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

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***Abstract*— This paper addresses the limited research on the comparative performance of virtual reality systems across desktop, head-mounted displays, and mobile platforms in WebXR, particularly regarding symmetrically designed interaction methods, guided by a universal design approach. We evaluate the fundamental interactions of selection, visual search, and general usability across desktop, tablet, and head-mounted display virtual reality platforms within the WebXR framework called Circles. We developed two virtual environments to evaluate performance and usability - (1) a selection, and visual search Fitts' law testing space, and (2) a virtual learning environment developed for use within a post-secondary gender diversity workshop. We found that performance and general usability produced results in line with past non-WebXR studies for the three WebXR platforms, suggesting that WebXR can perform adequately for learning. However, designing a compelling user experience in three-dimensional virtual environments remain challenging, though using web-based virtual reality platforms carries some intrinsic accessibility advantages due to its more open, ubiquitous, and multi-platform design. Finally, as this study was conducted remotely due to the COVID-19 pandemic, we also discuss how our system and study accommodate remote participation for a traditionally lab-based experience.**

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

I. Introduction

Virtual reality (VR) hardware and software have advanced significantly in recent years, resulting in their widespread application [42, 53, 74] and research endeavours [2, 20, 45, 47], for example, in education [17, 22, 50, 57]. Our research is motivated by the potential use of VR in social learning spaces, where users learn together and alone across continually shifting physical and virtual realities, such as classrooms and museums, using both physical and digital tools to re-create more authentic, engaging, and transformational learning experiences [57]. Despite current advances, there are many challenges to using VR in education where accessibility via multiple modalities is critical [9, 28]. The current focus of contemporary VR is on head-mounted displays (HMDs), with some VR learning endeavours additionally considering desktop VR [10, 35, 78]. Unfortunately, HMD VR users may experience cybersickness [19, 40, 57], social anxiety from using unfamiliar technology around others [46, 76], not having the physical means to "grasp" virtual objects [41], or the space to walk and navigate virtual environments (VEs) [33, 58]. A more inclusive and accessible approach to VR, particularly in education and other fields, should support multiple platforms to allow different users to experience the benefits of VR.

Some solutions explore multi-platform VR that supports desktop, mobile, and HMD platforms, but there has been limited contemporary research in this area, particularly on mobile platforms where the orientation of the display acts as a window [5] or "portal" [39] into a VE. A multi-platform approach to VR within social learning spaces appears significant [57] as many post-secondary learning institutions embrace a Universal Design for Learning (UDL) approach [25], where learning content must be accessible from a variety of modalities [28]. Additionally, the inclusive shortcomings of HMDs, and some prior multi-platform VR research that observe that users will strategically use multiple VR platforms for learning depending on task [78], suggest that all forms of immersive and non-immersive VR require more consideration and research. Currently, the only VR area that natively encourages support for desktop, HMD, and mobile VR is WebXR [75]. WebXR is noted as an essential pathway for democratizing immersive education [54] and can potentially contribute to making VR a more widespread and open medium for design and creativity [39].However, WebXR is understudied, particularly in how the three platforms it supports (desktop, mobile, and HMD) perform relative to each other, and if these comparisons are in line with previous non-WebXR studies. Fortunately, many developers and HMD manufacturers [18] are working towards better supporting and developing WebXR applications. For example, Mozilla Hubs [42] and FRAME [16] showcase WebXR technologies to bring people together in virtual communities. With few studies into WebXR and the frameworks that make developing with WebXR more accessible, it is essential to study its assumptions about interactions and support of several VR platforms.

The range of interactions within VR is extensive, so we chose to focus on selection and visual search performance, both within a virtual environment (VE), designed to limit distractions and focus on the technical interactions of select and visual search themselves. When evaluating any virtual reality (VR) interactive system, selection, manipulation, and navigation metrics are essential application performance indicators [3, 34]. Specifically, many systems rely on selection-based manipulation techniques such as "pointing" [34] and navigation techniques such as "selection-based travel," [34] which require selection targets to teleport a user around a space. These selection-based interaction methods can be essential as they reduce the physical movement necessary for VR users [19, 34, 40, 57]. Selection-based multi-platform VR interaction methods are an important research area, as existing selection techniques can be leveraged to make selections more accessible [13, 72], especially within social learning spaces where we cannot assume users have the physical space and abilities to use more immersive interaction techniques [55, 57]. However, we are unaware of such studies conducted within the WebXR space, using platforms beyond just desktop and HMD.

