IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 1, 2019, accepted July 23, 2019, date of publication August 2, 2019, date of current version September 3, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2933055

Comparison of Radial and Panel Menus in Virtual Reality

PEDRO MONTEIRO[1], HUGO COELHO[1], GUILHERME GONÇALVES[2], MIGUEL MELO[1], AND MAXIMINO BESSA[1,2]

[1]INESC TEC, 4200-465 Porto, Portugal
[2]Escola de Ciências e Tecnologia, University of Trás-os-Montes e Alto Douro, 5000-801 Vila Real, Portugal

Corresponding author: Pedro Monteiro (monteiro.p@outlook.pt)

This work was financed by the project "CHIC - Cooperative Holistic View on Internet and Content" under Grant N° 24498, financed by the European Regional Development Fund (ERDF) through COMPETE2020 - the Operational Programme for Competitiveness and Internationalisation (OPCI).

ABSTRACT Although selection menus are widely used for interaction, their use on 3D virtual reality applications needs to be objectively assessed. The focus of this study is to evaluate a traditional panel and a radial menu in two distinct virtual environment placements (i.e. fixed on the wall and following the users' hands). Fifty-one participants used two different menus of the four possible combinations. To evaluate the menus' effectiveness and efficiency, we measured usability (System Usability Scale Questionnaire), user satisfaction (After-Scenario Questionnaire), time to finish the tasks (in seconds) and the number of unnecessary steps (errors) performed by the users. Overall results showed a clear preference for the traditional panel menu type and the fixed wall placement of the menu. We conclude that all menu types perform well, despite different user preferences, and that fixing the menu to the wall gives users a better overview of both the menu and the virtual environment, improving their ability to perceive their actions on the menu.

INDEX TERMS Human computer interaction, virtual reality, user interfaces, graphical user interfaces.

I. INTRODUCTION

The massification of virtual reality (VR) that we have seen over the years, together with the increasing number of VR technologies and equipment, created a new paradigm to create and deliver new immersive multimedia content. Also, a wide variety of menus were created and evaluated to simplify the interaction process with VR.

HCI (human-computer interaction) is an area that researches the design and the use of computer technology, focused on interfaces between people and computers [1]. UI, as a component of HCI, consists of everything that allows the user to interact with the system to perform a given task or everything that gives information to the user about the state of the system [2]. An example of this is the monitor and keyboard of a computer or, if you apply this to most modern VR equipment, the head-mounted display (HMD) and its controllers acting like a bridge between humans and computers. With UI comes the user experience (UX), which is associated with emotional or aesthetic variables like fun, pleasure or even joy [3], [4] and because of this, there is no universal definition for UX [5].

In a desktop-based application, item-based menus are designed as lists, where each item is associated with a certain command [6]. An alternative to this approach is pie menus, where each item is a slice-shaped entry and every entry has the same proportion making them efficient regarding Fitts' law [7]. These menus are typically designed to perform simple commands, where more complex tasks like multiple selections should be done with additional user interfaces (UI) elements.

These menus could be applied to VR, but in [8] it is stated that many aspects should be considered when developing menus for VR. Desktop menus are two dimensional (2D) and are also presented in front of the user while, in the virtual environment (VE), the menu could be presented in any position and rotation and the user could have any position and rotation as well. This could mean that the menu is too far or too close, making it difficult for the user to read. Also,

The associate editor coordinating the review of this article and approving it for publication was Zhihan Lv.

the menu can be faced backwards, and the user might not see it.

One of the reasons to create new UIs is to increase productivity and performance of users and for that reason, it is important to evaluate them in terms of effectiveness, efficiency and user satisfaction and, according to [9], these concepts can be defined as follows: a) effectiveness — the efficiency and precision with which the proposed objective can be achieved by the user; b) efficiency — resources spent by the user to reach the proposed objective; and c) satisfaction — comfort and acceptance of the interface by users.

UIs can be evaluated with the use of subjective or objective data. Subjective data can be obtained by using questionnaires that measure systems' usability, and objective data can be obtained by direct observation including metrics like error rate, number of help requests, number of useless steps or even the time to complete tasks. These subjective and objective data allow UI creators to assess the efficacy or efficiency of the UI better [10].

UI design should contain three interactive tasks: navigation, selection/manipulation and system control. Navigation tasks include roaming or path lookup; Selection/manipulation consists in selecting, rotating or moving an object; and system control allows the user to change the interaction methodology or system state [11], [12].

Over the years, multiple interfaces have been proposed for immersive VR (IVR) like [13]–[15], but not much work has been done regarding their evaluation. Our focus is to evaluate the usability and satisfaction of the traditional UIs, panel and radial menus (also referred to as list and pie menu respectively), in an immersive virtual environment (IVE) using selection tasks.

II. RELATED WORK

One of the first studies done in HCI aimed at transposing the conventional desktop 2D menus into VR [8]. In their work, they created floating 2D menus where the main interaction was performed by creating a ray cast from the tip of the index finger. This type of menus has been studied over the years, in reference [15] the authors studied two types of linear menus (buttons displayed like a dropdown list - one was straight down and the other was a slant) and a pie menu. They reported that the pie menu was 25% faster than the straight menu. [14] studied two menus, pie or linear, and the position of the menu, fixed or contextual. Results supported the ones reported by [15], where radial menus were faster than linear ones. They also reported that selection time was quicker in the contextual location.

