An Evaluation of Pie Menus for System Control in Virtual Reality

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ABSTRACT

While natural interaction techniques in virtual reality (VR) seem suitable for most tasks such as navigation and manipulation, force-fitting natural metaphors for system control is often inconvenient for the user. Focusing on traditional 2D techniques like pie menus and exploiting their potential in VR offers a promising approach. Given that, we design and examine the four pie menus *pick ray* (PR), *pick hand* (PH), *hand rotation* (HR) and *stick rotation* (SR), addressing usability, user experience (UX), presence, error rate and selection time. In terms of UX and usability, PH was rated significantly better compared to HR and SR; PR was rated better compared to SR. Presence was not affected by menu design. Selection times for PH were significantly reduced compared to SR. PH and PR resulted in significantly decreased error rates compared to SR and HR respectively. Based on these findings, we eventually derive implications for developers of VR applications.

CCS CONCEPTS

• **Human-centered computing** → *Human computer interaction (HCI)*; Empirical studies in HCI; Interaction paradigms; *Virtual reality*.

KEYWORDS

Virtual Reality; System Control; Pie Menu; Radial Menu; Head-Mounted Dissplays

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1 INTRODUCTION

The rising popularity of consumer grade virtual reality (VR) head mounted displays (HMD) and corresponding input devices facilitates novel ways of interaction. An often stressed approach are natural user interfaces (NUI), which are usually based on realistic metaphors mimicking familiar everyday actions. In contrast to WIMP (Windows, Icons, Menus, Pointer) interfaces, NUIs blend the user's input and output space, offer direct interaction and leverage the rich potential of human sensory and motor skills [24].

With increasing complexity of current VR applications, the need for extensive interaction techniques, especially with regard to *system control*, increases accordingly. As one of the four main interaction tasks (the others being navigation, selection and manipulation), system control can be described as sending commands to the application or changing the mode of interaction and system state respectively [2]. More sophisticated system control tasks (e.g., loading, saving or filtering data) rarely correspond to realistic metaphors, as suggested by NUIs. While it is possible to force-fit such actions into real-world counterparts, it can be quite cumbersome for both the designer and the user [2].

We argue that most users have gotten used to WIMP metaphors by now. Due to its success in most traditional desktop-based operating systems and office applications, using a pointing device to interact with menus seems almost "natural" to the user. Certain aspects of the WIMP metaphor, especially menus, are exhaustively investigated and implemented in various shapes—e.g., a dropout menu as a list of items or a context-sensitive pie menu [22, 23]. Therefore, the adaption of familiar menu-based techniques for VR can be a reasonable approach for handling extensive system control. In contrast to navigation, selection and manipulation in VR, system control tasks are less frequently examined. Consequently, the review, adaption and evaluation of menu-based system control in VR may lead to new insights and implications for developers.

Our paper makes the following contributions:

- We discuss the design of four different pie menus for system control tasks in VR by extending existing work.
- We examine four different pie menus in respect to usability, user experience (UX), presence, selection time and error rate.
- We present the study results and derive implications for future menu designs.

2 RELATED WORK

In this section we discuss basic menu design approaches for 3D user interfaces, which serve as a foundation to our review of existing implementations, both 2D and 3D.

2.1 Basic Menu Design

Jacoby & Ellis list the following aspects of menu design: *invocation*, *location*, *reference frame*, *cursor*, *highlighting*, *selection* and *removal* [26]. Invocation refers to necessary user actions to bring up the menu, while location determines its position. The reference frame involves a possible movement of the menu according to the

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user's field-of-view or a point in space. The cursor aspect determines the presence of feedback while pointing. Highlighting covers visual aid while items are about to be selected, whereas the selection aspect includes how an item is eventually chosen. Removal refers to the menu's behavior after a selection was made (i.e., does it remain active or will it collapse).

A taxonomy developed by Dachselt & Hübner comprises, i.a., *intention of use*, *appearance and structure*, *placement*, *invocation and availability*, *interaction and I/O setting*, and *combinability* [6]. Intention of use describes the underlying goal of the user and corresponding options, hence determining the number of displayed items and a potentially hierarchical design. Appearance and structure cover the shape, layout, displayed data (e.g., text or images) as well as the size and spacing of displayed menu items. Placement includes the reference point (i.e., fixation of the menu in 3D space), orientation, and the ability to reposition the menu. Invocation and availability comprise how the menu is brought up, whether it is visible temporarily or continuously, how it is animated, as well as the ability of being collapsed. Interaction and I/O setting include input devices being used for interacting with the menu, the application type (e.g., VR or augmented reality), dimensionality (i.e., supported degrees of freedom (DOF) and congruent input mapping), appropriate feedback when highlighting a menu item, and the visualization of the selection path. Combinability describes the ability of the menu to include sub menus for realizing hierarchies.

