Exploring Selection and Search Usability Across Desktop, Tablet, and Head-Mounted Display WebXR Platforms

Anthony Scavarelli
Carleton University
Ottawa, Canada
anthony.scavarelli@carleton.ca

Robert J. Teather
Carleton University
Ottawa, Canada
rob.teather@carleton.ca

Ali Arya
Carleton University
Ottawa, Canada
ali.arya@carleton.ca

2023 9th International Conference on Virtual Reality (ICVR) | 979-8-3503-4581-0/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICVR57957.2023.10169549

***Abstract*— We present a comparative evaluation of a VR learning application on desktop, head-mounted displays, and tablet platforms. We first evaluated fundamental interaction, including selection and search, and general usability across these platforms using Circles, our custom-built WebXR application. We developed two virtual environments for the study: (1) a selection and search testbed, and (2) a virtual learning environment developed for use within a post-secondary gender diversity workshop. Performance and general usability results were consistent with past studies, suggesting that WebXR offers adequate performance to support learning applications. However, designing a compelling user experience in VR remains challenging, although web-based VR offers accessibility benefits due to its multi-platform design. Finally, as this study was conducted remotely during the COVID-19 pandemic, we also reflect on how our system and study accommodate remote participation, similar to a traditionally lab-based experience.**

Keywords—virtual reality, webxr, selection, search fitts law, learning, virtual learning environment

I. INTRODUCTION

Virtual reality (VR) technology has advanced significantly in recent years, resulting in widespread applications [16, 40, 70], novel research endeavours [19, 43, 45], and promising learning opportunities [17, 48, 52]. Our research focuses on using VR in social learning spaces, where users learn together or alone across physical and virtual realities, such as classrooms and museums. These social learning spaces can use physical and digital tools to re-create more authentic, engaging, and transformational learning experiences [52]. However, many challenges remain in using VR in social learning spaces, where accessibility is critical [9, 27]. Head-mounted displays (HMDs) are currently the predominant VR platform today, and yet, several limitations of HMD-based VR limit access to the technology. These include cybersickness [18, 38, 52], social anxiety from unfamiliar technology [44, 72], not having the physical means to "grasp" virtual objects [39], or the space to walk around in virtual environments (VEs) [32, 53]. Since learning requires an inclusive and accessible approach, we argue that VR-based education applications must support multiple hardware platforms so users with varying abilities, experience, and technology access can still benefit from VR. Notably, some VR learning applications support desktop and HMD-based VR in recognition of this goal [10, 34, 75].

Some multi-platform VR systems support desktop, mobile, and HMDs. However, there has been relatively little research in this area, especially on mobile platforms where a handheld device acts as a window or "portal" [37] into a VE. Designing usable VR applications is challenging due to the lack of 3DUI standardization, personal preferences, physiology, and user psychology [31]. These challenges are compounded in systems that adapt across various displays, devices, and inputs. A multi-platform VR approach to social learning spaces is essential [52] as many post-secondary institutions embrace a Universal Design for Learning (UDL) approach [25], where learning content must be accessible from a variety of modalities [27].

Previous multi-platform VR research has shown that users strategically change between VR platforms for learning depending on the task [75]. Yet, currently, the only VR platform that natively supports desktop, HMD, and mobile VR is WebXR [71]. However, there is little empirical evidence comparing the relative performance of the three platforms supported by WebXR (desktop, mobile, and HMD) or if the performance of the individual platforms is in line with non-WebXR studies in VR interaction. In addition, many developers and HMD manufacturers are now working towards better supporting WebXR applications such as Mozilla Hubs [40] and FRAME [16]. Yet, without comparative studies of WebXR's platforms and frameworks that make it more accessible, the relative effectiveness of each supported platform is unclear.

Our study consists of three parts: 1) a selection experiment, 2) a search experiment, and 3) a virtual learning environment (VLE) exploration experiment using selection and search techniques from earlier in the study. To narrow the scope, we focused on selection and search in VR. This has the advantage of enhanced experimental control while focusing on the technical interactions of selection and search. The most common VR interactions include selection (target acquisition), manipulation (changing the pose of objects), and navigation (moving through an environment) [2, 33]. In practice, many systems employ selection-based metaphors for both manipulation (e.g., remote pointing to move objects [33]) and navigation (e.g., selection-based travel via pointing at a location to teleport [33]). Selection-based travel often requires the environment to include selection targets that the user points at to teleport around space. These selection-based interaction methods are beneficial as they reduce the physical movement required of users [18, 33, 52]. Moreover, they align well with the capabilities of various platforms. For example, selection-based interaction can be used with an HMD controller (remote pointing), a desktop mouse (clicking selection targets), or a mobile touchscreen in mobile VR. Existing selection techniques can be leveraged to make selection more accessible [13, 67]. This is critical in social learning spaces where we cannot assume all users have the physical space and abilities to use more immersive interaction techniques [52]. We are unaware of past studies using WebXR to compare platform capabilities beyond desktop and HMD VR.

We aim to quantify performance differences between WebXR platforms and determine if they align with past VR selection and search studies. However, our study focuses less on including the distractor objects required for the formal definition of "visual search" [73] and more on the mechanical ability to orientate a viewport to select a static target from in and out of the user's view. Though visual search is the closest parallel, to avoid ambiguity, we will refer to our search task as "search" rather than "visual search." The quantitative performance evaluation part of our study consists of 1) a target selection experiment following a 3D extension [61] of Fitts' law [14, 36] employing the ISO 9249-9 standard [77] and 2) a search experiment in a basic VE, without distractors, to test general usability of look controls (Fig. 1). These two tasks frequently occur in most VR applications and are essential in learning applications. Note that interactions in our study employ the default display/controller interaction configurations provided by the A-Frame WebXR framework [1]. The HMD is paired with motion controller "laser controls," which use a ray cast from the controller to intersect with and select virtual objects, e.g., virtual objects and teleport checkpoints and HMD orientation for viewport orientation. The mobile conditions use finger-based tap for selection and device orientation for viewport orientation. In contrast, the desktop uses the left mouse click for selection and mouse drag for viewpoint rotation.

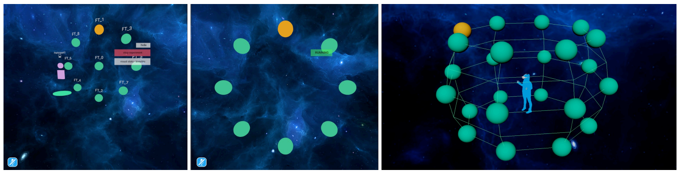

Fig. 1. The Circles framework's "Research Room" runs on Google Chrome (desktop) for both the researcher (left) and the participant (centre). The left and middle images show the Circles WebXR website running on two Google Chrome instances where users can be in the same virtual "research room" for a Fitts law task. First, the participant is asked to select the orange (active) target (centre), under the supervision of the researcher-observer, that can control the experiment start, end, and researcher visibility (left). Next, the (right) image is a render of the visual search task setup where the participant (blue Figure) is asked to select an orange target that appears in one of the 24 possible positions (the green targets, during the experiment, would not be visible to the participant).