The work done by [6] consisted of two studies, where the first one studied different selection methodologies to interact with radial menus like ray cast, hand projection and hand rotation. Results showed that ray cast was the best selection methodology. For the second study, they took the best selection methodology and implemented checkboxes, sliders and color maps inside the radial menu. Experts were asked to test the new menu and all of them could easily use all included features.

A multi-level radial menu was proposed by [16] where instead of one, three radial menus are displayed, each one responsible with one main task. The user can switch between radial menus by hovering over a different radial menu. To select an option, the user must leave the button in an outwards motion from the center of the menu. Observational results showed that most participants were quickly able to learn and use hand gestures to perform actions on screen.

Over the years, other types of menus were developed to make interaction methodologies seem more natural, being one of them the TULIP menu [17]. In this menu, each option is in one of the fingertips, but the thumb. When the users wanted to select an option, they would have to touch the thumb with the desired finger. They evaluated this menu by comparing it with a floating panel and pen and tablet menu over 30 trials. Comparing only the TULIP and the floating panel menus, for the last five trials, the mean completion time was almost the same.

A mixed reality menu was developed by [18] that allows the user to interact with a menu located in his forearm by attaching the Ovrvision and the Leap Motion to the HMD. This menu allows selection, dragging, sliding and rotation creating a variety of interaction methodologies. The debriefing session revealed that the menu is clear and easy to understand but lacked precision. Another point that the users reported was that to interact with the menu, the forearm needed to be visible and, when visible, it covered most of the field of view.

As one can see, there is little work in the state of the art that studies usability and satisfaction between these two interfaces and because of that our work intends to study them between these two interfaces. The next section will describe our study and the developed interfaces.

III. METHODS

The adopted methodology consists of a quasi-experimental design, cross-sectional study with a quantitative focus. The sampling technique used was the non-probabilistic convenience sampling procedure.

For easy reading, we defined Panel Menu on Wall as PW, Panel Menu on Hand as PH, Radial Menu on Wall as RW and Radial Menu on Hand as RH.

A. SAMPLE

The experiment was performed by 51 participants (27 men and 24 women) with ages varying between 18 and 48 years old ($M = 22.73,\ SD = 4.626$), recruited at the experiment site. The participants were mainly students (82%), with normal or corrected to normal vision and, on a 7-point Likert scale, reported good understanding of how computers work ($M = 5.86,\ SD = 0.96$), casual habits of playing video games ($M = 4.08,\ SD = 2.331$) and basic understanding of VR concept and technologies ($M = 3.96,\ SD = 1.897$). All

TABLE 1. Distribution of participants per all the 12 experiment groups. On the left are the first trial interfaces and on top the second trial ones.

Menu	PW	PH	RW	RH
PW	–	4	4	4
PH	4	–	4	4
RW	4	4	–	4
RH	6	5	4	–

FIGURE 1. VE used for the experiment trials. The VE consisted of a virtual living room of a smart house, where object states could be remotely controlled.

participants were naive to the experiment. Each participant performed the experiment twice using a different menu. Since there were four menus in total, and to balance the order each was performed, the participants were distributed by 12 groups varying the order of the two menus assigned to each, with every group having at least 4 participants (Table 1).

B. VARIABLES

The independent variables of the study were the menu type (panel and radial), the menu placement (wall and hand), and all the possible combinations of those ones (PW, PH, RW and RH).

The dependent variables were usability scores from the SUS questionnaire, user satisfaction scores from the ASQ questionnaire, effectiveness from the number of successfully performed tasks, and efficiency by the number of unnecessary steps performed during each trial and the time (in seconds) participants took to finish each trial.

C. MATERIALS

For this study, two different menus were developed for VR based on 2D desktop application menus — a panel and a radial menu. These menus had the same purpose and ability to change the state of some household objects found in a living room (i.e. TV, lights, and window blinds) in a smart house context. Fig. 1 shows the VE used during the trials.

The panel menu used the traditional WIMP (window, icon, menu and pointing device) concept (Fig. 2). This consisted of a scrollable list of buttons (available options) that would perform an action or give access to a sub-menu. These two types of buttons had a different appearance, with the ones that gave access to a sub-menu having an arrow on the right. When accessing a sub-menu, the items of the sub-menu would replace the list of buttons. The header of this menu would display the category of the current set of options and allowed the user to, at any time, go back to the previous menu or close the menu. By using a ray cast from a tracked controller of the used VR setup, perceived as laser pointer by the users, they were able to select the different buttons of the menu by pointing at them. The selected button would be activated by pressing a button of said controller.

The radial menu, on the other hand, consisted of a circular set of slices, each representing an action or giving access to a sub-menu (Fig. 3). Based on the number of slices (available options), they would be resized to all have the same size and fill the complete circle. The first option on the menu (placed on top) would always be the option to go back to a previous menu or close the menu. Like in the panel menu, the two types of options (actions and sub-menus) had a different appearance, with actions having a filled background and sub-menu buttons having only a slice of the background filled. A header title would show the current menu and when accessing a sub-menu, like in the panel type, the set of slices would be replaced by the ones of the sub-menu. For selecting the options, the circular options were mapped to a circular touchpad on the tracked controllers. By moving the finger around the touchpad, users were able to select the different options. To perform the action of the selected option, users had to press the touchpad in the same place they had their finger to select the option.