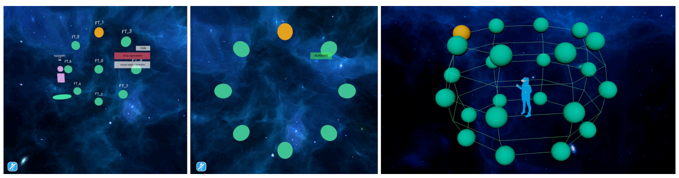

Fig. 1. The Circles framework's "Research Room" running on Google Chrome (Desktop) for both the researcher (left) and the participant (centre). The left and middle images show the Circles WebXR website running on two Google Chrome instances where both users can be in the same virtual “research room” for a Fitts law task. The participant is asked to select the orange (active) target (centre), under the supervision of the researcher-observer that can control experiment start, end, researcher visibility (left). 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).

Our goal is observe the performance differences between WebXR platforms and to confirm whether the performance differences follow past multi-platform VR selection and visual search studies. Our performance evaluation consists of 1) a selection-based Fitts' law [14, 38] study, extended into 3D contexts [66] applying the ISO 9249-9 standard [81], and 2) a "visual search" performance study within a basic VLE (Figure 1) whereby we measure the time and errors for finding and selecting targets. These tasks are essential in our field of interest (education) but apply to most VR applications. The selection interactions in this study represent the standard display/controller interaction configurations of the A-Frame general purpose WebXR framework [1]. Specifically, HMD is paired with motion controller "laser controls" (a ray cast from the controller that can intersect with and select virtual objects) against mobile/tablets with finger-based touch interaction and desktop with mouse and keyboard "First-Person" controls (WASD keys to move and mouse drag and click to look around and select). We followed up our interaction study with a more qualitative reflective general usability survey within a virtual learning environment (VLE). All interactions use the same selection and visual search tasks practiced in the previous parts of the study. The VLE walk-through is an example of an unguided learning activity [71] created for a gender diversity workshop (Figure 2). Finally, several questionnaires, including a self-consciousness scale [59], NASA-TLX [43], and the Intrinsic Motivation Inventory (IMI) [25], inquire about more subjective and personal differences between platforms. While the primary goal of our research is to compare the capabilities of VR platforms, the follow-up study helped us contextualize our research within the field of education. We ran all experimental tasks using the open-source Circles WebXR learning framework [55, 56], 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, 56] single selection actions across all supported WebXR platforms to make them more “simple and intuitive” [69].

Fig. 2. The Circles framework's "Women in Trades" Electrician's School Lab running on Google Chrome (Desktop), from a participant's perspective. These images show two of the three 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.

This study acknowledges that designing usable VR applications is challenging due to the many the lack of standardization around 3DUIs, personal preferences, physiology, and psychology of its users [32]; but that it is essential in making using VR lower friction within social learning spaces where everyone should be able to participate without physical (e.g., cybersickness) or psychological (e.g. social anxiety) harm. These UX challenges are further confounded by trying to create a system that adapts across various display sizes and reality-based inputs. Not unlike the hyper gravity seats of the future that change their shape to conform to the user’s physical bodies in Liu Cixin’s vast science-fiction trilogy “The Three-body Problem” [36].

Our research questions include:

RQ1. What are the selection performance, visual search performance, and usability differences between the desktop, tablet (mobile), and HMD WebXR platforms? Are they similar to prior multi-platform VR performance studies?

RQ2. Is using multi-platform WebXR, and more specifically the Circles framework, for learning activities a valuable direction for enhancing and contributing to social learning spaces?

Our hypotheses:

H1. For selection performance, we expect desktop performance will be the highest (fastest selection time and least number of errors), followed by the mobile tablet and, finally, the HMD. For visual search performance, we expect that findings targets in VR will be the highest performance (fastest find time) due to the much larger perceived FOV relative to a desktop monitor screen and least for the smaller tablet screen held at arm's length. We expect the WebXR study results will compare similarly to past studies, though performance may be slightly lower due to running on low-powered mobile devices, inside a web browser.

H2. We expect that users may prefer the HMD or the tablet for their novel reality-based interfaces. The interactions associated with each device are usable but could use some tweaking to make them more accessible. Circles, and associated WebXR frameworks, will have potential as more accessible VR frameworks for learning in social learning spaces, but there is room for improvement.

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 robust 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 [69]. We can reduce down most complex interactions to their fundamental forms of "visual search" and "selection".

