score of the disorientation subscale was higher than the scores of the other subscales for all displays. We found that the major symptoms of disorientation were difficulty focusing and blurred vision, which are symptoms that are related to disturbed visual processing and belonged to the category of oculomotor disturbances during the simulation. The results showed that there was a significant increase in oculomotor disturbances among the elderly after 3D virtual store exposure on 3D displays.

Figure 4 (right side) illustrates the interaction relationship between the effects of the depth perception cues and the display types. High-quality depth perception cues induced less severe cybersickness than low-quality cues for any display type. The association between the sense of presence and cybersickness was determined by performing Pearson's correlation test for all scale pairs. There was no statistically significant correlation between the experience of sense of presence and incidence of cybersickness ($r = -0.234$, $p = 0.072$). However, in cases with low-quality depth perception cues, the sense of presence interestingly exhibited a significant negative correlation with cybersickness ($r = -0.683$, $p < 0.000$). Moreover, significant negative correlations were observed between the sensory sub-factor and cybersickness ($r = -0.391$, $p = 0.032$); the realism sub-factor and cybersickness ($r = -0.487$, $p = 0.006$); and the involvement/control sub-factor and cybersickness ($r = -0.474$, $p = 0.008$). Additionally, exposure to low-quality depth perception cues via an autostereoscopic display resulted in the greatest negative correlation between sense of presence and cybersickness at $r = -0.841$, $p = 0.002$ (stereoscopic display, $r = -0.741$, $p = 0.014$; monocular display, $r = 0.637$, $p = 0.047$).

3.3 Task performance

Overall performance within the 3D virtual store was determined by the total time in seconds spent searching for and confirming the target objects. The total time spent finding six target objects in the showroom and writing down the correct positions on the check sheet was

Table 5 ANOVA analysis of the effects of depth perception cues and display types on cybersickness scores

Sources	Mean	SS	df	MS	F	P value
Depth cues						
Low quality	19.9	93.251	1	93.251	3.482	0.067
High quality	17.5					
Display types						
Auto-stereoscopic display	17.4	269.961	2	134.980	5.040	0.010*
Stereoscopic display	21.7					
Monocular display	17.0					
Interaction		36.834	2	18.417	0.688	0.507
Error		1446.318	54	26.784		
Total		1846.363	59			

* P < 0.05 significance level

Table 6 Turkey's post hoc tests for the effects of display types on cybersickness

(I) Display types	(J) Display types	Mean difference (I–J)	Std. error	P value
Auto-stereoscopic	Stereoscopic	−4.301*	1.637	0.011
	Monocular	0.374	1.637	0.820
Stereoscopic	Auto-stereoscopic	4.301*	1.637	0.011
	Monocular	4.675*	1.637	0.006
Monocular	Auto-stereoscopic	−0.374*	1.637	0.820
	Stereoscopic	−4.675*	1.637	0.006

* $P < 0.05$ significance level

Table 7 SSQ sub-scores for display types

Display types	SSQn	SSQo	SSQd
Autostereoscopic display			
Mean (scores)	8.586	17.434	20.880
Mean (times)	0.9	2.3	1.5
SD (scores)	6.113	4.330	7.141
Stereoscopic display			
Mean (scores)	11.925	20.087	26.448
Mean (times)	1.25	2.65	1.9
SD (scores)	4.238	4.451	6.225
Monocular display			
Mean (scores)	7.632	16.297	22.272
Mean (times)	0.8	2.15	1.6
SD (scores)	4.991	4.451	6.997

SSQn nausea, *SSQo* oculomotor disturbance, *SSQd* disorientation

recorded. The ANOVA of the performance time is shown in Table 8. The ANOVA result indicated that there was no significant difference between low-quality depth perception cues and high-quality depth perception cues. However, there was a significant difference across display types. Therefore, Tukey's post hoc test was used for the pair-wise comparisons of display types, and the results are shown in Table 9. The results showed that the response time spent searching for target objects in the monocular display was shorter than that spent using either 3D display. It seems that objects that were viewed as 2D images (i.e., low-quality depth perception cues) or as 3D stereo pictures (i.e., high-quality depth perception cues) did not influence the participants' object-searching ability, but this ability was influenced by the display type. Participants spent the shortest time completing the object-searching task with the 2D display and the longest time with the 3D display.