Both menu types could be either placed on a fixed position (wall) and following the user's hand by using the controllers' tracking capabilities. In the panel menu, during hand placement (Fig. 2 right), the menu would follow the hand that was not used to select the options and would always be straight up and facing the user independently of the rotation of the tracked controller. For the radial menu, when following the hand (Fig. 3 right), it was placed on top of the circular touchpad used for selection and as such, it would rotate with the tracked controller. Moreover, when following the hand, both menus were scaled down to fit the available field of view better (by not blocking it completely) and to be more comfortable to the users.

The VR application ran on a desktop computer featuring an Intel Core i7-6700K processor and an NVIDIA GeForce GTX 1080 graphics card, responsible for running the game engine and all the input and output devices required for the experiment.

The HTC Vive HMD was used for the visual stimulus and its controllers (held by the users) were used to interact with the VE and the menus. When placing a finger in the touchpad of these controllers, a visual hint appears in its virtual representation to improve the users' awareness of where their finger is on the controller. This HMD also features a 110° viewing angle and a per eye resolution of 1080×1200 pixels. Moreover, the audio stimulus was delivered with a surround system.

FIGURE 2. Panel menu type with the main menu options. Selection was made by pointing the controller at the menu. On the left is the wall placement and on the right is the hand placement.

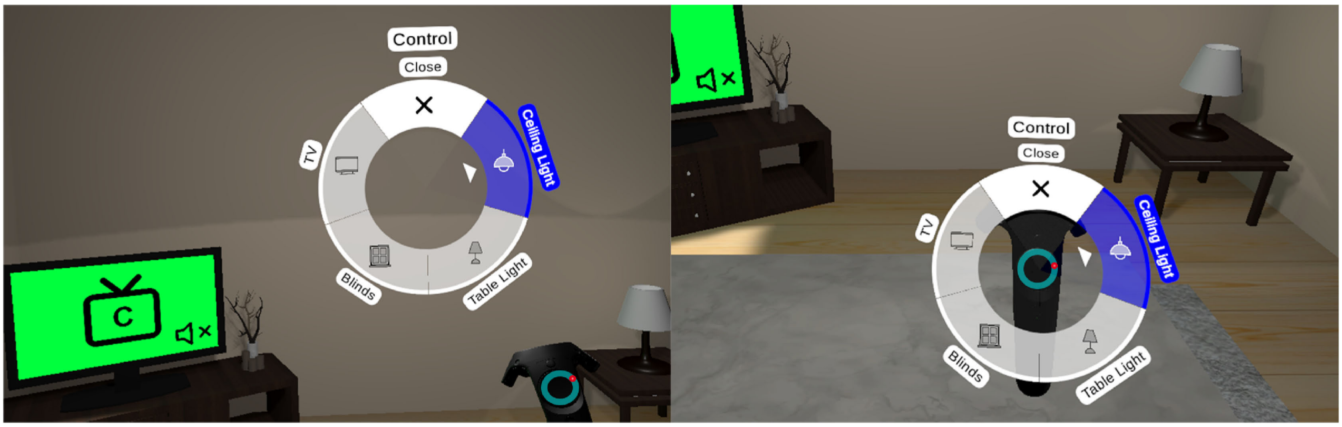

FIGURE 3. Radial menu type with the main menu options and the "Ceiling Light" option selected. The selection was made by placing the finger in the circular touchpad on the controller (red dot). On the left is the wall placement and on the right is the hand placement.

D. INSTRUMENTS

Regarding the questionnaires used, a simple sociodemographic questionnaire was used to determine the sample characteristics. To assess the menus' usability, and user satisfaction, well established and validated questionnaires were used:

- *Usability:* the System Usability Scale (SUS) [19] questionnaire was used to measure the menus' usability. The final SUS score is on a scale of 0 to 100, and is interpreted in percentiles, as shown in [20];
- *User satisfaction:* the After-Scenario Questionnaire (ASQ) [21] was used to assess the users' satisfaction with the experiment. The final score ranges from 0 to 10, with a higher value representing a higher user satisfaction.

Based on some items of the SUS questionnaire, a menu comparison questionnaire was created. This questionnaire had the purpose of assessing the participants' preference between the two menus they used during the experiment, and was composed by the following questions:

Q1: Which menu would you like to use more frequently?
Q2: Which menu was unnecessarily complex?
Q3: Which menu was easier to use?
Q4: Which menu had more inconsistencies?
Q5: Which menu would be easier to learn?
Q6: Which menu would be more inconvenient to use?
Q7: Which menu did you feel more confident to use?
Q8: Which menu would be faster to learn?

E. PROCEDURE

All experiments were carried out in a laboratory environment where all external variables were controlled. Participants were received at the experiment site and started by sitting in the middle of the VR system tracking area, filling a consent form and the sociodemographic questionnaire (Fig. 4).

The experiment consisted of two similar trials, each one using a different menu. Participants were equipped with the HMD and the respective remote controllers. Next, once seeing the VE, participants were instructed on how to use the controllers, what were the characteristics of the menu and how to interact with it. Participants were then given a few minutes to get used to interacting with the menu,

FIGURE 4. Participant seated in the experiment site, with the equipment, and ready to perform the experiment.

and once comfortable with it, the experiment scenario was loaded, and the experiment protocol took place with the first menu. Once finished, the participant filled the SUS and ASQ questionnaires. After this, the steps mentioned above were followed again for the second trial, using a different menu. Before leaving, participants filled the menu comparison questionnaire.

The experiment protocol for each trial consisted of 15 tasks (Appendix) the user had to complete using the menu and were chosen to force the participants to navigate through all the menus. These tasks were communicated by the researchers, one by one, during the experiment.