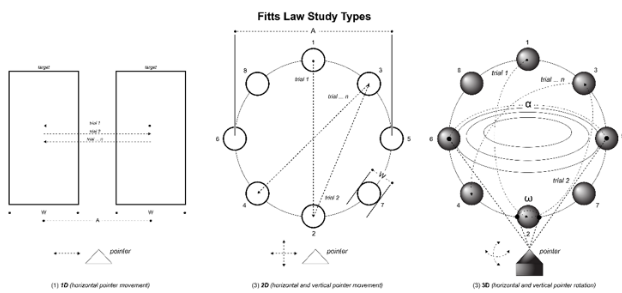

Fig. 3. The most common forms of Fitts Law selection studies (left) utilize a simple pointer device, and the user selects the center vertical target, moves from one side to the next, and back again for n number of trials. The 2D form (centre) asks the user to select targets number 1, then 2, and so on 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.

A. Selection Studies

Interactions within VEs are concerned with three main categories: viewpoint selection, manipulation, and travel [3, 34]. Furthermore, selection and manipulation techniques are classified into six interaction metaphors. These metaphors are 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 technique changes depending on the context of selection) [34].

Selection studies often compare performance between various input and display methods, i.e., comparing varying mouse gain values on desktop [70], pointing task performance with "fish-tank" VR displays [67], and comparing head-based and eye-based selection tasks [49]. Fitts' law has become the standard for studying 2D selection tasks and includes several proposals for using Fitts' law in three dimensions. These include discussions on target properties in 3D selections using virtual hands [65], the development of new models for more accurate predictions on pointing selection tasks [30, 79], and research into extending Fitts' law to incorporate depth [7] through both translation and rotation [64]. Many studies have validated Fitts' law across decades of HCI research [62].

1) Fitts' Law

As selection techniques are one of the most prominent interactions in both 2D and 3D contexts [34], many studies have investigated the selection performance difference between various input and display modalities. To standardize experimental design and results between selection studies, Fitts' law [14, 38] has become a widely used predictive model for studying selection performance, creating a more easily comparable "transmission of information" [24] as throughput (bits/second) [14, 30, 60]. Fitts' law was initially developed for 1D contexts [14], where movement time is collected as users repeatedly select between two vertical targets (Figure 1). However, in recent decades, Fitts' law has been re-purposed for use within 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 (Figure 1). However, for more immersive 3D tasks where a pointer is not directly manipulated but instead used to "ray-cast" selection a distance away from the user, Fitts' law has been modified to allow for immersive 3D "distal pointing" tasks [30, 64](Figure 3).More specifically, Fitts' law describes the model target selection time according to the distance and size of the target. The core element is what is called the Index of Difficulty (*ID*) described in the following "Shannon" [60, 62] variation of the formula used for 2D selections, i.e., selecting targets on a flat screen:

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

ID_{2D} is the Index of Difficulty for a 2D selection surface, A refers to the "amplitude" or distance to the target, and W refers to the width of the selection target. However, 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) is known as a "distal pointing interaction." We should consider the rotation movements of the wrist and arm [30], as much of the action will focus there to reduce arm fatigue or "gorilla-arm" effects [23]. Though there are several variations of formulae used to describe Fitts distal pointing tasks [30, 62, 64], we focus on Kopper et al.'s "ID_{angular}" form, as it has seen success in previous studies [49], which appears to consider the rotation-based motions our joints naturally take accurately. The formula for calculating angular distance follows [30, 64]:

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

Where α is the angular distance from the starting point to the selection target, and ω is the angular width of the target. k is used to describe a non-linear relationship between α and ω [30] as "distal pointing" often involves two phases – ballistic *and* correction [37]. As a final step in quantifying selection performance across VR platforms, throughput (*TP* in bits/second) 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 [62]:

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

B. Visual Search Study

Identifying an element or target within a virtual environment is a crucial skill for exploring and navigating within VEs. Often "visual search" tasks are an intrinsic part of VE navigation. Search tasks often combine both 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 [34]. Most strategies include landmarks [61] but other techniques, such as having overview or "view-in-view" maps [77] and may consist of stresses such as finding the exit in a virtual fire [6]. Search tasks are also important for finding objects, points of interest, or landmarks within VLEs, such as virtual museums.