4 Discussion

In this study, participants' experiences of the degree of presence and level of cybersickness when using different depth perception cues and different display types were compared. As expected, virtual scenes designed with high-quality depth perception cues provide a better sense of presence than scenes with low-quality depth perception cues, especially when shown on an autostereoscopic display. The results indicate that when objects were designed with low-quality depth perception cues (i.e., 2D images) the user's sense of presence and realism was significantly impaired. It was determined that 3D stereo pictures maintain the original three-dimensional content of an object and provide a realistic concept of the shape and depth of the object, thereby allowing the human observer to interpret

Table 8 ANOVA analysis of the effects of depth perception cues and display types on response time

Sources	Means	SS	df	MS	F	P value
Depth cues	753.1	120.417	1	120.417	0.058	0.811
Low quality	756.0					
High quality						
Display types						
Auto-stereoscopic display	692.4	1081410.100	2	540705.050	260.665	0.000*
Stereoscopic display	941.0					
Monocular display	630.3					
Interaction		2314.433	2	1157.217	0.558	0.576
Error		112013.900	54	2074.331		
Total		1195858.850	59			

* $P < 0.05$ significance level

Table 9 Turkey's post hoc tests for the effects of display types on response time

(I) Display types	(J) Display types	Mean difference (I–J)	Std. error	P value
Auto-stereoscopic	Stereoscopic	−248.65*	14.403	0.000
	Monocular	62.05*	14.403	0.000
Stereoscopic	Auto-stereoscopic	248.65*	14.403	0.000
	Monocular	310.70*	14.403	0.000
Monocular	Auto-stereoscopic	−62.05*	14.403	0.000
	Stereoscopic	−310.70*	14.403	0.000

* $P < 0.05$ significance level

objects adequately. As we know, stereopsis is one of the processes of the human visual system that extracts depth information from a viewed scene and builds a 3D understanding of that scene. Stereopsis makes use of the slight difference in perspective of one eye relative to the other (i.e., binocular disparity). A lack of binocular disparity may reduce one's perception of presence within a VE (Hale and Stanney 2006). If the 3D virtual store was shown on a 3D display with high-quality depth perception cues, the 3D stereo pictures may have provided enough stereopsis within the 3D display to produce an enhanced binocular disparity for users examining objects from multiple viewpoints. Furthermore, participants would feel a stronger sense of presence within the virtual store. Monocular display images provide a two-dimensional representation of a three-dimensional scene. Information pertaining to the third dimension, that is, the range or distance to each pixel, is lost as the scene is flattened onto the image plane. Although the feeling of presence with high-quality depth perception cues was better than that with low-quality cues on a monocular display, the overall feeling of presence of a 2D display was less than that of a 3D display. The other interesting outcome from the rating items was that those participants who perceived the virtual store with the autostereoscopic display demonstrated a stronger overall sense of presence, including the sensory, realism and involvement/control sub-factors, than they did with the stereoscopic display. It is possible to hypothesize that there are some disadvantages to studying the elderly when influencing the sense of presence within a stereoscopic display. First, when worn for long periods, an ill-fitting pair of glasses can pinch the nose. This pinching can cause pain, making the glasses uncomfortable to wear. Second, while glasses provide a clear forward view, they can limit peripheral vision. As participants are more likely to move their whole head to focus the glasses on the object of interest, fatigue and inattention can more easily occur. Finally, the constant shuttering of glasses might bother some individuals who are sensitive to low refresh rates, and the shuttering may also cause flickering. Therefore, participants experienced a lesser degree of presence when using the stereoscopic display than they did when using the autostereoscopic display. Moreover, when participants wore glasses for viewing the virtual store in a stereoscopic display, they would spend some time to adjust the glasses and forehead angle to reduce the influence of oculomotor disturbances. This situation often occurred in these elder participants during exposure, but not happened in an autostereoscopic display. Therefore, the response time in a stereoscopic display is longer than in an autostereoscopic display.