LaViola et al. propose the three aspects *representation and structure*, *selection* and *placement* [16]. Representation and structure include the menu's size, shape and spacing as well as possible clustering and sequencing or the establishment of a functional hierarchy. Selection determines the way users choose a menu item, involving appropriate mapping of the device's DOF on the menu's DOF and suitable input. Placement covers the positioning of the menu in 3D space. The aspects suggested by LaViola et al. provide a condensed yet sufficiently fine-grained classification for the following review of related menu implementations as well as for the menu design, which will be discussed later in this work.

2.2 Representation and Structure

In traditional WIMP applications, menus are often rectangular-shaped and structured as linear lists of items. For *pie menus*, however, items are arranged along the circumference of a circle. Each item has the same shape and is equidistant from the circle's center.

Calahan et al. compared linear menus to pie menus in a 2D desktop environment [4]. For pie menus, both target seek times and error rates were decreased. The authors argued that these advantages can be seen as a result of better memorability and the fixed distance between initial pointer position and selection target, according to *Fitts's Law* [8]. However, users were undecided concerning their subjective preference. Santos et al. showed that selection times of pie menus were significantly reduced compared to list menus in VR, while neither error rates nor user preferences have been significantly affected [29]. Das & Borst examined pie menus in contrast to list menus in VR [7]. Item selection time for pie menus was lowered by 10 % and the error rate was significantly reduced.

Regarding the disadvantages of pie menus, Gerber & Bachmann found that with an increasing number of menu items, selection times and error rates were rising accordingly, hence strongly limiting the maximum number of simultaneously displayed items [10]. Additionally, Hopkins noted that pie menus need particularly more screen space compared to list menus [12].

2.3 Selection

Gebhardt et al. examined *pick ray*, *hand projection* and *hand rotation* for selecting items from a pie menu in a projection-based VR [9]. For pick ray, a beam is rendered from the input device, indicating the cursor position. This method exploits the input device's full 6-DOF tracking capabilities. Hand projection maps the device's position to the 2D menu (2-DOF), whereas hand rotation further reduces the DOF by limiting the selection to the rotation of the input device in its forward direction (1-DOF). For each method, the selection is confirmed by a button press. While error rates were low in general, the majority of errors was made by using hand rotation. Selection times of pick ray compared to hand projection and hand rotation were significantly reduced. Pick ray was also most preferred, followed by hand rotation. Techniques similar to hand rotation were evaluated by various other studies with partially positive results in respect to selection time and error rate [5, 10, 18, 28].

A study performed by Poupyrev et al. compared two methods for selection and manipulation purposes: *virtual hand* and *virtual pointer* [21]. For both techniques, hands were rendered in VR, whose position and orientation were defined based on a tracked 6-DOF input device. Object selection using the hand was realized by moving it into the object and confirming the choice by a button press. For virtual pointer, a ray was attached to the hand, which allowed interaction from afar by pointing at an object and pressing a button on the input device. In close range, there were no significant differences between virtual hand and pointer in terms of object selection time.

Das & Borst introduced two pointer-attached-to-menu techniques: *PAMT* and *PAMO* [7]. Both were realized by attaching a selection ray directly to the menu. PAMT employed transition and rotation for item selection, whereas PAMO simply mapped the rotation. Both techniques were compared to a conventional method using a ray cast. The ray cast was preferred by 53 % of the users. Selection times were reduced by 6 % compared to PAMO but not significantly reduced compared to PAMT. Ray cast error rates were not significantly decreased—neither compared to PAMO nor PAMT.

LaViola et al. argue that buttons on the input device (e.g., joystick or dial) can be used to select menu items. In modern games, the selection of inventory items is frequently performed via pie menus using the analog stick of dedicated input hardware [11, 14, 27]. However, this approach is rarely addressed in scientific work. To the best of our knowledge, solely Wolf et al. examined menu selection via *analog stick* for 3D pie menus by comparing it to a *multimodal approach* using voice and gesture commands [34]. For analog stick, menus items were highlighted according to the direction the stick was pushed and eventually selected by pressing a button on the input device, the Oculus Touch™ controller. Participants rated the multimodal menu significantly better in terms of usability and the perceived feeling of presence. However, neither error rate nor selection time was measured in the study. It also lacked a comparison to ray-based techniques or other methods using an input device.