F. STATISTICAL PROCEDURES

All statistical procedures were performed using the IBM® SPSS® 24 software and the level of significance was maintained at 95% (alpha level of 0.05) for all statistical tests. Shapiro-Wilk test was used to assess the normality of the data.

For data that does not follow a normal distribution ($p > 0.05$), non-parametric tests were used to compare the different conditions, namely the Kruskal-Wallis H and Mann-Whitney U tests, and data distribution similarity was assessed by visual inspection.

Data that follows a normal distribution ($p <= 0.05$) was analyzed with the use of one-way ANOVA and independent samples t-test, and the assumption of homogeneity of variances was assessed with Levene's test of equality of variances.

IV. RESULTS

Results are shown for each trial and globally for the menu comparison questionnaire. Moreover, for each trial, results are detailed with comparison between the menu type (panel vs. radial), menu placement (wall vs. hand) and a comparison between the four possible combinations. Table 2 sums up the statistically significantly different results ($p < 0.05$) found in each trial.

TABLE 2. Dependent variables where a statistically significant difference was found ($p < 0.05$) between the menus. Between parenthesis are the menus that scored a higher value.

Menu	Trial 1		Trial 2	
P	SUS	(W)	SUS ASQ	(W) (W)
R	U. Steps	(H)	–	
W	SUS U. Steps Time	(P) (R) (R)	SUS ASQ Time	(P) (P) (R)
H	–		–	
PW RW PH RH	SUS U. Steps Time	(PW > RH) (RW > PW, PH, RH) (RW > PW, PH)	SUS ASQ Time	(PW > PH, RW, RH) (PW > RW) (RH > PW)

Effectiveness results are constant between all tested conditions, since every participant managed to complete all experiment tasks with success.

A. FIRST TRIAL

In this subsection we present the results of comparing the four interfaces in the first trial. Descriptive statistics for ASQ scores, SUS scores, number of unnecessary steps and total interaction time (in seconds) are displayed in table 3.

1) MENU PLACEMENT PREFERENCE

Considering the panel type only, distributions of the SUS scores, ASQ scores and number of unnecessary steps for the wall and hand placements of the menus were similar. Median SUS score was statistically significantly higher in the wall than in the hand ($U = 34.500$, $z = -2.316$, $p = 0.021$), whereas ASQ scores ($U = 53.000$, $z = -1.369$, $p = 0.171$) and number of unnecessary steps ($U = 81.000$, $z = 0.567$, $p = 0.630$) were not. There was homogeneity of variances for the interaction times ($p = 0.179$) and the 2.50 s (95% CI $[-5.900, 10.911]$) increase from wall to hand was not statistically significant ($t(22) = -0.618,\ p = 0.543$).

For the radial menu type, distributions of SUS scores, ASQ scores and number of unnecessary steps were also similar. No statistically significant differences were found between the two places in the SUS score ($U = 70.000$, $z = -0.986$, $p = 0.324$) and in the ASQ score ($U = 87.000$, $z = -0.169$, $p = 0.866$). However, wall placement had significantly more unnecessary steps than the hand placement, $U = 32.000$, $z = -2.843$, $p = 0.004$. There was homogeneity of variances for interaction times ($p = 0.073$), but the 12.130 s (95% CI $[-5.671, 29.932]$) increase from hand to wall was not statistically significant ($t(25) = 1.403,\ p = 0.173$).

2) MENU TYPE PREFERENCE

Considering the wall placement alone, distributions of the SUS scores, ASQ scores and number of unnecessary steps for panel and radial types were similar. Median SUS score was statistically significantly higher in the panel than in the

TABLE 3. First trial means, medians and standard deviations for each menu type relative to the SUS and ASQ questionnaires, menu interaction times (seconds) and unnecessary number of steps.

Menu	SUS			ASQ			Interaction Time			Unnecessary Steps		
	M	Mdn	SD	M	Mdn	SD	M	Mdn	SD	M	Mdn	SD
PW	96.458	100.000	8.357	6.917	7.000	0.208	73.105	71.377	7.301	1.333	0.000	1.875
PH	89.375	93.750	10.667	6.750	7.000	0.352	75.610	73.188	11.992	1.833	0.500	2.290
RW	91.875	95.000	10.451	6.610	7.000	0.650	100.303	94.022	25.670	9.250	7.000	7.263
RH	89.000	92.500	9.719	6.623	7.000	0.615	88.173	86.920	19.278	3.007	3.000	3.218

radial type ($U = 33.500$, $z = -2.344$, $p = 0.019$), whereas ASQ scores were not ($U = 57.000$, $z = -1.141$, $p = 0.254$). The number of unnecessary steps was significantly higher in the radial menu, $U = 132.500$, $z = 132.500$, $p < 0.001$. There was no homogeneity of variances for interaction time ($p < 0.001$), and the mean increase of 27.198 s (95% CI [11.221, 43.175]) from the panel to the radial menu was statistically significant ($t(12.768) = -3.530$, $p = 0.004$).

For the hand placement, distributions of SUS scores, ASQ scores and number of unnecessary steps were also similar. No significantly differences were found between the two menu types in the SUS score ($U = 85.500$, $z = -0.221$, $p = 0.825$), in the ASQ score ($U = 87.000$, $z = -0.165$, $p = 0.869$) and in the number of unnecessary steps ($U = 111.000$, $z = 111.000$, $p = 0.323$). There was homogeneity of variances for interaction time ($p = 0.100$), and the mean increase of 12.562 s (95% CI [−0.578, 25.703]) from the panel to the radial menu was not statistically significant, although a trend was found ($t(25) = -1,969$ $p = 0.060$).