After selecting and searching, participants completed a more qualitative and holistic exploration experiment within a VLE. All interactions in this part used the same selection and search techniques practiced in the first part of the study. The VLE walk-through is an example of an unguided learning activity [66] created for a gender diversity workshop (Fig. 2). Finally, we collected subjective data via several questionnaires, including a self-consciousness scale (SCS) [54], NASA-TLX [41], the Intrinsic Motivation Inventory (IMI) [24], focusing on subjective and personal differences between platforms, and a System Usability Score (SUS) to capture general usability [4]. We also used a Slater, Usoh, and Steed (SUS) presence questionnaire [69]. Although it is not recommended for vastly different platforms, presence is not a focus of this study. The SUS questionnaire provided a basis for a difference between platforms. While the primary goal of our research was to compare the VR platforms, the follow-up part contextualizes our work within learning research and draws linkages between learning outcomes and quantitative performance metrics.

The study used the open-source Circles WebXR learning framework [51], built with A-frame, as Circles aims to reduce interactions, such as navigation and object manipulation, to symmetric (working similarly regardless of VR platform) [12, 51] single selection actions across all supported WebXR platforms to make them more "simple and intuitive" [64].

Fig. 2. The Circles framework's "Women in Trades" Electrician's School Lab runs on Google Chrome (desktop) from a participant's perspective. These images show two virtual artefacts, safety gloves, a clipboard, and a drill. Users learn more about challenges in learning spaces by selecting a virtual learning artefact (VLA) and finding more information via audio and text narration and object manipulation via the three-button selection-based UI under the artefact.

Our research questions include the following:

RQ1. What are the differences between the desktop, tablet (mobile), and HMD WebXR in terms of selection and search performance, and usability? Are these differences consistent with prior multi-platform VR performance studies?

RQ2. Does multi-platform WebXR, specifically the Circles framework, show potential for usably supporting learning activities within social learning spaces?

Our hypotheses:

H1. Selection performance (in terms of selection speed and error rate) will be best with desktop, then mobile, then HMD.

H2. Search will be fastest with the HMD due to the larger field of view and natural head movement orientation, then desktop, and slowest with mobile.

H3. Performance results will be similar to past studies.

H4. Circles, and WebXR more generally, will show potential for learning in social learning spaces.

II. RELATED WORK

Several environmental constraints exist when discussing the performance and usability of a multi-platform WebXR framework within a social learning context. Specifically, when learners use a VR device, the experiences should have interactions that allow for rich interaction within a physically stationary (non-moving) position. Furthermore, these interactions should be simple and intuitive across all supported platforms [64]. Within this context, we can reduce most complex interactions to their fundamental "selection" and "search" forms.

A. *Selection Studies*

VR interactions fall under three main categories: selection, manipulation, and travel [2, 33]. Furthermore, selection and manipulation techniques are classified into six interaction metaphors. These include grasping (e.g., using a virtual hand), pointing (e.g., ray-casting), surface (e.g., using a 2D multi-touch surface), indirect (e.g., a ray-cast selection and multi-touch gestures to modify without directly selecting the object of interest), bimanual (using two hands to interact), and hybrid interaction techniques that change depending on the context of selection [33].

Selection studies often compare performance between various input and display methods, i.e., comparing varying mouse gain values on desktop [65], pointing task performance with "fish-tank" VR [62], and comparing head-based and eye-based selection tasks [47]. Fitts' law – a human performance model of rapid aimed movements – is frequently employed for studying 2D selection. There are several proposals for using Fitts' law in three dimensions. These include discussions on target properties in 3D selections using virtual hands [60], the development of new models for more accurate predictions on pointing selection tasks [29, 76], and research into extending Fitts' law to incorporate depth [7] through both translation and rotation [59]. Many studies have validated Fitts' law across decades of HCI research [57].

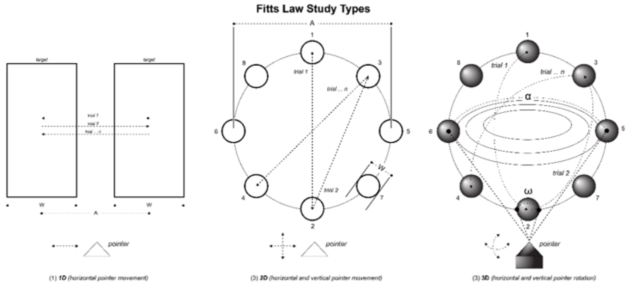

Fig. 3. The most common forms of Fitts Law selection studies (left) utilize a simple pointer device, and the user selects the center vertical target, moves from one side to the next, and back again for n number of trials. The 2D form (centre) asks the user to select targets number 1, then 2, and so on for n trials where the user can move in both the vertical and horizontal direction. The 3D version (right) is similar to the 2D version but requires a pointer device, i.e., a laser pointer. Due to the use of a "laser/ray-casting" pointer, the angular (rotational) distance (deg) is used to determine the width of targets (ω) and distance between targets (α). This study uses 2D and 3D forms.

1) *Fitts' Law*

As selection is one of the most prominent interactions across 2D and 3D contexts [33], many studies have investigated the selection performance difference between various input and display modalities. To standardize experimental design and improve consistency between study results, Fitts' law [14, 36] is widely used for studying selection performance by comparing the "transmission of information" [23], represented via the throughput metric (bits/second) [14, 29, 55].

Fitts' law was initially developed for 1D contexts [14], where movement time is recorded as participants repeatedly select two vertical targets (Fig. 3, left). Fitts' law was later re-purposed for 2D contexts where several targets are arranged in a circular pattern. Users select each target in a clockwise sequence, moving from one side of the circular arrangement to another (Fig. 3, centre). For 3D tasks employing ray-casting to select remote targets, Fitts' law has been modified to quantify distal pointing tasks [29, 59].

Fitts' law is a predictive model of target selection time based on the distance to and size of the target. The log term in Equation 1 below is the Index of Difficulty (*ID*); this variant presents the "Shannon" formulation of ID [55, 57] commonly used for 2D selections, e.g., selecting targets on a flat screen:

$$ID_{2D} = \log_2\left(\frac{A}{W} + 1\right) \tag{1}$$

ID_{2D} is the Index of Difficulty for a 2D selection surface, where *A* refers to the amplitude or distance to the target, and *W* refers to the width of the selection target. However, distal pointing involves selecting targets within an immersive virtual or physical 3D space (e.g., selecting virtual targets within an HMD or selecting targets on a screen using a physical pointing device). This should consider rotation movements of the wrist and arm [29], which better reflect user movement to reduce arm fatigue or the "gorilla-arm" effect [22]. Though several formulae are used to describe Fitts distal pointing tasks [29, 57, 59], we focus on Kopper et al.'s form, which considers the rotation-based motions of our joints naturally [47]. However, the relationship between translational and rotational movements is not always clear in 3D tasks [68]. The formula for calculating angular distance follows [29, 59]:

$$ID_{angular} = \log_2\left(\frac{\alpha}{\omega^k} + 1\right) \tag{2}$$

where α is the angular distance from the starting point to the selection target, and ω is the angular width of the target. The term k describes a non-linear relationship between α and ω, as target selection often involves two phases – ballistic *and* correction [29, 35].