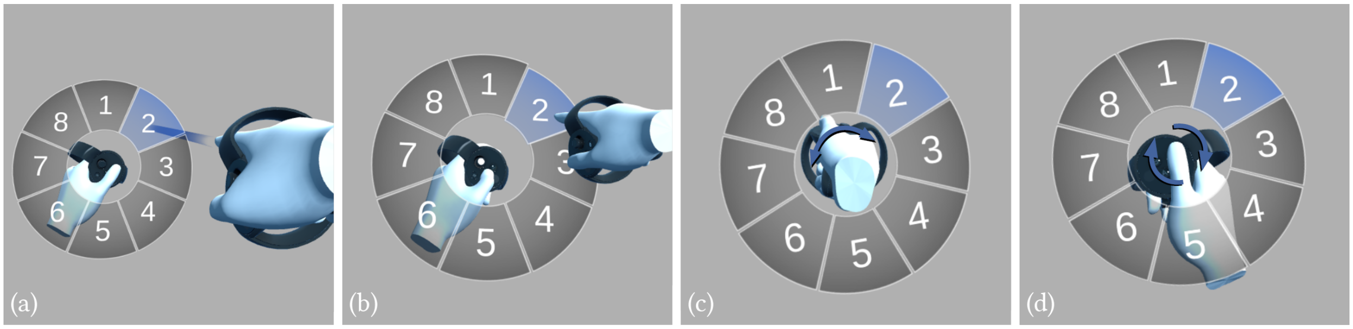

Figure 1: Menu designs: (a) pick ray (PR); (b) pick hand (PH); (c) hand rotation (HR); (d) stick rotation (SR)

2.4 Placement

Regarding the positioning of a 3D menu, LaViola et al. consider the aspects *world-referenced*, *object-referenced*, *head-referenced*, *body-referenced* and *device-referenced* [16]. While world-referenced menus are placed at a fixed location in 3D space, object-referenced menus are attached to an 3D object offering control in the sense of a context menu. According to Das & Borst such a *context-sensitive* placement can lead to a reduction of selection times by 18 % compared to a fixed world-referenced position [7].

Both head- and body-referenced menus yield a strong reference frame, making it easy for the user to locate the menu in 3D space [16]. According to Mine et al., body-referenced hand-held widgets benefit interaction by stimulating the rich potential of human proprioception and by enabling users to move the widget outside their field of view and consequently reducing occlusion [19]. Exploiting *body awareness and skills* by addressing the proprioceptive sense of users is one of the key aspects (the others being *naïve physics*, *environment awareness & skills*, *social awareness & skills*) of *reality-based interaction* (RBI) and can have a positive impact on the overall UX [13, 24]. Wolf et al. developed a body-referenced pie menu attached to the users hand, following its every movement through the 3D tracking space [34], which can even facilitate eyes-off interaction [16].

While the former mentioned aspects address the placement in virtual space, device-referenced menus can be bound to actual physical devices providing additional haptic feedback [16].

3 MENU DESIGN

This section describes the design process of the menus. We propose the four menu styles *pick ray* (PR), *pick hand* (PH), *hand rotation* (HR) and *stick rotation* (SR). Each menu's design is based on the aspects structure, placement and selection proposed by LaViola et al. [16]. We use two 6-DOF Oculus Touch™ controllers to interact with the menus—one for each hand. The input devices are tracked in real time and offer additional digital buttons as well as analog sticks and triggers. In VR, both of the user's hands are displayed bound to the respective input devices' position and orientation.

3.1 Representation and Structure

Due to the significant advantages of radial menu structures compared to linear ones [4, 7, 29], every suggested menu style in this paper (PR, PH, HR, and SR) uses a radial layout. We limit the maximum number of displayed menu items to eight. This value is drawn from the implementation developed by Gebhardt et al. [9], whereby the maximum number of nine up to eleven items proposed by Gerber & Bachman is not exceeded [10]. Each menu item has an upper bound of about 11 cm and a lower bound of about 5 cm in length as well as lateral bounds of about 8.5 cm in length. The whole menu has a diameter of 28.5 cm. The currently selected item is highlighted by a change of color. In addition, auditory and vibrotactile feedback is provided.

3.2 Selection

The selection of menu items is the main difference between the four menu styles. For PR, a ray is cast from the virtual finger (i.e., the input device) of the dominant hand into 3D space, indicating the cursor position [9, 21] (see Figure 1a). The selection is performed explicitly by pressing a dedicated button ("A" or "X" respectively) on the input device. PH exploits the virtual hands of the user by allowing selection using the tip of the index finger to press down a virtual menu item (see Figure 1b). When interacting with the button, it is visually pushed down according to position of the finger tip, stimulating known properties of the physical world. This approach reflects the naïve physics dimension of the RBI framework [13] and can benefit the overall UX [24]. While limiting the interactive space to the user's reach, we expect no drawbacks in terms of performance compared to remote selection techniques (e.g., ray cast) in close range [10]. HR uses the wrist's rotation around its forward direction to highlight a menu item [5, 10] (see Figure 1c). To avoid strain, a constant rotational gain of factor 2.5 is applied [9]. The highlighted item is selected by releasing the invocation button. SR uses the input device's analog sticks. Similar to Wolf et al. [34] and a variety of modern games [11, 14, 27], moving the stick in a certain direction causes the corresponding item to be highlighted [34] (see Figure 1d). The highlighted item is eventually selected by releasing the invocation button.