3) OVERALL MENU PREFERENCE

When comparing the four menus combined, distributions of SUS scores and number of unnecessary steps were not similar between the groups, but ASQ scores were. SUS scores were statistically significantly different between the menu types, $\chi^2(3) = 10.125$, $p = 0.018$. Subsequently, pairwise comparisons were performed using Dunn's procedure [22] with a Bonferroni correction for multiple comparisons. This post hoc analysis revealed SUS score of the RH menu was significantly lower than the one obtained with the PW menu ($p = 0.016$), whereas no other group combination revealed statistically significant differences. However, participants that used menus on the wall reported on average slightly higher scores than the ones who did not.

No statistically significant differences were found between the ASQ scores ($\chi^2(3) = 2.367$, $p = 0.500$). However, looking at the mean scores, there was a slightly preference for the panel menus compared to the radial ones.

The number of unnecessary steps was significantly different between the menus, $\chi^2(3) = 18.211$, $p < 0.001$. A post hoc analysis revealed users performed more unnecessary steps in the RW menu than in the PW ($p = 0.001$), PH ($p = 0.003$) and RH ($p = 0.049$) menu types, whereas no other group combinations revealed statistically significant differences.

The assumption of homogeneity of variances was violated for the interaction times ($p < 0.001$) and there was a statistically significant difference between the menus, Welch's $F(3, 24.203) = 5.834$, $p = 0.004$. Games-Howell post hoc analysis revealed that the increase from PW to RW (27.198 s, 95% CI [4.530, 49.867]) was statistically significant ($p = 0.017$), as well as the increase of 24.693 s (95% CI [1.224, 48.162]) from PH to RW ($p = 0.038$).

B. SECOND TRIAL

In this subsection we present the results of comparing the four interfaces in the second trial. Descriptive statistics for ASQ scores, SUS scores, number of unnecessary steps and total interaction time (in seconds) are displayed in table 4.

1) MENU PLACEMENT PREFERENCE

Comparing the panel type menus, distributions of SUS scores, ASQ scores and number of unnecessary steps were similar between the two placement options. Median SUS score was statistically significantly higher on the wall than on the hand ($U = 27.000$, $z = -3.163$, $p = 0.001$), as well as the ASQ score ($U = 49.000$, $z = -2.801$, $p = 0.043$), but no statistically significant differences were found in the number of unnecessary steps ($U = 107.500$, $z = 0.876$, $p = 0.430$). There was homogeneity of variances in the interaction times ($p = 0.4515$) and the mean increase of 7.154 s (95% CI [−0.482, 14.790]) from wall to hand was not significant ($t(25) = -1.930$, $p = 0.065$).

Regarding the radial menus, distributions of SUS scores, ASQ scores and number of unnecessary steps were also similar. However, no statistically significant differences were found between the two placements in the SUS score ($U = 84.000$, $z = 0.696$, $p = 0.514$), in the ASQ score ($U = 79.000$, $z = 0.421$, $p = 0.713$) and in the number of unnecessary steps ($U = 65.500$, $z = -0.388$, $p = 0.713$). There was homogeneity of variances in the interaction times ($p = 0.652$) and the increase of 2.750 s (95% CI [−9.721, 15.220]) from the wall to the hand placement was not statistically significant ($t(22) = -0.457$, $p = 0.652$).

TABLE 4. Second trial means, medians and standard deviations for each menu type relative to the SUS and ASQ questionnaires, menu interaction times (seconds) and unnecessary number of steps.

Menu	SUS			ASQ			Interaction Time			Unnecessary Steps		
	M	Mdn	SD	M	Mdn	SD	M	Mdn	SD	M	Mdn	SD
PW	96.786	97.500	4.539	7.000	7.000	0.000	66.264	65.654	8.537	1.143	0.000	1.610
PH	79.039	77.500	16.725	6.307	7.000	1.094	73.418	74.709	10.681	1.692	1.000	1.843
RW	80.417	81.250	11.766	6.389	6.670	0.680	77.107	74.976	13.191	2.250	2.000	2.598
RH	83.542	86.250	11.454	6.472	6.665	0.627	79.857	75.046	16.121	2.250	1.000	3.049

2) MENU TYPE PREFERENCE

Considering the wall placement alone, distributions of SUS scores, ASQ scores and number of unnecessary steps were similar between the two menu types. Median SUS scores were statistically significantly higher in the panel menu type than in the radial type ($U = 17.500$, $z = -3.469$, $p < 0.005$) and median ASQ scores followed the same trend ($U = 28.000$, $z = -3.527$, $p = 0.003$). No statistically significant differences were found in the number of unnecessary steps ($U = 107.500$, $z = 1.314$, $p = 0.231$). The assumption of homogeneity of variances were met for the interaction times ($p = 0.097$) and the mean increase of 10.844 s (95% CI [1.978, 19.709]) from the panel to radial type was statistically significant, $t(24) = -2.524$, $p = 0.019$.

For the hand placement, distributions of SUS scores, ASQ scores and number of unnecessary steps were also similar. No statistically significant differences were found between the two menu types in the median SUS scores ($U = 87.000$, $z = 0.492$, $p = 0.650$), in the median ASQ scores ($U = 78.500$, $z = 0.029$, $p = 1.000$) and in the number of unnecessary steps ($U = 77.500$, $z = -0.028$, $p = 0.979$). There was homogeneity of variances for interaction times ($p = 0.232$) and the increase of 6.439 s (95% CI [−4.789, 17.667]) was not statistically significant ($t(23) = -1.186$, $p = 0.248$).