Several studies investigate search performance across various factors, with several characteristics described, such as determining that the display's Field of View (FOV) plays a role in allowing users to find targets within a training system [44], though perhaps not enough of an effect to help train for real-world scenarios [52]. Additionally, head-rotation amplification may aid search tasks [51]. Some studies also suggest that audio cues may help users find targets, particularly those outside the FOV of the display [15], while other researchers use search tasks to help with neurorehabilitation [29]. However, in all noted studies, there appears to be no standard form of assessing search performance, as there are for selection tasks and Fitts' law. In addition, many studies are performed within complex VEs or "information-rich virtual environments" [44], often as virtual recreations of real-world spaces.

C. Multi-Platform VR

Very few modern VR experiences support more than one platform (i.e., supporting mobile and immersive HMD VR). The only real exceptions are the WebXR-based Mozilla Hubs [42] and Frame [16], which support VR across several platforms - desktop, mobile, and HMD. In addition, some social VR experiences, such as VRChat [61] and AltspaceVR [2], have desktop clients to increase participation in social VR experiences, as exclusive HMD-supported applications appear not yet to be commercially viable [68].

In multi-platform research, studies suggest that HMD VR performs better than desktop VR for 3D navigation tasks [63]. One study found participants perform better using desktop VR over HMD VR for spatial tasks [58], which aligns with another study 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 [48]. However, we could not find studies comparing desktop, tablet/mobile, 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, 78]. 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 [35, 78] and better multitasking with desktop VR [78].

III. Methodology

Our investigation consisted of three separate tasks. The first and second focused on selection and visual search, respectively, within a simple virtual environment to avoid any distractions. The third study was an open exploration to investigate general usability in a simulated virtual learning environment as a more authentic use-case. Designed initially as a lab-based within-subjects study for comparison between three VR platforms – desktop, mobile (tablet), and HMD, we switched the study to a between-subjects remote study when 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 and used a web-based social VR platform called Circles [55] and an associated "Research VE" (see Figure 2) we developed for connecting with participants as virtual avatars with their given VR platform. For each participant, within this research VE, we performed the selection and visual search experiments, 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.

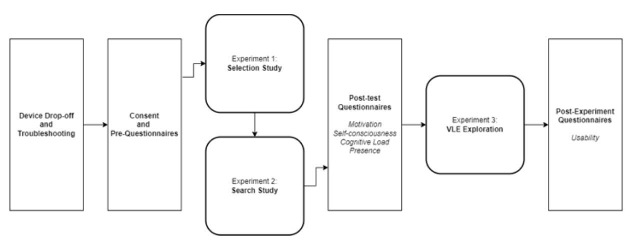

Fig. 4. A flow-chart of our three-part study, describing our study process.

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 Quest 1 HMDs, and for 8 of the 15 mobile participants, we lent out a 10.4" Samsung Galaxy Tab S6 Lite tablet (the others used a variety of personal tablet devices). We had 15 HMD devices and 2 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" Apple iPad tablets, and most desktop systems used 21.5" 1920x1080 displays with a mouse and keyboard. We recorded display resolution, pixel density, and scale to calculate target sizes across the variety of personal tablet and desktop screen sizes used in this study.The complete study consists of three experimental tasks – a "selection" task, a "visual search" task, and an "open exploration" task (see Figure 2). For the selection task, the participant selects all targets displayed one at a time in a circular and "jumping to alternating sides" clockwise format common to Fitts' law studies (see Figure 1, far left). Afterwards, the participant starts the search task, where targets display one at a time around the participant to find and select in the same research VE (Figure 1, far 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" task, the participant is introduced to a single VLE recreation of a college electrician's lab created for a "women in technology" workshop (see Figure 2). The participant is tasked to explore the VLE and select and manipulate the three VLAs present (a drill, a clipboard, and a pair of safety gloves), where the researcher asks the participant to "talk aloud" their thoughts on the virtual environment, interactions, feelings, sounds etc. The researcher captures these thoughts as observer notes. Finally, the participant is given another survey link to follow and complete a post-experiment questionnaire. At the end of the experiment, the researcher asks if there are any questions or if they have any other thoughts on their experience. Throughout the study, the researcher asks often about how they physically feel so that we can pause or stop the study if any participant felt any physical or psychological discomfort. Fortunately, all participants were able to complete the experiment with minimal issues.