3.3 Placement

While object-referenced placement can lead to reduced selection time [7], it prevents a more general application due to its inherent context-sensitive nature. We favor a non object-referenced, more flexible approach—e.g., as a main menu. World-referenced as well as device-referenced menus lack a strong reference frame, while head-referenced menus following the user's every move, can occlude crucial parts of the virtual environment. Body-referenced and hand-held menus in particular offer both a strong reference frame and the opportunity to manually handle occlusion [16, 19]. For PR and PH, the menu is attached to the non-dominant, for HR and SR to the dominant hand. Menu invocation is handled by pushing down the trigger on the input device with the index finger. The menu is closed when the trigger used for invocation is released or a selection is confirmed.

4 USER STUDY

We conducted a user study in order to examine the influence of the menu styles PR, PH, HR and SR on different measures. Our basic study design drew upon the concept presented by Mundt & Mathew [20], addressing error rate, selection time, overall usability and UX—as suggested by the majority of related work [5, 9, 10, 18, 21, 28]. As a crucial phenomenon in VR, we also observed presence (i.e., the feeling of being in the VR) [32], which has hardly been considered by related work and solely been addressed by Wolf et. al [34].

4.1 Hypotheses

Related work suggests that ray-based techniques are superior in terms of selection time, usability and user preference [7, 9]. However the arbitrary initial pointer position of PR does not exploit the advantages of pie menus regarding Fitts's Law [4, 8]. Based on Fitts and Calahan et al., we rather expect SR to be superior in terms of selection time and error rate, due to its short distance between the selection target and initial pointer position, as well as the virtually infinite target size within certain radial bounds [4, 8]. According to Preim & Dachselt, addressing RBI's naïve physics to offer realistic feedback for PH could benefit the overall UX [24]. Additionally, Slater states that a strong plausibility (i.e., understandable, realistic behavior) in VR can positively affect the perceived presence [32].

Drawn upon these findings we expect to observe the following effects:

(H1) PR has the highest usability
(H2) SR requires the shortest selection time
(H3) SR is the least error prone
(H4) PH provides the highest UX
(H5) PH shows the highest presence

4.2 Participants

24 subjects (7 female and 17 male, age $M = 28.33$ years, $SD = 4.58$ years) participated in the user study. All participants reported normal or corrected to normal sight. Regarding their experience with VR, 15 participants reported usage on a regular basis, 14 had little or some experience, and 3 participants never experienced VR before.

4.3 Apparatus

The experiment's VR environment was developed using Unity 2018 and displayed on the Oculus Rift™ HMD. Two Oculus Touch™ controllers were used for input—one dedicated device for each hand. The study was run on an Intel® Core™ i7-8700K computer with 32 GB of memory and a Nvidia GeForce GTX 1080 Ti video card.

4.4 Task

We chose a generic selection task, where radial menu items were represented by numbers from one to eight. Participants had to select randomized sequences from a defined set of menu items (1, 3, 4, 6, 8) for five times. The current item of concern was presented visually and acoustically.

The selection task was composed of three basic sub tasks:

- Invoke menu
- Highlight menu item
- Confirm highlighted menu item and close menu

4.5 Procedure

At first, the participants were seated on a chair with armrests so that they could rest their arms between conditions. They were handed out a written study description outlining the task and interaction with the four menus. Then, they answered questions regarding their age, gender, sight and dominant hand, as well as possible experience with VR. Afterwards, the first condition (i.e., menu style) was assigned to the user. In order to avoid learning effects or fatigue, all conditions were counterbalanced. Each condition was accompanied by a short training phase, after which the selection task was eventually carried out. After completing the selection task, the participants left the experimental VR scenario and filled out a series of questionnaires. The sense of perceived presence was evaluated using the IPQ [30]. Since all participants were native German speakers, the IPQ was preferred over other presence questionnaires due to its validation for the German language. The SUS [3] addressed the usability and the UEQ [15] was used to measure the UX. This approach was repeated for all remaining conditions. The entire procedure took about 45 to 60 minutes per participant.

5 RESULTS

Analysis was conducted in R [25] using the packages ez [17] for analysis of variance and ggplot2 [33] for producing figures. The data was analyzed using a one-way ANOVA with repeated measures. All results are reported at a significance level of .05. Table 1 shows the main metrics.