3) OVERALL MENU PREFERENCE

Comparing the four menu types, distributions of SUS scores were similar, but ASQ scores and number of unnecessary steps distributions were not. SUS scores were statistically significantly different between the different menu types, $\chi^2(3) = 16.922$, $p = 0.001$. Subsequently, pairwise comparisons performed using Dunn's procedure [22] with a Bonferroni correction for multiple comparisons, showed SUS score of the PW menu was significantly higher than the one from the RW menu ($p = 0.003$), than the PH one ($p = 0.004$) and than the RH menu ($p = 0.020$), whereas no any other group combination revealed statistically significant differences.

Statistically significant differences were found between ASQ scores ($\chi^2(3) = 11.802$, $p = 0.008$). Pairwise comparisons showed a significant higher ASQ score in the PW menu compared with the RW one ($p = 0.011$). Although no other group combinations showed significant differences, there was a clear trend with PW having a higher ASQ score than both the RH ($p = 0.074$) and the PH ($p = 0.075$).

No statistically significant differences were found regarding the number of the unnecessary steps performed, $\chi^2(3) = 1.860$, $p = 0.602$.

The assumption of homogeneity of variances was met for the interaction times ($p = 0.201$) and there was a statistically significant difference between the menus, $F(3, 47) = 3.0244$, $p = 0.039$. A Tuckey post hoc analysis revealed that the increase from PW to RH (13.593 s, 95% CI [0.725, 26.462]) was statistically significant ($p = 0.035$). Although no other significant interactions were observed, overall mean interaction times were lower in the PW menu, followed by PH, then by RW and finally by the RH menu.

C. MENU COMPARISON QUESTIONNAIRE

Fig. 5 shows, for each menu (reference), the percentage of participants that chose that menu over the others, grouped by question. Overall results show: participants would like to use more frequently the PW menu; participants perceived no menu as unnecessarily complex; a strong preference for the PW regarding ease of use; low inconsistencies in the four menus; participants reported the PW menu would be easier and faster to learn; and, participants felt more confident using the PW menu.

V. DISCUSSION

Overall results have shown a preference for the panel menu type and a preference for the fixed wall placement. This preference was corroborated by both the objective and subjective measures.

By using a ray cast type selection in the panel menu, we expected better performance results. This expectation was met, in both trials, with the panel having shorter task times and a lower number of unnecessary steps performed by the users, which was also found in reference [6]. Usability wise, although all interfaces scored in the A percentile [20], the SUS scores were also higher in the panel menu, denoting that this menu type is "excellent" to use.

Also, this study differs from most of the studies that compared radial menus to panel menus [14], [15], and where the radial type was generally better. We suspect this is due to the characteristics of the input method used for selection in this menu type. Selection in 2D desktop radial menus is

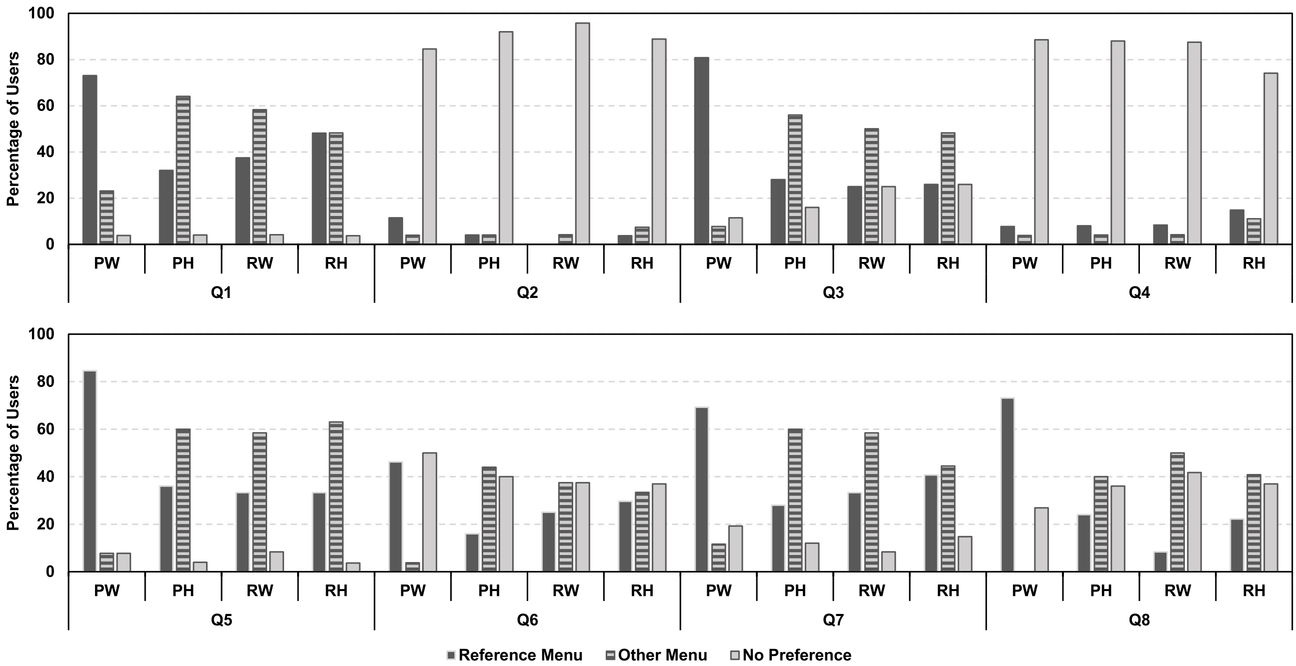

FIGURE 5. Percentage of participants that chose, for each menu (reference), that menu over the others, grouped by question.

usually done by overflowing the mouse to the direction of the option slice [16], giving it a broader target selection area. In the developed menu, as the selection was done by moving the finger around a confined round touchpad, and even though the used equipment could precisely identify the finger position with users being able to see their finger placement on the touchpad, this required participants to perform small and more precise movements, increasing the time they took to complete the trials.