C. Design

The first task of the three-part study is a between-subjects 3x3x3 Fitts' law selection study where the independent variables are the input method (Desktop, Mobile, HMD) , selection targets of widths (0.25m, 0.5m, 0.75m), and depths (5.0m, 7.0m, 9.0m). Our dependent variables are selection time and the number of errors. For each selection configuration, we ran 16 trials for 3platforms (desktop, tablet, HMD) * 3 selection widths * 3 selection depths * 16 trials * 15 participants for each platform for a total of 6480 selection data points. For the selection task, the participant would click each circle/target highlighted in orange as it appears clockwise around the circles seen in Figure 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 downloads at the end of the task to analyze post-study.

For the second task of the study, we asked the user to search and select a single target somewhere around them at pre-defined semi-random positions capturing selection time and selection errors, using device orientation (HMD and mobile platforms) and mouse movement (desktop). For the search experiment, we had 3 platforms * 3 possible x-axis positions on a sphere around the user * 8 y-axis positions * 4 trials * 15 participants for each platform for a total of 4320 total find data points (some data points failed to capture due a minor bug we fixed later, so the actual total is 4198). See Figure 2, far-right, for a visualization off all search targets visible.

For the third task, participants used the selection and visual search techniques they practiced in the first two experiments to explore a complex VLE created for a gender diversity workshop (see Figure 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 on their own 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 [55, 56].

IV. Results and Analysis

In the selection experiment, the ANOVA single factor for our between-subjects design revealed significant differences in selection time ($F_{1,45} = 17.65$, $p < .05$) and throughput (bits/s) ($F_{1,45} = 8.85$, $p < .05$) for the Fitts study, and using Tukey HSD post hoc tests we found significance between the desktop and HMD, but not so between Tablet and HMD platforms with the order of selection efficiency starting with desktop and tablet, then HMD. We found no significant differences in the number of errors and thus did not report them. However, the average error rates described in Table 1 appear to align with similarly designed Fitts' law studies [49].

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

The lack of significance between Desktop and Tablet, the higher-than-expected TP of desktop, and the large SD error bars (see Figure 5) suggest the high variability of the many personal desktop devices introduced a large amount of noise into the study. Still, the general themes expected are present where the desktop is superior in performance [62]. We can summarize that direct manipulation techniques are more efficient than the reality-based interactions of motion controllers to ray-cast and point toward selection targets, where arm fatigue may become an issue [27]. Also noted is that contrary to many Fitts' law studies that compare selection techniques using the same platform, the IDs of the Tablet and Desktop are roughly the same, but the HMD ID is slightly offset relatively (see Figure 5). We suspect this is an effect of using the $ID_{angular}$ formula, which takes in units as degrees (Formula 2, Section 2.1) for the HMD ray-cast distal pointing rather than the standard 2D form used for Desktop and Tablets that takes in units as distances (Formula 1, Section 2.1). We should also note that we kept the k value of $ID_{angular}$ at 1.0 to match up with previous studies that have used it [49]. Perhaps changing this value could have created a better fit. However, as throughput is generally unitless (bits/s), it still feels relevant to compare various devices using it [62], even if the numbers do not align due to vastly different VR displays and inputs.

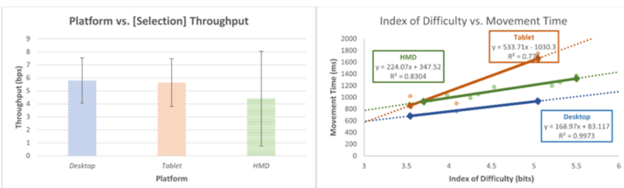

Fig. 5. Left: Throughput (bits per second) by VR platform. Errors bars show ± 1 SD.]. Right: Linear regression model for all VR platforms, showing the relationship between ID and MT.

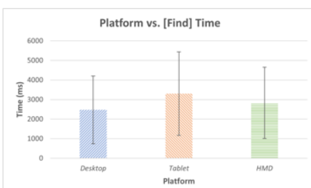

Fig. 6. Visual Search Time (milliseconds) by VR platform. Errors bars show ± 1 SD.

A. *Visual Search Performance*

For the search part of the study, ANOVA single factor for the find target performance study, we found significant differences in visual search time ($F_{1,45} = 8.63$, $p < .05$) and in selection errors ($F_{1,45} = 4.17$, $p < .05$), with Tukey post hoc tests revealing significant differences between Tablet and Desktop, Tablet and HMD (see Figure 6). This suggests that the search performance of the tablet was significantly less than both the desktop and HMD platforms. This is likely explained by a much smaller screen and FOV on the tablets. Interestingly, search performance between the desktop and HMD platforms appears roughly the same, albeit faster than the tablet.