A primary component to facilitate objective comparison between conditions is the throughput measure (*TP*). Throughput is a standard measure for understanding the relationship between *ID* and movement time (*MT*) across various selection inputs. The formula for *TP* is as follows [57]:

$$TP = \frac{ID}{MT} \tag{3}$$

B. *Search Study*

Identifying an element or target within a virtual environment is crucial for exploring and navigating VEs. More formally, Visual search tasks "determine if a specific target item is or is not present among the distractor items" [73]. Visual search tasks are an intrinsic part of VE navigation, such as wayfinding, whereby a user must understand their place within a VE and be able to plan a route through it and the travel or movement through the VE itself [33]. Most strategies include landmarks [56] but other techniques, such as having overview or "view-in-view" maps [74] and may incentivize participants through means such as finding the exit in a virtual fire [6]. Search tasks are essential for finding objects, points of interest, or landmarks within VEs and VLEs, such as virtual museums.

Several studies investigate search performance across various factors. For example, studies assessing search performance under different display field of view (FoV) conditions have shown that FoV, and target movement from out of view, plays a vital role in allowing users to find targets [20, 42], though perhaps not enough of an effect to help train for real-world scenarios [50]. Additionally, head-rotation amplification may aid search tasks [49]. Some studies also suggest that audio cues may help users find targets, particularly those outside the FoV of the display [15]. At the same time, other researchers have investigated the use of search tasks to help with neurorehabilitation [28]. However, in all noted studies, there appears to be no standard form of assessing search performance, as there is for selection tasks and Fitts' law. In addition, many studies are performed within complex VEs or information-rich virtual environments [42], often as virtual recreations of real-world spaces.

C. Multi-Platform VR

Very few modern VR frameworks support more than one platform (e.g., supporting mobile and immersive HMD VR). The only real exceptions are the WebXR-based Mozilla Hubs [40] and Frame [16], which support VR across several platforms - desktop, mobile, and HMD. In addition, some social VR experiences, such as VRChat [61], have desktop clients to increase participation in social VR experiences, as exclusive HMD-supported applications appear not yet commercially viable [63].

In multi-platform research, studies suggest that HMD VR performs better than desktop VR for 3D navigation tasks within a maze using smooth locomotion [58]. One study found participants perform better using desktop VR over HMD VR for spatial tasks [58], which aligns with other results showing significant differences between desktop VR and HMD VR in the gazing behaviour of participants [11]. Still, the differences were negligible in the wayfinding plans detailed at the end of the study [11]. Another study examines the differences between tablet and HMD AR for 3D selection performance, finding the HMD less fatiguing [46]. However, we could not find studies comparing desktop, tablet, and HMD VR simultaneously, though these VR platforms are highlighted by early researchers in the VR field [5].

With the exploration into more accessible VR and APIs such as WebXR natively supporting multi-platform VR, there is potential to explore multi-platform VR research, even if many implementations currently do not support mobile well and may have usability and technical issues [10, 75]. Additionally, there is evidence that supporting multi-platform VR allows individuals to switch between platforms to use better each platform's advantages and disadvantages, such as higher presence and focus with HMD VR [34, 75] and better multitasking with desktop VR [75].

III. METHODOLOGY

Our investigation consisted of three separate experiments. The first and second focused on selection and search within a simple virtual environment to avoid distractions. The third experiment was an open exploration to investigate general usability in a simulated VLE as a more authentic use case. Initially designed as a lab-based within-subjects study to compare three VR platforms – desktop, tablet (mobile), and HMD- we switched the study to a between-subjects remote study during the COVID-19 pandemic [8] shut down university campuses. A between-subjects design allowed us to recruit participants that only required one of the three VR platforms rather than all three. We scheduled 45-minute meetings with recruited participants via video calling for communication. We used a web-based social VR platform called Circles [51] and an associated "research VE" (see Fig. 2) we developed for connecting with participants as virtual avatars with their given VR platform. We performed the selection and search tasks within the research VE for each participant, collecting performance data (time for target selection and the number of times a selection target is not correctly selected). For the third part of the study, we asked participants to explore a VLE more informally and its three virtual learning artefacts (VLAs) in Circles, asking them to talk aloud so that we could capture notes about their exploration and experience of the virtual environment.

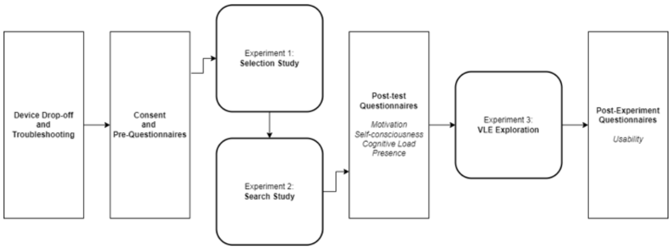

Fig. 4. A time-based flowchart of our three-experiment study.

A. Participants

We recruited a total of 45 post-secondary students (18 female, 23 male, 3 non-binary, and 1 did not answer) between the ages of 18-44 (M = 26.93 years, SD = 7.64 years), with 15 participants assigned to one of each VR platform – desktop, mobile, or HMD. All participants were technically inclined and aware of VR, though many had not personally tried HMD VR.

B. Apparatus

For all HMD users, we lent out Oculus [Meta] Quest 1 HMDs. For 8 of the 15 mobile participants, we lent out a 10.4" Samsung Galaxy Tab S6 Lite tablet (the others used various personal tablet devices). We had 15 HMD devices and two mobile tablet devices that we could lend out, and each device was sanitized, dropped off, and picked up at each participant's residence. Each participant with a borrowed device had it for approximately two weeks (at least one week before the study to have time to set up and troubleshoot any issues with the researcher). All desktop participants used their own devices.

Most of the tablets used were 10 in. Apple iPad tablets and most desktop systems used 21.5 in. 1920x1080 displays with a standard mouse and keyboard. We recorded display resolution, pixel density, and scale to calculate target sizes across this study's various personal tablet and desktop screen sizes. The complete study consists of three experiments, each composed of multiple unique tasks: selection tasks, search tasks, and open-ended exploration tasks that ask the user to select and manipulate three VLAs (Fig. 4). For selection tasks, the participant selects each target displayed one at a time. This employs a predictable pattern crossing the circle of targets with each subsequent selection as recommended by the ISO 9241-9 standard (Fig. 3, centre). E.g., the participant would click each circle/target highlighted in orange as it appears clockwise around the circles seen in Fig. 1 right (changing to various target widths and depths), and the Circles apparatus would capture and record the time of selection of the number of errors to a spreadsheet file the researcher can downloads at the end of the experiment to analyze post-study.