Mauchly's test indicated that the assumption of sphericity has been violated for *selection time* ($p <$ **.001**). The degrees of freedom were therefore corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.542$). The corrected analysis of variance revealed a main effect of menu style on selection time ($F(1.63, 37.43) = 13.792$, $p <$ **.001** (*GG*)). Post-hoc analysis using a Bonferroni-adjusted paired t-test indicated that PH was faster than SR ($p =$ **.010**). However, selection time did not significantly differ between PH-HR ($p = .083$), PH-PR ($p = 1.0$), PR-SR ($p = .068$), PR-HR ($p = .400$) or HR-SR ($p = 1.0$). Figure 2 shows the mean selection time.

While the assumption of sphericity has been violated, a Greenhouse-Geisser-adjusted ($\varepsilon = 0.576$) analysis of variance indicated a main effect of menu style on *error rate* ($F(1.73, 39.76) = 8.770$, $p <$ **.001** (*GG*)). Error rates were low in general and throughout the whole study, participants using PH made no errors at all. A Bonferroni-adjusted

Table 1: Mean values (standard deviation) over all participants for the menu styles pick ray (PR), pick hand (PH), hand rotation (HR), and stick rotation (SR) [n = 24]

	Selection Time (s)	Error (count)	SUS	Pragmatic Quality	Hedonic Quality	Attractive-ness	IPQ
PR	1.37 (0.45)	0.00 (0.01)	78.33 (19.01)	1.76 (1.03)	1.15 (1.08)	1.28 (1.05)	3.06 (1.03)
PH	1.28 (0.26)	0.00 (0.00)	86.46 (13.12)	2.16 (0.65)	1.27 (1.09)	1.76 (1.25)	3.20 (1.02)
HR	1.63 (0.43)	0.04 (0.04)	65.52 (22.19)	1.03 (1.27)	0.81 (1.12)	0.61 (1.32)	2.74 (0.92)
SR	1.72 (0.66)	0.04 (0.06)	60.21 (26.08)	0.85 (1.68)	0.06 (1.26)	0.08 (1.67)	2.51 (1.10)

paired t-test revealed that errors were significantly less often made with PH in comparison to SR (p = **.001**) and HR (p = **.002**). Using PR also lead to a reduced error rate compared to HR (p = **.003**) and SR (p = **.002**). Statistically significant differences occurred neither between PH-PR (p = 1.0) nor HR-SR (p = 1.0). The error means are displayed in figure 3.

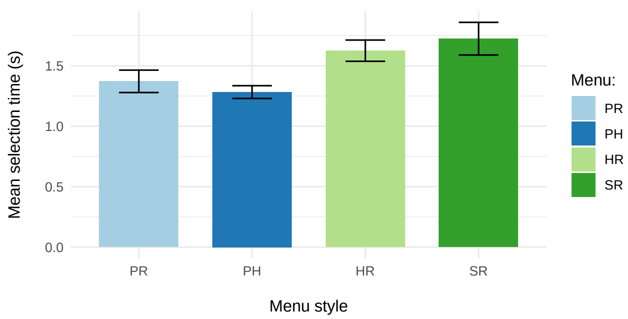

Figure 2: Mean selection time in seconds for the menu styles PR, PH, HR and SR. Error bars indicate the standard error of mean.

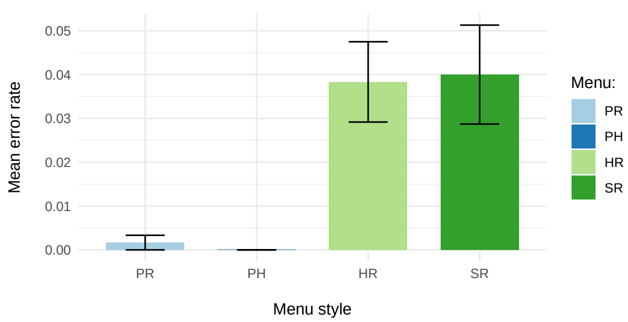

Figure 3: Mean error rates for the menu styles PR, PH, HR and SR. Error bars indicate the standard error of mean.

The analysis of the SUS questionnaires revealed a main effect of menu style on *usability* ($F(3, 69) = 9.632$, p < **.001**) . Post-hoc analysis using a Bonferroni-adjusted paired t-test showed that PH was ranked significantly higher than SR (p < **.001**) and HR (p = **.004**), respectively. While participants ranked PR higher compared to SR (p = **.018**), the score did not significantly differ between PR and HR (p = .205). There were also no differences between PH-PR (p = 1.0) and HR-SR (p = 1.0). Figure 4 shows the mean SUS scores. According to the SUS's adjective rating scale by Bangor et al. [1], SR and HR offered an "OK" usability, while PR reached a "good" result and PH was just ranked "excellent" (see Figure 5).