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.

We also analyzed our post-test questionnaire data and, using the non-parametric Kruskal-Wallis test on the ordinal survey data, we were not able to find significant differences between VR platforms in intrinsic motivation' interest/enjoyment (p = 0.25) or perceived competence (p = 0.25). However, we did get a significant result with the SUS presence questionnaire [73] ($h(2)$ = 10.92, p = 0.0042), with a Dunn's Post-test showing that the HMD creates more presence than both the tablet (p = 0.015) and desktop (p = 0.0016). Additionally, we saw a significant result using a Kruskal-Wallis test in the "public social consciousness" scale ($h(2)$ = 7.31, p = 0.025) and a Dunn's post-test showing significance between the desktop and tablet groups (p = 0.0067).

B. *Open Usability Exploration*

The VLAs and VLEs quickly become the focus of the conversation, as the visuals were often described as "cool" and the detail incredibly "full," "more lived-in [which] … makes it feel like more my reality." Additionally, 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 accompanying vocal narration when clicking on the VLAs. The verbal narration of a woman speaking from a first-person account of challenges they faced within the trades as a woman was appreciated as the narration "helped with reading" the mirrored "text bubbles" (see Figure 2). However, there were several UX issues noted by participants. Selecting menu items was challenging to understand as being parented to the virtual camera often resulted in occlusion by objects within the VLE. Also, several menu items had unclear iconography, i.e., the "down arrow" meant for releasing or dropping a VLA was interpreted as a "download" icon and ignored. Many of the users found the VLEs easy to navigate the virtual space using the teleport pads dotted throughout the room, and the mouse/tablet orientation/headset orientation to look around. However, there were many challenges beyond the aforementioned UX issues when selecting and manipulating artefacts. These issues generally centered around technical issues i.e., wi-fi cutting out, some audio issues, and some graphical glitches noticed (door not to scale), and physical discomfort i.e., headset is too heavy, holding a tablet for too long is difficult, and moving their head too fast resulting in mild cybersickness. There were also issues noted by some users i.e., cats scratching at the door or roommates talking in the physical environments interfering with their immersion or that they would be uncomfortable wearing the headset in a classroom around others, which appears to refer to a concept described by other researchers as "social embarrassment" [4] that is understudied in the public VR learning space.

To provide an additional perspective to our VLE exploration finding within the more complex "gender diversity" VLE, we also coded the observation notes and the required open-ended post-experiment questionnaire question – "Is there anything else you would like to add?" (Appendix 1). We quickly found that much of the discussion centered around the User experience, VLAs, and VLEs. Often, this included challenges around not being aware of how to manipulate the objects, i.e., not seeing the manipulation buttons or realizing that they were for object manipulation due to ambiguous iconography and lack of labels. The appreciation of the VLAs also applied to the audio narration that accompanied selecting each artefact, though many found it difficult to follow if reading the accompanying text box simultaneously. We also analyzed our post-experiment questionnaire data and, using the non-parametric Kruskal-Wallis test on the ordinal survey data, we were not able to find significant differences between VR platforms in cognitive load using the NASA-TLX (p = 0.47).

V. Discussion

There are several interesting themes noted within this study that we will summarize here.

A. Selection Performance

In this study, it appears evident that performance across platforms follows our first hypothesis where the desktop performs best, with both the tablet and HMD falling behind in selection performance. Desktop provides the highest selection performance due to the mouse's familiarity and fine movements, whereas the finger-touch reality-based controlled [26] tablet offers a very close second. The HMD "pointing controls" fell farther behind, likely due to the more significant motor movements required. However, there is a noted discrepancy between the expected throughput expected of desktops in previous studies, with ours being higher (5.9 bits/s) than the expected range (3.7 – 4.9 bits/s) [62]. We expect this from the variety of personal desktop machines used, where we collected information from each participant on their devices, such as display resolution and size, as the system only captured times between selection and number of errors. Unfortunately, some of this may have been misreported by participants. Perhaps we should have asked permission to screen-share and go into their machine settings, but we elected not to do this as it seemed an unreasonable breach of privacy. In a lab-controlled environment, with the same desktop machine used for all participants, we expect that we would have seen numbers more in line with previous studies. We had a similar issue with some participants using their personal tablets. Still, our team supplied most of the tablets, and for the personal tablets, it is easier to research for more precise specifications. Thus, we feel that the tablet numbers are more accurate, though we note that running this study under noisier real-world conditions results in data not be as clear as data collected in a lab-controlled study.