Upon completing the selection experiment, the participant starts the search experiment. Targets were displayed one at a time around the participant to find and select in the same research VE (Fig. 1, right). After all targets are selected, the participant is asked to follow a web link for a post-test questionnaire. In the final VLE Exploration experiment, the participant is introduced to a single VLE recreation of a college electrician's lab created for a women in technology workshop (Fig. 2). We asked participants to explore the VLE and select and manipulate the three VLAs present (a drill, a clipboard, and a pair of safety gloves). Next, the researcher asks the participant to talk aloud about their thoughts on the VLE, interactions, feelings, sounds etc., in real-time. The researcher recorded these thoughts as observer notes. Finally, we gave the participants another survey link to follow and complete a post-experiment questionnaire. At the end of the experiment, the researcher asked if they had any questions and solicited any further participant feedback. Throughout the study, the researcher frequently asked how participants felt about pausing the experiment and if participants experienced any discomfort. All participants completed the experiment with minimal issues.

C. *Procedure & Design*

The first experiment is a between-subjects (VR platform) 3×3×3 Fitts' law selection experiment where the independent variables are the input method (desktop, tablet, HMD), target width (0.25m, 0.5m, 0.75m), and depths – z-distance from participant to target (5.0m, 7.0m, 9.0m). Our dependent variables included selection time (ms), error rate (% of targets missed), and throughput (bit/s) calculated as described in Equation 3, Section 2.1. Each condition included 16 trials, i.e., individual target selections. In total, participants completed a total of 3 platforms × 3 target widths × 3 depths × 16 trials × 15 participants for a total of 6480 selection data points.

The second experiment is a between-subjects (VR platform) 3×3 search experiment where the independent variables are the input method (desktop, tablet, HMD), x-axis position (3 possible positions), and y-axis position (8 possible positions). Each condition included 4 trials. In total, each participant completed a total of 3 platforms × 3 x-axis positions × 8 y-axis positions × 4 trials × 15 participants for each platform for a total of 4320 total search data points (some data points failed to capture due to a minor bug we fixed later, so the actual total is 4198). Fig. 2, right depicts all search targets positions. Our dependent variables included selection time (ms) and error rate (% of targets missed). After the selection and search experiments, participants filled out a post-test questionnaire capturing the self-consciousness scale [54], NASA-TLX [41], the Intrinsic Motivation Inventory [24], and SUS presence [69].

For the open usability experiment, participants used the selection and search techniques they practiced in the first two tasks to explore a complex VLE created for a gender diversity workshop (Fig. 2) and select and manipulate (using selection-based techniques) three VLAs found within. We felt that exploring this space in an informal and unguided manner best followed a learning activity that instructors may ask their students to explore inside or outside of classrooms for a few minutes, and we wanted to keep an open mind to how participants would use the Circles framework and explore the associated VLE. This concept aligns with Circles' proposed objective of not replacing classrooms but instead acting as a learning tool alongside other more traditional analog and digital teaching methodologies [51]. After the open usability experiment, we captured general usability with a questionnaire capturing the System Usability Score [4]

IV. RESULTS AND ANALYSIS

We describe the results for each of the three tasks below.

TABLE I. RESULTS FOR THE SELECTION AND SEARCH STUDIES

Platform	**Select. Time (ms)**	**Select. Error %**	**Select. ID**	**Select. TP.**	**Search Time (ms)**	**Search Error %**
Desktop	795.99	0.066	4.22	5.80	2472.60	0.17
Tablet	829.35	0.15	4.19	5.63	3301.36	0.30
HMD	1099.98	0.12	4.49	4.40	2830.85	0.12

A. *Selection Performance*

One-way ANOVA detected significant differences in selection time ($F_{1,45} = 17.65$, $p < .05$) and throughput ($F_{1,45} = 8.85$, $p < .05$). Tukey-Kramer HSD post hoc tests revealed that that the HMD was significantly worse than the tablet and HMD platforms. We found no significant differences in the number of errors and thus do not report statistical results. The average error rates in TABLE I are in ranges expected from similarly designed Fitts' law experiments [47].

The absence of a significant difference between desktop and tablet and the higher-than-expected TP of desktop suggests that the variety of personal desktop devices introduced some noise into the experiment, reflected in the large standard deviations seen in Fig. 5 (left). Still, the general themes align with past results demonstrating superior performance with desktop input over VR-based input [57]. In general, 2D-based direct manipulation techniques offered better performance than the 3D motion controllers, likely due to a combination of arm fatigue and complexity from the additional degrees of freedom required for control [26]. Typically, Fitts' law studies compare selection techniques on a single platform using consistent IDs across conditions. Using the $\text{ID}_{\text{angular}}$ calculation for the HMD yielded slightly different IDs than the desktop and tablet. The $\text{ID}_{\text{angular}}$

equation treats distance and width as angles measured in degrees (Equation 2, Section 2.1). This was necessary for the HMD distal ray-based pointing, as the usual ID formulation used for desktops and tablets uses straight-line distances (e.g., in pixels or cm, see Equation 1, Section 2.1). We note that we used a k value of 1.0 in our $\text{ID}_{\text{angular}}$ calculation for consistency with previous studies [47]. Changing k might have yielded IDs closer to those used with the tablet and desktop. However, as throughput results in the same units of "information" (bits/s), it still feels relevant to compare various devices using it [57], even if the numbers do not align due to vastly different VR displays and inputs.

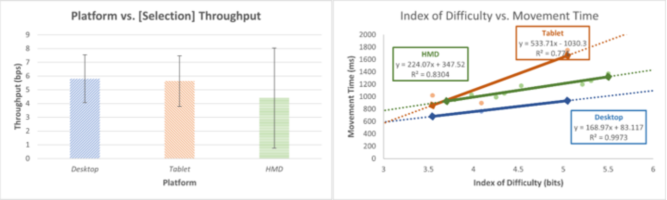

Fig. 5. Left: Throughput (bits per second) by VR platform. Errors bars show ± 1 SD.]. Right: Linear regression model for all VR platforms, showing the relationship between ID and MT.

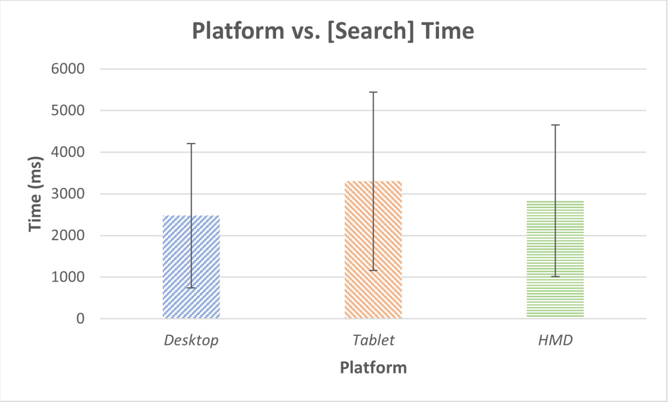

Fig. 6. Search Time (milliseconds) by VR platform. Errors bars show ± 1 SD.