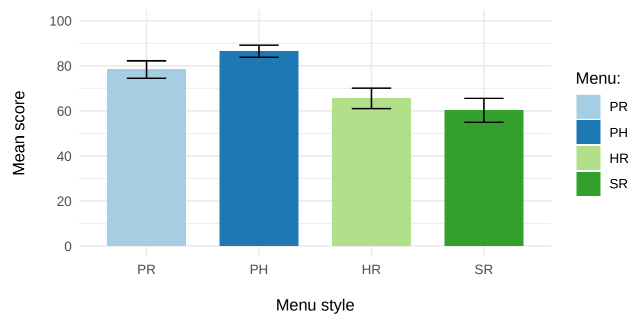

Figure 4: Mean SUS (scale from 0 to 100) score for the menu styles PR, PH, HR and SR. Error bars indicate the standard error of mean.

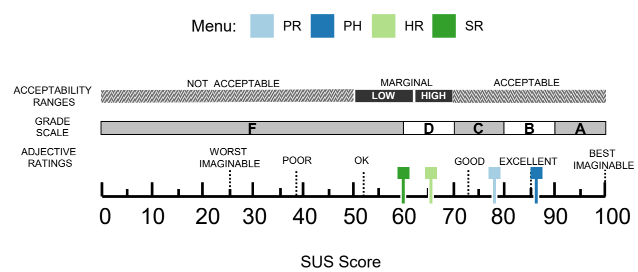

Figure 5: Adjective ratings, acceptability scores, and school grading scalese of the menu styles according to Bangor et al. [1]

Addressing the UEQ, the analysis of variance indicated a main effect of the menu style on the *pragmatic quality* ($F(3, 69) = 6.998$, p < **.001**). While a Bonferroni-adjusted post-hoc analysis showed significantly higher pragmatic quality of PH compared to SR (p = **.002**) and HR (p = **.010**), there were no differences between PR-SR (p = .070), PR-HR (p = .245), PH-PR (p = 1.0) and HR-SR (p = 1.0). Due to the violation of the assumption of sphericity, indicated by Mauchly's test (p = **.044**), the degrees of freedom for UEQ's *hedonic quality* were corrected using Huynh-Feldt estimates of sphericity ($\varepsilon = 0.852$). The

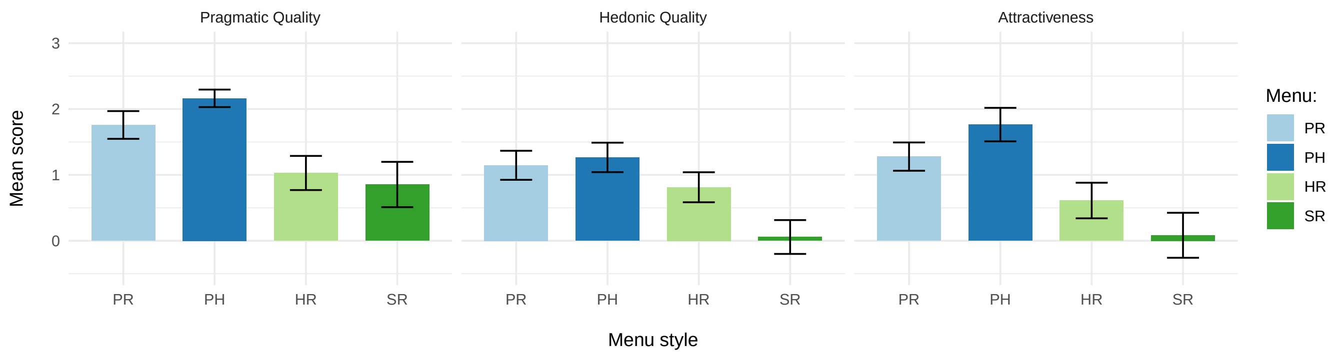

Figure 6: Mean UEQ (scale from -3 to 3) ratings asd for the menu styles PR, PH, HR and SR. Error bars indicate the standard error of mean.