B. Visual Search Performance

In our search performance experiment, it appears that the HMD and desktop are better performers, which alludes to the ability of an HMD to look around a space using the familiar interaction of physically moving our heads as we do as a more efficient and comfortable interaction. Many visual search studies focus on the ability to find targets in environments with distractors and varying specific variables, i.e., the field of view (FoV) or rotation gain [15, 51, 52]. This study focuses more on the entire platform experience, in which each platform has a different FoV, rotation method, interaction style etc. This totality of multiple variables makes comparison difficult but does allow us to compare standard platforms as they would be used in real-world scenarios and explore what challenges and opportunities there are for each platform to be explored within the associated WebXR frameworks i.e., A-Frame and Circles.

Using the desktop is a typical and comfortable interaction, especially for a group of more technically inclined students, many of whom play First-Person Shooter (FPS) games - something noted during the "VLE Exploration" talk-aloud trials. Conversely, the tablet requires one to hold the device as a "moveable window" and look around for a target in a much smaller Field of View (due to the smaller screen size). Participants appeared to enjoy the novelty of holding the tablet as a “window in hand” to see into a virtual world but soon grew weary of its weight. Though performance and presence would likely significantly decrease, performing the study again, focusing more on real-world explorations of VLEs and smaller handheld phones rather than a tablet, would be interesting to explore. Specifically, if students would be interested in moving between various VR platforms within the same session, depending on the task.

C. Insights and Themes

We captured some interesting insights and themes with several experiments conducted with the same WebXR framework across several platforms. Much of this qualitative data was captured via talk-aloud discussion during the study as they proceeded through these virtual environments. Combined with the performance data collected, open-ended questions on the post-experiment questionnaire allowed users to post what engaged and challenged them. Though there are some aspects to be improved, these observations confirm our second hypothesis that there is much potential in using multi-platform WebXR, and frameworks such as Circles for learning activities, to enhance and contribute to social learning spaces.

1) Usability

In general, usability was the major weakness of the Circles framework due to misleading UI icons where an " arrow" did not suggest releasing an artefact but instead "downloading," the rotate button a "browser refresh button," and the zoom button looked more like a "search button.". Additionally, as the teleport targets got smaller in the distance, they became hard to select using a pointer, in-line with Fitts' law expectation. Perhaps a ray-cast pointer should instead utilize a "cone cast" where one need not click so precisely on any interaction element and instead select in the vicinity of a user’s selection target. There were also some concerns about the text being difficult to read in VR, and though the A-Frame framework uses resolution-independent fonts [21], they are still dependent on the relatively low HMD display resolutions [80]. Circles tries to minimize text-reading fatigue by also including audio narration, but the audio should match the text. Also, the tablets being held were quite fatiguing for participants, suggesting that perhaps the tablet/mobile mode should have a toggle between the device orientation control to a finger-only interface where a participant can hold a mobile device in any orientation (including stationary on desk or table).

However, once participants were comfortable with the controls and could explore the “women in technology” VLE, most did not find the usability issues challenging. Also, as noted in Appendix 1, there was a theme of “personal preferences” where some users preferred to have the option to have smooth locomotion, suggesting that having personalization options available would help advanced users’ engagement.

2) Open Exploration

Generally, participant feedback captured during talk-aloud discussions during the study showed great interest in using this technology in their classrooms, though some noted reluctance to use it for entire lectures. Many suggested that it may be a better place as one of many learning activities to use in remote or face-to-face learning rather than replacing the classrooms themselves due to physical fatigue and discomfort over extended periods. That participants preferred to see this technology as a learning activity/tool confirms Circles’ purpose not to replace social learning spaces but rather to become a flexible reality tool within them. Participants generally focused on the 3D visuals and details, noting how they heightened their presence in the VLE. They were often pleasantly surprised by the ambient sounds within the VLE that helped contribute to that intensified presence, even noting surprise i.e., "I am a bit surprised that you can have VR on the web." Negative feedback surrounded how to interact with artefacts, as the UI wasn't always clear about button functionality. Labels could help.