B. *Search Performance*

One-way ANOVA revealed significant differences in search time ($F_{1,45} = 8.63$, $p < .05$) and in selection errors ($F_{1,45} = 4.17$, $p < .05$). Tukey-Kramer post hoc tests revealed that the tablet offered significantly worse search performance than either the desktop and HMD (Fig. 6). This is likely due to the much smaller screen and the tablets. Search performance with the desktop and HMD were roughly the same and not significantly different. We will ignore the errors here as the only significance revealed by post hoc analysis was between tablet and HMD, suggesting that participants' more refined movements of using their fingers resulted in fewer errors than the gross motor skills required to use their wrist and arm to select targets with the motion controller connected to the HMD. Selection is also not the focus of the "search" study.

We also analyzed our post-test questionnaires (IMI, SCS, NASA-TLX, SUS presence) using the non-parametric Kruskal-Wallis test. We did not find significant differences between platforms for intrinsic motivation, interest/enjoyment ($p = 0.25$) or perceived competence ($p = 0.25$). In addition, we did not find significant differences between platforms in cognitive load using the NASA-TLX survey ($p = 0.47$). However, we did see a significant difference for the SUS presence questionnaire [69] ($h(2) = 10.92$, $p = 0.0042$). Furthermore, Dunn's posthoc test revealed that participant presence with the HMD was significantly higher than with either the tablet ($p = 0.015$) or the desktop ($p = 0.0016$). This was expected due to the more immersive qualities of the HMD, which likely enhanced presence. Finally, there was a significant difference between platforms for the public social consciousness scale ($h(2) = 7.31$, $p = 0.025$). Dunn's posthoc test revealed a significance between the desktop and tablet groups within the public social consciousness scale ($p = 0.0067$), where desktop scored higher than tablet. Public self-consciousness "refers to a tendency to think about those self-aspects that are matters of public display, qualities of self from which impressions are formed in other people's eyes" [54]. This difference suggests that participants were more aware of the researcher using desktop. This is likely because they used the same device to video chat with the researcher to complete the study. Whereas, with tablet and HMD, participants used a secondary desktop computer for video-calling and did not directly engage with the researcher during the study.

C. *Open Usability Exploration*

As seen in TABLE I, the main themes found in this part of the study were "Artefact," "Discussion," "Enthusiasm," "Learning Potential," "Navigation," "Personal Preferences," "Suggestions," "Surprising," "Technical Challenges," "UX Challenges," and "Virtual Environment." The VLAs and VLEs quickly become the focus, as the visuals were often described as "cool" and the detail incredibly "full," "more lived-in [which] … makes it feel like more my reality". The ambient sounds of exhaust fans and people's voices were noted often, with several participants commenting that they "love" the ambient sounds and the VLA's audio narration. The verbal narration of a first-person description of the challenges they faced within the trades as a woman was appreciated as the narration "helped with reading" the mirrored text bubbles (Fig. 2).

However, there were also several UX issues noted by participants. Selecting menu items was notably challenging to understand since being parented to the virtual camera often resulted in occlusion by objects within the VLE. Also, several artefact control items had unclear iconography. For example, the down arrow (bottom-middle button, under the held artefact in Fig. 2) used for releasing or dropping a VLA was interpreted as a download icon and ignored. Many participants found the VLEs easy to navigate the virtual space using the teleport pads dotted throughout the room and mouse, tablet orientation, or HMD orientation to look around. However, there were many challenges beyond the UX issues. Some technical issues included Wi-Fi failing, audio issues, graphical glitches (e.g., a door not to scale), physical discomfort (e.g., HMD too heavy, holding a tablet for too long is difficult), and mild cybersickness. Some non-technical issues included "daily life" disruptions, such as cats scratching at the door, roommates talking in the room, and feeling uncomfortable wearing the HMD around others, suggesting feelings of social embarrassment [3].

TABLE II. The qualitative data was analyzed in observation notes and open-ended post-questionnaire questions about the final "VLE Exploration" experiment in this study. First, with an expected set of thematic codes from our literature review (deductive), then adding codes found with data that did not fit easily or were surprising (inductive), we determined 11 central themes.

Deductive Codes	# of Refs.	Deductive Codes (cont.)	# of Refs.
Artefact UX Negative	36	Technical Challenges	11
Artefact UX Positive	4	VE Negative	0
Discussion	15	VE Positive	20
Enthusiasm	19	WebXR Novelty	3
Interaction Negative	7	Presence	9
Interaction Positive	5	Psychological Discomfort	1
Personal Preferences	10	Suggestion	22
Physical Discomfort	18		

Inductive Codes	# of Refs.	Inductive Codes (cont.)	# of Refs.
Artefact Positive	3	Surprising	10
Competitive	1	Unexpected Behaviour	5
Gaming Experience	1	UX Positive	12
Learning Potential	7	Navigation	7
Social Embarrassment	1		

Final Themes (after the merge and sort of codes)	
Artefact	Suggestions
Discussion	Surprising
Enthusiasm	Technical Challenges
Learning Potential	UX Challenges
Navigation	Virtual Environment
Personal Preferences	

We also coded the observation notes and the post-experiment questionnaire data for the more complex "gender diversity" VLE (TABLE I)—much of the discussion centered around the UX, VLAs, and VLEs. Participants commented on challenges like being unaware of how to manipulate objects, e.g., not seeing manipulation buttons or not realizing they were for manipulation due to ambiguous iconography and lack of labels. Participants also appreciated the audio narration accompanying each artefact selection, although many found it challenging to follow audio narration while reading the simultaneously displayed text. We also analyzed our post-experiment questionnaire data using the non-parametric Kruskal-Wallis test. We did not find significant differences between platforms using the SUS usability test ($h(2) = 10.92$, $p = 0.66$)., suggesting UX challenges were universal across all VR platforms.

V. DISCUSSION

In this section, we summarize themes found in the study.

A. Selection Performance

Selection performance with each platform confirms hypothesis H1: the desktop performed best, followed by tablet and HMD, though our throughput scores appear high. As previously found [61], the familiarity and precision of the desktop mouse offered superior performance over the 3D controller [25], while tablet was a close second—the HMD ray-pointer controls required significantly more motor movements. Though these results are in line with past studies (hypothesis H3), we do note a discrepancy between our throughput scores, which are higher at 5.9 bits/s than typically expected of desktops (~3.7 – 4.9 bits/s) [57]. This higher performance may be related to the variety of personal desktop machines used, participant familiarity with their own devices and better hardware (e.g., gaming mice) not commonly employed in lab-based studies. While we collected display resolution and size, participants may have misreported. Screen-sharing to view participant computer settings would have helped, but we elected not to as it seemed an unreasonable privacy breach.

Additionally, our HMD ray-pointer results were also higher than expected [47, 61], suggesting that using the angular Fitts' law equation (Equation 2, Section 2.1) may not capture all details in both rotating and translating during a distal pointing task, something noted by other researchers [68]. Additionally, Henrikson et al. found that Kopper et al.'s angular Fitts model did not match their data well [21], noting "this contrast to prior work warrants future investigation" [21]. The WebXR-based apparatus may introduce some unknown factors into the capture of selection time, but that also the use of ray-pointer evaluation within stereoscopic HMD VR is inconsistent.