corrected analysis still revealed a main effect of menu style on the hedonic quality ($F(2.56, 58.77) = 6.164$, $p < \mathbf{.001}$ (HF)). A post-hoc Bonferroni-adjusted paired t-test showed that PH ($p = \mathbf{.002}$) and PR ($p = \mathbf{.008}$) ranked significantly higher than SR. However, the hedonic quality did not differ between PH-HR ($p = 1.0$), PH-PR ($p = 1.0$), PR-HR ($p = 1.0$) and HR-SR ($p = .144$). For UEQ's *attractiveness* the assumption of sphericity was again violated ($p = \mathbf{.002}$). The Huynh-Feldt-corrected ($\varepsilon = 0.849$) analysis of variance revealed a main effect of the menu style ($F(2.55, 58.55) = 7.997$, $p < \mathbf{.001}$ (HF)). A Bonferroni-adjusted paired t-test indicated that the attractiveness is significantly higher for PH compared to SR ($p < \mathbf{.001}$) and HR ($p = \mathbf{.022}$) as well as for PR compared to SR ($p = \mathbf{.016}$). The post-hoc analysis also revealed that there is no difference between PR-HR ($p = .533$), PH-PR ($p = 1.0$) and HR-SR ($p = 1.0$). The mean scores for each of the UEQ's dimensions are shown in figure 6.

While the analysis of variance suggested a main effect of menu style on *presence* measured by the IPQ ($F(3, 69) = 10.632$, $p < \mathbf{.001}$), the post-hoc paired t-test using Bonferroni adjustment revealed no significant differences between PH-SR ($p = .131$), PH-HR ($p = .730$), PR-SR ($p = .391$), PR-HR ($p = 1.0$), PH-PR ($p = 1.0$) or HR-SR ($p = 1.0$). This may be due to insufficient statistical power. Figure 7 shows the mean presence.

Most participants preferred PR (37.50 %) and PH (29.17 %). A minority preferred SR and HR (16.67 % each). Half of the participants disliked SR the most, 37.50 % considered HR the least preferable. Only one user least preferred PH, while two users did so for PR (see Figure 8).

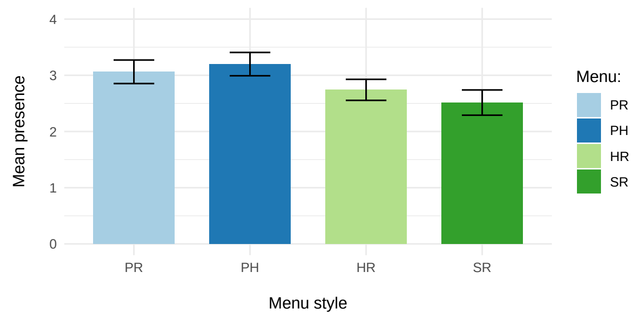

Figure 7: Mean IPQ (scale from 0 to 6) ratings for the menu styles PR, PH, HR and SR. Error bars indicate the standard error of mean.

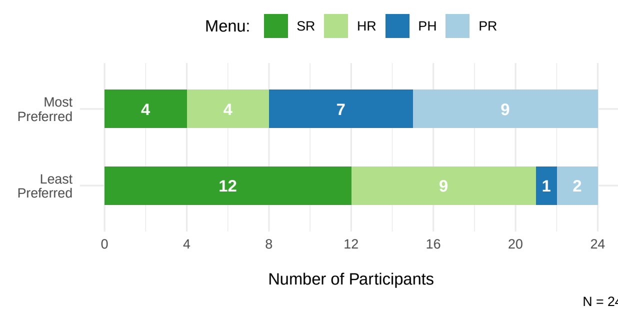

Figure 8: Most and least preferred menu styles SR, HR, PH and PR

6 DISCUSSION

We have to reject **H1** (PR has the highest usability). SUS's analysis suggested that PR's usability was higher in comparison to SR only and did neither differ from PH nor HR. The pragmatic quality assessed by UEQ supports this finding by also indicating no significant difference between PR and HR, or PR and PH respectively. However, while not differing from PR, PH has shown a significantly higher usability than HR or SR—according to both the SUS and the UEQ's pragmatic quality. The "excellent" rating of PH (see Figure 5) according to the adjective interpretation of Bangor et al. [1] further supports these findings and suggests that PH may offer the highest usability—at least compared to SR or HR.

H2 (SR requires the shortest selection time) has to be rejected. The results even suggested that for SR, the mean selection time was particularly high. SR was the only menu style which had a significantly longer selection time compared to at least one other menu style (PH). Though we based our hypothesis on the short movement and low motor strain benefiting the selection when using SR's analog sticks, the motion required to move the stick in the right direction may have been too precise. Therefore, over-and undershooting could have occurred more frequently, which may have lead to corrections and thus to a longer selection time. Mean selection time using PR did not differ from PH, which is supported by the work of Das & Borst [7]. In contrast to the findings of Gebhardt et al., which indicated a reduced selection time of ray based approaches, we found PR not to be significantly superior to any other menu style [9]. Furthermore, we did not find any differences between HR and any other style, which contradicts the findings of Poupyrev et al., claiming a significantly reduced selection time of a ray-based technique compared to a rotation-based one [21]. Given the seemingly rather long distance between pointer and target as well as the particularly high motor effort, we did not expect PH to have shorter selection times compared to any of the other menu styles. The presumably natural character of PH, which was influenced by the real world action of pushing a button, may have benefited the selection time. For PR and PH we observed that most participants used the chair's armrests not only for recreational purposes between trials, but to hold the non-dominant hand in a comfortable position while the dominant hand was moved to perform the selection tasks. Furthermore, most users kept their dominant hand in a prepared position, expecting the next selection task. This behavior could have benefited PR and especially PH, leading to shorter selection times compared to SR and HR, where this kind of priming was not possible. We assume that selection times would have been negatively affected for PR and PH when participants had to return both arms to an initial position (e.g., the chair's armrests) before each selection.