The sense of presence has been identified as the defining characteristic, a design goal or a desirable outcome of VE participation (Steuer 1992; Wilson 1997). Any relationship with side effects, especially cybersickness, is complex. The experimental results in 3D displays appear to support Singer and Witmer (1996), who reported that the experience of sickness may detract from the sense of presence. However, the cybersickness rating evaluated on the monocular display was not significantly different when using high- and low-quality depth perception cues, but the feeling of presence was significantly different. This result indicates that cybersickness and a lower sense of presence may be produced independently even though they are related to oculomotor disturbances. If the objects are presented as 2D images shown on a 3D display, the depth perception cues might disappear, thus inducing mismatched oculomotor cues (i.e., accommodation and convergence). These conflicting stimuli would promote an inappropriate ocular response when viewing a virtual environment. It is expected that participants experiencing low-quality depth perception cues may have a poor sense of objects and lose depth perception cues within the virtual store, leading to increased oculomotor disturbances when compared to high-quality depth perception cues. Therefore, participants exposed to a virtual store with low-quality depth perception cues on a 3D display may report some level of cybersickness and experience a reduced sense of presence. However, in a monocular display, both 2D and stereo 3D images become monocular cues with the same pictorial depth perception cues and motion cues, and the oculomotor disturbances may, therefore, be expected to be slighter. However, sensory conflicts will be serious whenever the sensory information is not the stimulus that the participant expects based on experience. Thus, regardless of the quality of the depth perception cues within a monocular display, sensory conflicts will arise easily. Consequently, the severity of cybersickness symptoms is similar when using high- and low-quality depth perception cues in a monocular display. Additionally, glasses were required for participants to view the virtual store in a stereoscopic display. When oculomotor disturbances occurred during VE exposure, participants would adjust the glasses and forehead angle to reduce the influence of oculomotor disturbances, but the symptom of blurred vision would increase. Simultaneously, the participants spent more time to search target objects than in autostereoscopic display. Therefore, the total scaled cybersickness scores were lowest for the autostereoscopic display.

Waterworth (2000) examined participant performance using a dexterity game and concluded that stereopsis reduced both errors and time-on-task when using a stereoscopic display compared to the results obtained when performing the same task with monocular representation. Barfield et al. (1999) found that subjects' performance time on a wire-tracing task performed was significantly reduced by the addition of stereopsis. These previous studies examined the performance of participants on both monoscopic and stereoscopic displays. However, the tasks were stationary. The current study, which assessed a searching performance task within a virtual store, required participants to engage in a moving task with different levels of depth perception cues and different types of displays. The findings indicated that even among those who may not be able to fully benefit from 3D displays, the time to find a target object was in fact higher with a 3D display than with a 2D display under the same VE conditions. These results can be explained by assuming that the 3D virtual store with 3D displays and high-quality depth perception cues provided enhanced interaction with objects; thus, participants in the VE might click and hold the mouse cursor, thereby moving, dragging or zooming in/out within the overall environment. Therefore, the time spent finding the target object in a 3D display was expected to be longer than that in a 2D display. In other words, participants are willing to spend more time engaged in the virtual store when they experience good stereopsis within the 3D environment. However, as participants required glasses to see the virtual store in the stereoscopic display, they occasionally needed to stop or slow down the search to adjust the glasses and forehead angle; thus, the response time was longest in this condition.

5 Conclusion

Virtual stores with 3D images and thus high-quality depth perception cues allow older users to experience good stereo acuity. The current study found that the elderly who browsed in a 3D virtual store with high-quality depth perception cues benefitted from binocular disparity within a 3D display and were able to experience a good sense of presence. Although the 3D displays provided a stereopsis environment, the side effect of cybersickness from exposure in a VE can be serious when the depth perception cues are poor, especially within a stereoscopic display. Overall, the reported sense of presence when browsing a virtual store within a 3D display was positive when the symptoms of cybersickness were slight. However, cybersickness and a lower sense of presence were independent of each other when using a monocular display. Thus, the theorized assumption that an experience of sickness may detract from the sense of presence was not supported. Our conclusion is that presenting a virtual store via an autostereoscopic display with high-quality depth perception cues will produce a good sense of presence and realism in stereopsis, thereby allowing the elderly to engage with and become involved in the virtual store. However, if the depth perception cues are poor, 3D displays, especially stereoscopic displays, should be avoided to prevent the elderly from experiencing cybersickness and, consequently, losing interest in the 3D virtual store, as the cybersickness experienced with this display is more serious than that experienced with a monocular display.

Due to advancements in technology, psychological tests of presence and self-reported symptoms of cybersickness on holographic displays should be considered as the technological problems associated with holographic displays (e.g., high control voltage and limited viewing angle, high costs) are solved. Additionally, this research would be a step toward designing a warning system to detect operational problems and prolonged exposure, and such a system could help to combat cybersickness within a 3D environment.

Acknowledgments The authors would like to thank the National Science Council of the Republic of China for financially supporting this work under Contract No. MOST 103-2221-E-238-003.

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