B. Search Performance

The HMD and desktop offered the best search performance, confirming hypothesis H2. This is likely because of the naturalness with which users can look around an environment relying on the motion-sensing capabilities of the HMD. Many search studies focus on the ability to find targets in environments with distractors and varying specific variables, e.g., the FoV or rotation gain [15, 49, 50]. Our study focused mainly on the entire platform experience, each with a different FoV, rotation method, and interaction style. While these multiple variables make comparing platforms difficult, it has the advantage of being representative of how standard platform configurations would be applied in real-world scenarios. This facilitates a more holistic exploration of the challenges and opportunities for each platform within the associated WebXR frameworks.

The desktop represents the most common and likely most comfortable interaction style. This is especially true for more technically inclined participants, many of whom play first-person shooter (FPS) games. Conversely, the tablet requires one to hold the device as a "moveable window" into the virtual environment and search for targets in a much smaller window due to the smaller screen size. Although participants initially enjoyed the novelty of holding the tablet as a window into the virtual world, they soon grew weary of its weight. Due to the unique experimental setup, we cannot confirm if the search results align with previous work (hypothesis H3).

C. Insights and Themes

We captured several insights and themes through three experiments conducted with the same WebXR framework across several platforms (Table II). Much of this qualitative data was captured via talk-aloud discussion during the study as participants proceeded through the virtual environments. Though there is room for improvement, our observations support our hypothesis H5 that multi-platform WebXR and frameworks such as Circles can enhance and contribute to social learning spaces and thus show potential for learning activities, confirming hypothesis H4.

1) Usability

In general, usability was a significant weakness of the Circles framework. Misleading UI icons included an arrow used for releasing an artefact that was misinterpreted as downloading, the rotate button mistaken for a "browser refresh button," and the zoom button that looked more like a search button. Additionally, as users moved around the environment farther away, teleport targets' became smaller. As a result, they became hard to select using a pointer, as predicted by Fitts' law. An alternative cone cast interaction technique would reduce participant precision requirements relative to ray casting, e.g., selecting targets near a user's selection target.

There were also concerns about the text being difficult to read in VR, likely due to the low resolution of the HMD. Holding the tablets for extended periods was also uncomfortable. However, once participants were comfortable with the controls and could explore the VLE, most found the interactions usable. Also, as noted in Table II, there was a theme of "personal preferences," where some users preferred the option to have smooth locomotion, suggesting that having personalization could help advanced users' engagement.

2) *Open Exploration*

Generally, participant feedback captured during talk-aloud discussions demonstrated significant interest in using WebXR in their classrooms. Some participants noted reluctance for long lectures, however. Participants generally focused on the 3D visuals, noting how they heightened their presence in the VLE. They were pleasantly surprised by the ambient sounds within the VLE, noting surprise, e.g., "I am a bit surprised that you can have VR on the web." Negative feedback surrounded artefact manipulation, as the UI wasn't clear about functionality.

Some HMD users also preferred a grabbing interaction. This suggests that a selection-only interface may work well across all platforms for accessibility but that more personal preferences should be available for advanced users. Several participants also found the content compelling, creating discussion around the VLAs and associated gender diversity subject matter. To address UX challenges, further studies should investigate which interactions are the most preferred as default, with advanced methods available through an options menu. Several participants also suggested more complex interactions, e.g., being able to use the virtual drill - a desire for greater agency.

3) *WebXR, A-Frame, and Circles*

Supporting all VR platforms presents many challenges, as can be understood from participant feedback on the UX, but WebXR provides an excellent foundation for multi-platform VR. However, the default controls of the laser-pointer for HMD, device orientation to rotate for tablet, and WASD keyboard and mouse to move and rotate can be challenging for unfamiliar users. Perhaps the laser controls used in A-Frame and Circles may not be usable. Exploring more direct manipulation methods, e.g., grasping [33], may be a more desirable option for some users. However, laser controls may be adequate for interactions out of reach and where the user can't physically grasp. To help improve selection accuracy, developers should consider using cone or cylinder-type interactions to help decrease user error when selecting smaller objects. Using orientation to rotate the virtual space is novel. However, in the case of tablets, it can create fatigue. Switching between a device orientation and another mode that doesn't require holding the device would be preferable. For desktop controls, using a mouse to select objects and rotate the viewpoint appeared to work well, as Circles uses selection-based targets to simplify movement.

D. *Conducting a Remote Synchronous VR Study*

Changing this study from a within-subjects design, with more closely controlled equipment and lab space, to a between-subjects design with a large variety of personal equipment was necessary and presented many challenges [30]. This online study was particularly difficult for users unfamiliar with the Oculus [Meta] Quest HMDs used in this study. Connecting the standalone HMDs to participants' smartphones presented issues, and the researcher had to help guide them. For the equipment lent out, we made a great effort to sanitize HMDs and tablets between participants and work with participants via video conferencing or distanced outdoor visits to troubleshoot. However, an advantage of the remote deployment was access to a broader network of participants online. We also took great care to partially automate the study so that a researcher need not be present. In this fashion, online VR studies could conceivably lead to vast and diverse participant pools. This is further enhanced by deploying experimental software via web hyperlinks rather than participants downloading an application.

E. *Limitations*

There were several limitations to this study. First, since this study was conducted remotely and with several personal devices, there is more significant variability in selection and search experiments [30]. For example, we could not control the participants' physical environments and personal device preferences configured. Nevertheless, that we arrived at results comparable to previous non-WebXR studies is a testament to the versatility of Fitts' law as a methodological tool. However, some further exploration into the higher *TP* scores is required. Additionally, though this study is likely a more accurate representation of how these devices would be used in a real-world case study, there is much room for improvement. For example, running a similar study within a more controlled environment, using more complex VLEs for the selection and search tasks to account for VLE distractions, landmarks, and natural occlusions, would likely be fruitful [15, 49, 50].

VI. CONCLUSION

This three-part study explored the selection, search, and usability differences between three WebXR platforms – desktop, mobile (tablet), and HMD. We found that selection performance favoured desktop and tablet, whereas search performance favoured HMD and desktop. The selection results fell within reasonable ranges of past studies and in conjunction with themes captured, suggest that WebXR is a competent medium for learning, with some advantages in being easier to connect with learners using familiar web technologies. However, low usability for all three platforms due to UX ambiguity within the Circles framework UI, and VR platform limitations (weight, resolution), suggest that designing cross-platform VR is difficult. However, participants enjoyed the experience and were interested in further exploring VLEs and VLAs as shorter learning activities within their social learning spaces. This suggests potential in further exploring cross-platform WebXR technology such as Circles.

REFERENCES

[1] A-Frame: *https://aframe.io/*. Accessed: 2018-01-04.

[2] Bowman, D.A. and Hodges, L.F. 1999. Formalizing the Design, Evaluation, and Application of Interaction Techniques for Immersive Virtual Environments. *Journal of Visual Languages and Computing*. 10, (1999), 37–53.