We have to reject **H3** (SR is the least error prone). The fine motion required to select items using SR may also have lead to a significantly increased error rate compared to PR or PH respectively. Participants using PH made no errors over the entire course of action; PR provided a similarly low error rate. The error rate of HR was significantly higher than PR, which is confirmed by the findings of Gebhardt et al. [9].

We cannot confirm **H4** (PH provides the highest UX). While PH's hedonic and pragmatic quality was ranked higher compared to SR only, it's attractiveness was significantly increased in comparison to both SR and HR. Therefore, PH may not be providing the highest but a significantly high UX—especially in terms of attractiveness. The ordinary, more traditional approach using the analog stick, may have lead to the particularly low UX provided by SR.

We have to reject **H5** (PH shows the highest presence). In fact, we did not find any significant differences between the menu styles, although it was suggested by the analysis of variance. This was probably due to insufficient statistical power. Also, it is worth noting that the measurement of presence using questionnaires is discussed quite controversially in the scientific community [31].

Although we expected different, the analysis suggested that SR performed particularly poorly. The common use of this technique in modern video games [11, 14, 27] is seemingly not a valid indicator for its suitability to perform system control tasks—at least in VR, where more natural ways of interaction can be addressed using 3D input devices. This is also supported by the subjective user preferences, where SR is reported the least preferred menu style by half of the participants, closely followed by HR. PR and PH, which performed relatively well, were in sum preferred by two-thirds of the participants, which is supported by the findings of Poupyrev et al., claiming that the ray-based technique was preferred by roughly 53 % of the participants [21] and by Gebhardt et al., according to whom the ray-based style was also the most preferred [9].

7 CONCLUSION

In this work we described the design of four different pie menu styles—mainly distinguished by item selection and menu placement. While pick ray (PR) employed a ray cast from the user's dominant hand to pick an item from the menu attached to the user's non-dominant hand, pick hand (PH) pursued a more natural approach using the mere fingertips. The menu styles hand rotation (HR) and stick rotation (SR) were both attached to the user's dominant hand. Selections were made by either rotating the dominant hand or the analog stick on the input device.

The menus were compared in an empirical evaluation investigating their impact on usability, UX, presence, error rate and selection time. The results indicated that PH provided a significantly higher usability than HR and SR. PR's usability was increased compared to SR. In terms of UX, PH was rated significantly better compared to HR and SR, whereas PR tended to be better than SR. Selection times were the lowest for PH, but only significantly reduced compared to SR. Using PH and PR resulted in significantly less errors compared to SR and HR respectively. Presence has not been affected by menu style. A majority of seven-eights least preferred either HR or SR, whereas two-thirds most preferred PR or PH.

We found all menu styles to be usable in general, but no configuration truly superior. Consequently, providing known interaction techniques in form of pie menus can be seen as a reasonable approach regarding system control tasks in VR.

In order to address different preferences, we suggest to merge the two menu styles PR and PH. When interacting with the menu from afar, selection is done PR-style—with the ray visible, rendered from the tip of the stretched index finger. In close range, however, the ray vanishes and selection is done PH-style, using the mere finger tip.

Based on user preferences and partly based on subjective and objective measures, two categories seemed to have emerged: PR and PH, as well as HR and SR. Exploring these categories for pie menu interaction may be addressed in future work. We suggest the following possible dimensions: two- vs. single-handed, pointing- vs. rotation-based, and 6-DOF vs. 1-DOF (or maybe a classification by DOF in general). Designing pie menus fitting these categories and evaluating them in user studies may lead to new findings.

Regarding the suggested categories, we speculate that a trade-off may exist between two- and single-handed pie menus. Two-handed menus may be more usable or at least more preferred than single-handed ones, but lack the opportunity to leave one hand open for parallel or additional interaction tasks. We also suspect another trade-off concerning the involved DOF. Addressing only one DOF may lead to less screen space being occupied, but it may also have a negative influence on the menu performance. Developers designing pie menus for system control tasks in VR may keep that in mind.

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