Regarding the menu placement, the developed menus could be either fixed on the wall or following the user's hands. Usability scores showed a preference for wall placement, especially in the panel menu type and when comparing all the menus against each other. We expected the hand placement to score higher on the radial menu, as it was better integrated with the environment and provided more context regarding the input method (i.e. the finger overlapped the slices on the menu). Anecdotal evidence collected during the trials suggests participants found the hand placement more integrated with the environment, but that they felt more comfortable with the wall placement.

We suspect that the preference for the wall placement is directly related to the VR technology and equipment, where an HMD with a bigger field of view or the use of more natural interaction techniques, like using hand gestures, could yield different results. During the trials with hand placement, users rarely moved the hands to bring the menus to their field of view, instead preferring to move their heads around. Because of this, the hand placement had the disadvantaged of not allowing the users to perform the actions and see their outcome at the same time, while the wall placement allowed to both see the whole menu and see the objects that could be influenced by it.

VI. CONCLUSION AND FUTURE WORK

In this study, we aimed to evaluate the effectiveness and efficiency of using traditional UI menus in a 3D VR application. For this, we used a selection task where the user needed to use a menu to change the state of some living room objects of a smart house. Two different menus were developed for this task, one following a more traditional approach (panel menu) and one with a radial menu where options were presented in a circular pattern.

By measuring the menu's usability, user satisfaction, interaction times (in seconds) and the number of unnecessary steps performed, we concluded that in this VR context the panel menu was highly preferred by users as well as showed better performance results. Also, when comparing the placement of the menu in the 3D space, users preferred when the menu was fixed on the wall, instead of following their hands, since the fixed placing provided a better overview of both the menu and the virtual environment at the same time. Despite the found preference, both menu types at both placements scored well in all metrics, indicating that they can be useful and have a good performance in a 3D environment.

As there was no menu placement next to each of the objects that could change state (no context menus), we should investigate in the future how these context menus perform compared to fixed and moving menu types. Moreover, traditional menus should also be compared to more novel approaches where natural interaction is used.

ACKNOWLEDGMENT

All the works were conducted at INESC TEC's MASSIVE VR Laboratory.

APPENDIX

EXPERIMENT PROTOCOL FOR EACH MENU

Using one of the possible menus, participants were asked to perform, in order, the following tasks during the experiment:

1) *Set the ceiling light intensity to 0*
2) *Set the table light intensity to 0*
3) *Lower the blinds to half their height*
4) *Turn on the TV*
5) *Switch the TV to channel C*
6) *Increase the TV volume* 2 *levels*
7) *Lower the blinds completely*
8) *Set the table light intensity to 8*
9) *Set the table light color to the same color of the TV screen*
10) *Switch the TV to channel A*
11) *Lower the TV volume* 1 *level*
12) *Set the table light color to white*
13) *Set the table light intensity to 10*
14) *Set the ceiling light intensity to 10*
15) *Turn off the TV*

REFERENCES

[1] J. Zimmerman, J. Forlizzi, and S. Evenson, "Research through design as a method for interaction design research in HCI," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst. (CHI)*, New York, NY, USA, 2007, pp. 493–502. doi: 10.1145/1240624.1240704.

[2] J. W. Satzinger and L. Olfman, "User interface consistency across end-user applications: The effects on mental models," *J. Manage. Inf. Syst.*, vol. 14, no. 4, pp. 167–193, Mar. 1998.

[3] E. Law, V. Roto, A. P. O. S. Vermeeren, J. Kort, and M. Hassenzahl, "Towards a shared definition of user experience," in *Proc. 26th Annu. Extended Abstr. Hum. Factors Comput. Syst.*, New York, NY, USA, 2008, pp. 2395–2398.

[4] E. L.-C. Law, V. Roto, M. Hassenzahl, A. P. O. S. Vermeeren, and J. Kort, "Understanding, scoping and defining user experience: A survey approach," in *Proc. 27th Int. Conf. Hum. Factors Comput. Syst. (CHI)*, New York, NY, USA, Apr. 2009, pp. 719–728.

[5] G. Walton, "What user experience (UX) means for academic libraries," *New Rev. Academic Librarianship*, vol. 21, no. 1, pp. 1–3, Jan. 2015.

[6] S. Gebhardt, S. Pick, F. Leithold, B. Hentschel, and T. Kuhlen, "Extended pie menus for immersive virtual environments," *IEEE Trans. Vis. Comput. Graphics*, vol. 19, no. 4, pp. 644–651, Apr. 2013.

[7] P. M. Fitts and J. R. Peterson, "Information capacity of discrete motor responses," *J. Exp. Psychol.*, vol. 67, no. 2, pp. 103–112, Feb. 1964.