Interestingly, a minority of HMD users noted how they might prefer a more "grabbing" type of interaction. This preference for a more "reality-based" [26] approach suggests that working towards a selection-only interface may work well across all platforms for accessibility and familiarity but that more personal preferences should be available for more advanced and familiar VR users. Several participants also found the content itself compelling, creating discussion around the learning content around the VLAs and their descriptions on the challenges women face in technology. Concerning the UX challenges surrounding the artefact interactions, further studies should investigate which interactions are the "safest" and most preferred to keep as default, with more advanced methods being available through an options menu. Additionally, many of the participant suggestions surrounded adding additional interaction to the artefacts, i.e., being able to use the drill to drill holes or drive screws, suggesting a want for agency within these spaces.

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

Supporting all VR platforms presents many challenges, as can be understood from participant feedback on the UX, but the WebXR API and the A-Frame framework that Circles is built on abstracts most interactivity to work uniquely for each WebXR-supported platform. However, the default controls of 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. This suggests the default "laser-controls" used in A-Frame and, thus, also Circles may not always be the most usable controls and that exploring more direct manipulation methods, i.e., "grasping" [34], may be a more desirable option for some users. Laser controls may be more effective for interactions out of reach, and the user does not fully control their hands. To help increase laser-pointer accuracy, developers should consider using cone or cylinder-type interactions to help decrease user error when selecting smaller objects. In the case of tablets, using the device orientation to rotate the virtual space is novel. However, it can also be tiring. A toggle to switch between a device orientation and a finger drag mode that also works for looking up and down would be helpful. For desktop controls, using a mouse to select objects and rotate the viewpoint appeared to work well, as Circles uses selection-based targets to help simplify movement.

D. *Conducting a Remote Synchronous 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 but did present many challenges. The challenges and opportunities of running remote VR studies align with previous overviews of VR studies during the COVID-19 pandemic, where it is more challenging to supervise participants and ensure the equipment is set up correctly. Still, there is the ability to recruit more significant numbers of participants [31]. This online study was particularly challenging for users unfamiliar with the Oculus [Meta] Quest HMDs used in this study. Connecting the standalone HMDs to participants' smartphones to set up the HMD devices presented some connection issues where the researcher had to help guide and direct. For the equipment we lent out, there was a great effort to deliver sanitized HMD and tablet equipment and work with participants across video conferencing calls or distanced outdoor visits to troubleshoot issues. However, we were able to reach out over a more comprehensive network of potential participants online, and without device delivery and automating the study so that a researcher need not be present in the future, online VR studies could result in even larger sample sizes. This is further helped by hosting web hyperlinks, rather than asking users to download and install an application.

E. *Limitations*

There were several limitations to this study that we should highlight. Specifically, since this study was conducted remotely and with several personal devices, there is some noise found within the quantitative studies performed in the study of the selection and visual search experiments. This included being unable to control the environments participants conducted the study in and personal preferences baked into their devices that may not have been accounted for in the results. That we were able to display results in line with previous non-WebXR studies adequately is a testament to the power and versatility of Fitts Law. Additionally, though this study is likely a more accurate representation of how these devices would be used in a real-world case study of multi-platform VR in social learning spaces, there is much room for improvement. Running a similar study within a more controlled environment, using more complex VEs for the selection and visual search tasks (perhaps the electrician's lab environment from the open-exploration part of the study) to account for typical VLE distractions, landmark identification, and natural occlusions would likely be fruitful [15, 51, 52].

VI. Conclusion

This three-part study explored the selection, visual 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. These results fell within reasonable ranges of past studies suggesting that WebXR is a competent medium for remote learning activities and has some intrinsic advantages in being easier to connect with learners and research participants with standard and open web-based technologies. Usability for all three platforms was generally low due to some button UX ambiguity used in the Circles framework, suggesting that designing cross-platform VR is complex, and also because holding handheld platforms and using HMD platforms to read, interact, and explore for extended periods was fatiguing. However, participants generally enjoyed the experience, and were interested in well-designed VLEs and VLAs in shorter learning activities in their own social learning spaces. This suggests potential in further exploring cross-platform WebXR technology such as Circles.

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Appendix I

TABLE II. Analysis of the qualitative data captured in observation notes and open-ended post-questionnaire questions, in reference to the final “VLE Exploration” experiment in this three-part study. Starting off with an expected set of thematic codes from our literature review (deductive), then adding additional codes found with data that did not fit easily, or were surprising, we then were able to determine 12 central themes.

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

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

Final Themes (after merging and sorting codes)
Artefact
Discussion
Enthusiam
Learning Potential
Navigation
Personal Preferences
Suggestions
Surprising
Technical Challenges
UX Challenges
Virtual Environment