[3] Brignull, H. and Rogers, Y. 2002. Enticing People to Interact with Large Public Displays in Public Spaces. *Proceedings of INTERACT*. 3, (2002), 17–24.

[4] Brook, John. 1996. SUS-A quick and dirty usability scale. *Usability evaluation in industry*. 189, 194 (1996), 4–7.

[5] Buxton, B. and Fitzmaurice, G.W. 1998. HMDs, Caves & Chameleon: A Human-Centric Analysis of Interaction in Virtual Space. (1998).

[6] Cao, L. et al. 2019. A virtual reality based study of indoor fire evacuation after active or passive spatial exploration. *Computers in Human Behavior*. 90, March 2018 (2019), 37–45.

[7] Clark, L.D. et al. 2020. Extending Fitts' law in three-dimensional virtual environments with current low-cost virtual reality technology. *International Journal of Human Computer Studies*. 139, (Jul. 2020).

[8] Coronavirus disease (COVID-19) pandemic: 2022. *https://www.who.int/emergencies/diseases/novel-coronavirus-2019*. Accessed: 2022-04-10.

[9] Dombrowski Matt and Smith, P.A. and M.A. and S.J. 2019. Designing Inclusive Virtual Reality Experiences. *Virtual, Augmented and Mixed Reality. Multimodal Interaction* (Cham, 2019), 33–43.

[10] Eriksson, T. 2021. Failure and success in using mozilla hubs for online teaching in a movie production course. *Proceedings of 2021 7th International Conference of the Immersive Learning Research Network, iLRN 2021* (May 2021).

[11] Feng, Y. et al. 2022. Wayfinding behaviour in a multi-level building: A comparative study of HMD VR and Desktop VR. *Advanced Engineering Informatics*. 51, November 2021 (2022), 101475.

[12] Figueroa, P. et al. 2018. Heterogeneous, Distributed Mixed Reality Applications. A Concept. *25th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018 - Proceedings*. March (2018), 549–550.

[13] Findlater, L. et al. 2010. Enhanced Area Cursors: Reducing Fine Pointing Demands for People with Motor Impairments. *Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology* (New York, NY, USA, 2010), 153–162.

[14] Fitts, P.M. 1954. The Information Capacity of the Human Motor System in Controlling the Amplitude of Movement. *Journal of Experimental Psychology*. 47, 6 (1954), 381–391.

[15] Flanagan, P. et al. 1998. Aurally and visually guided visual search in a virtual environment. *Human Factors*. 40, 3 (1998), 461–468.

[16] FRAME: 2022. *https://framevr.io/*.

[17] Freina, L. and Ott, M. 2015. A literature review on immersive virtual reality in education: state of the art and perspectives. *Proceedings of eLearning and Software for Education (eLSE)* (Bucharest, 2015), 133–141.

[18] Gilbert, R.M. 2019. *Inclusive Design for a Digital World*. Apress.

[19] González-Zamar, M.D. and Abad-Segura, E. 2020. Implications of virtual reality in arts education: Research analysis in the context of higher education. *Education Sciences*. 10, 9 (Sep. 2020), 1–19.

[20] Grinyer, K. and Teather, R.J. 2022. Effects of Field of View on Dynamic Out-of-View Target Search in Virtual Reality. *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (2022), 139–148.

[21] Henrikson, R. et al. 2020. Head-Coupled Kinematic Template Matching: A Prediction Model for Ray Pointing in VR. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2020), 1–14.

[22] Hincapié-Ramos, J.D. et al. 2014. Consumed endurance: A metric to quantify arm fatigue of mid-air interactions. *Conference on Human Factors in Computing Systems - Proceedings*. (2014), 1063–1072.

[23] Hornbæk, K. and Oulasvirta, A. 2017. What is interaction? *Conference on Human Factors in Computing Systems - Proceedings*. 2017-May, (2017), 5040–5052.

[24] Intrinsic Motivation Inventory (IMI): *https://selfdeterminationtheory.org/intrinsic-motivation-inventory/*. Accessed: 2019-09-11.

[25] Jacob, R.J.K. et al. 2008. Reality-Based Interaction : A Framework for Post-WIMP Interfaces. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (2008).

[26] Jang, S. et al. 2017. Modeling cumulative arm fatigue in mid-air interaction based on perceived exertion and kinetics of arm motion. *Conference on Human Factors in Computing Systems - Proceedings*. 2017-May, (2017), 3328–3339.

[27] King-Sears, M. 2009. Universal design for learning: Technology and pedagogy. *Learning Disability Quarterly*. 32, 4 (2009), 199–201.

[28] Knobel, S.E.J. et al. 2021. Development of a search task using immersive virtual reality: Proof-of-concept study. *JMIR Serious Games*. 9, 3 (2021), 1–14.

[29] Kopper, R. et al. 2010. A human motor behavior model for distal pointing tasks. *International Journal of Human Computer Studies*. 68, 10 (2010), 603–615.

[30] Kroma, A. et al. 2022. The reality of remote extended reality research: Practical case studies and taxonomy. *Frontiers in Computer Science*. 4, (2022).

[31] Langbehn, E. et al. 2018. Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. *Proceedings of the Virtual Reality International Conference-Laval Virtual* (2018).

[32] Langbehn, E. et al. 2018. Shadow-Avatars: A Visualization Method to Avoid Collisions of Physically Co-Located Users in Room-Scale VR. *Proceedings of IEEE Workshop on Everyday Virtual Reality (WEVR)* (2018).

[33] LaViola Jr., J.J. et al. 2017. *3D User Interfaces: Theory and Practice (Usability)*. Addison-Wesley.

[34] Le, D.A. et al. 2020. Enhancing the Experience of Virtual Conferences in Social Virtual Environments. *Proceedings - 2020 IEEE Conference on Virtual Reality and 3D User Interfaces, VRW 2020* (Mar. 2020), 485–494.

[35] Liu, L. et al. 2009. Comparing aimed movements in the real world and in virtual reality. *Proceedings - IEEE Virtual Reality*. (2009), 219–222.

[36] MacKenzie, S.I. 1992. Fitts' law as a research and design tool in human-computer interaction. *Human-Computer Interaction*. 91–139.

[37] MacIntyre, B. and Smith, T.F. 2018. Thoughts on the Future of WebXR and the Immersive Web. *Adjunct Proceedings - 2018 IEEE International Symposium on Mixed and Augmented Reality, ISMAR-Adjunct 2018* (Jul. 2018), 338–342.

[38] Mott, M. et al. 2019. Accessible by design: An opportunity for virtual reality. *2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)* (2019), 451–454.

[39] Mott, M. et al. 2020. "I Just Went into It Assuming That I Wouldn't Be Able to Have the Full Experience": Understanding the Accessibility of Virtual Reality for People with Limited Mobility. *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility* (New York, NY, USA, 2020).

[40] Mozilla Hubs: 2018. *https://github.com/mozilla/hubs*. Accessed: 2018-11-30.