[8] R. H. Jacoby and S. R. Ellis, "Using virtual menus in a virtual environment," in *Visual Data Interpretation*, vol. 1668, J. R. Alexander, Ed. Bellingham, WA, USA: SPIE, Jun. 1992. doi: 10.1117/12.59654.

[9] *Ergonomics of Human-System Interaction, International Organization for Standardization*, ISO Central Secretary, Geneva, Switzerland, Apr. 2017.

[10] A. Dix, *Human-Computer Interaction*. New York, NY, USA: Springer, 2009.

[11] A. G. Sutcliffe, C. Poullis, A. Gregoriades, I. Katsouri, A. Tzanavari, and K. Herakleous, "Reflecting on the design process for virtual reality applications," *Int. J. Hum. Comput. Interact.*, vol. 35, no. 2, pp. 168–179, Mar. 2019.

[12] C. Sun, W. Hu, and D. Xu, "Navigation modes, operation methods, observation scales and background options in UI design for high learning performance in VR-based architectural applications," *J. Comput. Des. Eng.*, vol. 6, no. 2, pp. 189–196, May 2018.

[13] H. Coelho, M. Melo, J. Martins, and M. Bessa, "Collaborative immersive authoring tool for real-time creation of multisensory VR experiences," *Multimedia Tools Appl.*, vol. 78, no. 14, pp. 19473–19493, Jul. 2019. doi: 10.1007/s11042-019-7309-x.

[14] K. Das and C. W. Borst, "An evaluation of menu properties and pointing techniques in a projection-based VR environment," in *Proc. IEEE Symp. 3D User Interfaces (3DUI)*, Mar. 2010, pp. 47–50.

[15] R. Komerska and C. Ware, "A study of haptic linear and pie menus in a 3D fish tank VR environment," in *Proc. 12th Int. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst. (HAPTICS)*, Mar. 2004, pp. 224–231.

[16] M. M. Davis, J. L. Gabbard, D. A. Bowman, and D. Gracanin, "Depth-based 3D gesture multi-level radial menu for virtual object manipulation," in *Proc. IEEE Virtual Reality (VR)*, Mar. 2016, pp. 169–170.

[17] D. A. Bowman and C. A. Wingrave, "Design and evaluation of menu systems for immersive virtual environments," in *Proc. IEEE Virtual Reality*, Mar. 2001, pp. 149–156.

[18] T. Azai, S. Ogawa, M. Otsuki, F. Shibata, and A. Kimura, "Selection and manipulation methods for a menu widget on the human forearm," in *Proc. CHI Conf. Extended Abstr. Hum. Factors Comput. Syst. (CHI EA)*, New York, NY, USA, 2017, pp. 357–360.

[19] J. Brooke, "SUS—A quick and dirty usability scale," in *Usability Evaluation in Industry*. New York, NY, USA: Taylor & Francis, 1996, pp. 189–194.

[20] J. Brooke, "SUS: A retrospective," *J. Usability Stud.*, vol. 8, no. 2, pp. 29–40, Feb. 2013. [Online]. Available: http://uxpajournal.org/sus-a-retrospective/

[21] J. R. Lewis, "IBM computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use," *Int. J. Hum.-Comput. Interact.*, vol. 7, no. 1, pp. 57–78, Jan. 1995.

[22] O. J. Dunn, "Multiple comparisons using rank sums," *Technometrics*, vol. 6, no. 3, pp. 241–252, Aug. 1964.

PEDRO MONTEIRO received the B.S. and M.S. degrees in computer science from the University of Trás-os-Montes e Alto Douro, Vila Real, Portugal, in 2015 and 2018, respectively.

Since 2016, he has been a Research Fellow with the INESC TEC, Porto, Portugal. His research interests include virtual reality, the use of multisensory stimuli in virtual reality applications, virtual reality interaction, and virtual reality user interfaces.

Mr. Pedro received the Best Young Researcher Communication (Grupo Português de Computação Gráfica, Porto, Portugal), in 2017.

HUGO COELHO received the B.S. and M.S degrees in computer science from the University of Trás-os-montes e Alto Douro, Vila Real, Portugal, in 2015 and 2018, respectively, where he was a Research Fellow, from 2017 to 2018.

Since 2018, he has been a Research Fellow with the INESC TEC, Porto, Portugal. His research interests include virtual reality, multisensory virtual reality applications, virtual reality interaction, virtual reality user interfaces mixed reality, and mixed reality applications.

GUILHERME GONÇALVES received the bachelor's degree from the University of Trás-os-Montes e Alto Douro (UTAD), Vila Real, Portugal, in 2015, where he is currently pursuing the M.Sc. degree in multimedia. His research interest mainly includes multisensory virtual reality.

MIGUEL MELO is currently an Invited Lecturer with the Department of Engineering, University of Trás-os-Montes and Alto Douro, Portugal. He is also the Manager of MASSIVE Virtual Reality Laboratory. He has been a Postdoctoral Researcher with the INESC TEC, since 2010. His research interests include computer graphics, high dynamic range, and multisensory virtual reality.

MAXIMINO BESSA is currently an Assistant Professor, with Habilitation, with the Department of Engineering, University of Trás-os-Montes and Alto Douro, Portugal. He is also the Director of the Multisensory Virtual Reality Laboratory MASSIVE. He has been a Senior Researcher with the INESC TEC, since 2009. He is a member of the Eurographics Association, since 2003. He was the Vice-President of the Portuguese Computer Graphics Chapter, from 2016 to 2018.