[41] NASA TLX: Task Load Index: 2019. *https://humansystems.arc.nasa.gov/groups/tlx/*. Accessed: 2020-05-09.

[42] Ni, T. et al. 2006. Increased display size and resolution improve task performance in information-rich virtual environments. *Proceedings - Graphics Interface*. 2006, (2006), 139–146.

[43] Oh, C.S. et al. 2018. A Systematic Review of Social Presence: Definition, Antecedents, and Implications. *Frontiers in Robotics and AI*. 5, October (2018), 1–35.

[44] Outlaw, J. 2018. *Virtual Hasrassment : The Social Experience of 600+ Regular Virtual Reality Users*.

[45] Peck, T.C. et al. 2020. Mind the Gap: The Underrepresentation of Female Participants and Authors in Virtual Reality Research. *IEEE Transactions on Visualization and Computer Graphics*. 26, 5 (May 2020), 1945–1954.

[46] Plasson, C. et al. 2019. Tabletop AR with HMD and tablet: A comparative study for 3D selection. *ISS 2019 - Proceedings of the*

2019 ACM International Conference on Interactive Surfaces and Spaces. (2019), 409–414.

[47] Qian, Y.Y. and Teather, R.J. 2017. The eyes don't have it: An empirical comparison of head-based and eye-based selection in virtual reality. *In Proceedings of the 5th Symposium on Spatial User Interaction (SUI '17)* (New York, NY, USA, 2017), 91–98.

[48] Radianti, J. et al. 2020. A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers and Education*. 147, November 2019 (2020), 103778.

[49] Ragan, E.D. et al. 2017. Amplified Head Rotation in Virtual Reality and the Effects on 3D Search, Training Transfer, and Spatial Orientation. *IEEE Transactions on Visualization and Computer Graphics*. 23, 8 (2017), 1880–1895.

[50] Ragan, E.D. et al. 2015. Effects of field of view and visual complexity on virtual reality training effectiveness for a visual scanning task. *IEEE Transactions on Visualization and Computer Graphics*. 21, 7 (2015), 794–807.

[51] Scavarelli, A. et al. 2019. Towards a Framework on Accessible and Social VR in Education. *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (Osaka, Japan, 2019), 1148–1149.

[52] Scavarelli, A. et al. 2021. Virtual reality and augmented reality in social learning spaces: a literature review. *Virtual Reality*. 25, (2021), 257–277.

[53] Scavarelli, A. and Teather, R.J. 2017. VR Collide! Comparing Collision-Avoidance Methods Between Co-Located Virtual Reality Users. *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA '17)* (2017), 2915–2921.

[54] Scheier, M.F. and Carver, C.S. 1985. The Self-Consciousness Scale: A Revised Version for Use with General Populations. *Journal of Applied Social Psychology*. 14, 5 (1985), 687–699.

[55] Shannon, C.E. 1948. A mathematical theory of communication. *The Bell system technical journal*. 27, 3 (1948), 379–423.

[56] Sharma, G. et al. 2017. Influence of landmarks on wayfinding and brain connectivity in immersive virtual reality environment. *Frontiers in Psychology*. 8, JUL (2017), 1–12.

[57] Soukoreff, R.W. and MacKenzie, I.S. 2004. Towards a standard for pointing device evaluation, perspectives on 27 years of Fitts' law research in HCI. *International Journal of Human Computer Studies*. 61, 6 (2004), 751–789.

[58] Sousa Santos, B. et al. 2009. Head-mounted display versus desktop for 3D navigation in virtual reality: a user study. *Multimed Tools Appl*. 41, (2009), 161–181.

[59] Stoelen, M.F. and Akin, D.L. 2010. Assessment of fitts law for quantifying combined rotational and translational movements. *Human Factors*. 52, 1 (2010), 63–77.

[60] Stuerzlinger, W. and Teather, R.J. 2014. Considerations for Targets in 3D Pointing Experiments. *Proceedings of HCI Korea* (2014), 162–168.

[61] Teather, R.J. and Stuerzlinger, W. 2013. Pointing at 3D Target Projections with One-Eyed and Stereo Cursors. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. (2013), 159–168.

[62] Teather, R.J. and Stuerzlinger, W. 2011. Pointing at 3D targets in a stereo head-tracked virtual environment. *3DUI 2011 - IEEE Symposium on 3D User Interfaces 2011, Proceedings*. 1 (2011), 87–94.

[63] The Fall and Rise of VR: The Struggle to Make Virtual Reality Get Real: 2019. *https://fortune.com/longform/virtual-reality-struggle-hope-vr/*. Accessed: 2019-12-31.

[64] The Principles of Universal Design: 1997. *https://projects.ncsu.edu/ncsu/design/cud/about_ud/udprinciplestext.htm*. Accessed: 2020-04-16.

[65] Thompson, S. et al. 2004. Gain and Angle of Approach Effects on Cursor-Positioning Time with a Mouse in Consideration of Fitts' Law. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*. 48, 5 (2004), 823–827.

[66] Topu, F.B. and Goktas, Y. 2019. The effects of guided-unguided learning in 3d virtual environment on students' engagement and achievement. *Computers in Human Behavior*. 92, July 2018 (2019), 1–10.

[67] Trewin, S. et al. 2006. *Developing Steady Clicks: A Method of Cursor Assistance for People with Motor Impairments*.

[68] Triantafyllidis, E. and Li, Z. 2021. The Challenges in Modeling Human Performance in 3D Space with Fitts' Law. *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems* (2021), 1–9.

[69] Usoh, M. et al. 2000. Using Presence Questionnaires in Reality Using Presence Questionnaires in Reality Using Presence Questionnaires in Reality. *Presence*. 9, 5 (2000), 497–503.

[70] VRChat: *https://www.vrchat.net/*. Accessed: 2018-01-04.

[71] WebXR Device API: 2019. *https://www.w3.org/TR/webxr/*. Accessed: 2019-12-31.

[72] Why Women Don't like Social Virtual Reality: A Study of Safety, Usability, and Self-Expression in Social VR: 2017. *https://extendedmind.io/social-vr*. Accessed: 2019-10-09.

[73] Wolfe, J.M. 1998. What Can 1 Million Trials Tell Us About Visual Search? *PSYCHOLOGICAL SCIENCE*. 9, 1 (1998), 33–39.

[74] Wu, A. et al. 2009. Evaluation of wayfinding aids in virtual environment. *International Journal of Human-Computer Interaction*. 25, 1 (2009), 1–21.

[75] Yoshimura, A. and Borst, C.W. 2020. *Evaluation and Comparison of Desktop Viewing and Headset Viewing of Remote Lectures in VR with Mozilla Hubs*. McMahan.

[76] Yu, D. et al. 2019. Modeling endpoint distribution of pointing selection tasks in virtual reality environments. *ACM Transactions on Graphics*. 38, 6 (Nov. 2019).

[77] 2000. ISO 9241-9, Ergonomic requirements for office work with visual display terminals (VDTs) - Part 9: Requirements for non-keyboard input devices. International Organization for Standardization.