Effects of Field of View on Dynamic Out-of-View Target Search in Virtual Reality

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Abstract

We present a study of the effects of field of view (FOV), target movement, and number of targets on visual search performance in virtual reality. We compared visual search tasks in two FOVs (~65°, ~32.5°) under two target movement speeds (static, dynamic) while varying the visible target count, with targets potentially out of the user's view. We examined the expected linear relationship between search time and number of items, to explore how moving and/or out-of-view targets affected this relationship. Overall, search performance increased with a wide FOV, but decreased when targets were moving and with more visible targets. FOV more strongly influenced search performance than target movement. Neither FOV nor target movement meaningfully altered the linear relationship between visual search time and number of items. Participants also rated perceived workload for each condition; FOV and target movement both negatively affected the perceived workload, with target movement being a more significant factor.

Keywords: Mobile VR, field of view, moving targets, search.

Index Terms: Human-centered computing → Virtual reality

1 Introduction

Virtual reality (VR) has surged in popularity over the past decade and is becoming more commonplace. Various VR applications are being developed for entertainment [11], 30], tourism [38], training [14, 23, 37], and more. Many of these applications – particularly on smartphone-VR devices such as Google Cardboard – involve looking around environments for specific objects/targets. This activity is an example of *visual search* [36]. Visual search in 2D user interfaces has been well-studied, and average search time is known to increase linearly with the number of items in a set [33]. However, in 3D immersive virtual environments, search tasks are more complex due to the increased number of degrees of freedom (DOF), the size of the virtual environment (VE), and the possibility that target objects may actually be *behind* the searcher, necessitating more complex search strategies [6]. Two major factors influencing search strategy, and thus performance is field of regard (FOR) and field of view (FOV).

FOR is the total space in the VE that can be viewed by physical head and body rotation [37]. Meanwhile, FOV determines how much of the VE space the user can perceive at any given time. FOV varies greatly between commercial head-mounted displays (HMDs) [32]. Thus, the effects of FOV are an important VR research topic. FOV affects many elements of VR such as immersion, navigation, and cybersickness [31]. We focus on the effect of FOV on search tasks in 3D environments. Past research has shown a wider FOV improves search performance and target discovery rates [16, 25, 37]. However, these positive effects are reduced when visual guidance cues are in play [25]. A wider FOV can also yield less natural search patterns and make users overconfident [2]. Past studies reveal that a narrow FOV makes users search more thoroughly resulting in fewer errors [2, 7, 9]. However, while the effects of FOV on search performance for stationary and in-view targets has been extensively studied, the effects of FOV on *moving* and *out-of-view* target search, without visual guidance cues, are comparatively understudied. Yet, such tasks are likely the norm rather than the exception in "real-world" search tasks (e.g., target acquisition in a VR game).

Dynamic target selection is common in VR applications, such as entertainment and education [30]. This task is impacted by target speed and requires spatial and timing accuracy, rhythm, and consistency. Past research has shown faster targets reduce hit rate, and the target movement direction affects accuracy [30]. Dynamic target selection is more complex than stationary target selection tasks because it is affected by many factors including time, space, labelling cues, and the environment. Despite this, there is little research on dynamic target acquisition in 3D environments. Current research prioritizes selection over search [1].

To address this gap in the literature, we conducted a remote study using a Google Cardboard, comparing the effects of FOV on moving target search without visual guidance cues. We developed a VR system to evaluate search performance of two stereoscopic FOVs (~65°, ~32.5°), two target movement conditions (static, dynamic), and a varying number of targets (2, 5, 8, 11, 14, 17, 20, 23, 26). We asked participants to search for and select targets under each of the four combinations of FOV and target movement conditions. Within each combination, a set number of potential targets between 2 and 26 were visible and users were instructed to search for 81 specified targets, one at a time. The study design was influenced by past work [33] noting the linear relationship between search time and number of items; as the number of items increases, search time increases. This relationship is well documented for in-view, stationary target search tasks [13, 19, 26, 33]. We sought to determine if searching for out-of-view or moving targets still yields the expected linear relationship. Our hypotheses included:

H1: Search time will be shorter with a larger FOV, since participants can see more targets at a given time and thus can react faster to select them.

H2: Search time will be shorter with stationary targets as it's easier to locate and identify targets when they are not moving.

H3: The relationship between search time and number of items will not be linear with moving targets and a small FOV; as the number of items increase, search time will increase nonlinearly due to increased difficulty.

2 Related Work

A visual search task occurs when a user examines a set of items, looking for a specific one [33]. Past research has established a linear relationship between search time and the number of items to scan [13, 19, 26, 33].

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2.1 FOV and HMDs

The human eye has an individual FOV of 150° while one's binocular FOV averages 120°, creating a combined FOV of roughly 180° [31]. Many aspects of a VR experience are positively affected by an increased FOV; however, these positive effects plateau after the FOV reaches 120° [31].

Over the past 20 years, VR HMDs have drastically increased in quality and lowered in price. Arthur's 2000 dissertation [2] compared the FOV and price of HMDs of the day. He reports that high-end HMDs were priced around $100,000 USD and had FOVs between 100-145°, while lower-end HMDs were priced between $1,000-$10,000 USD and had FOVs between 25-50°. A very recent (2020) comparison of six VR devices released since 2010 revealed that prices now range from $25-$799 USD [32]. The mean FOV of these six systems ranged from 39.6-55° with the highest FOV belonging to the *HTC Vive*[1] at 110°. The Oculus *Rift S*[2] has a FOV of 115° and was released in 2019 at $399.99 USD but was not included in this comparison. Comparing these six newer HMDs and Oculus Rift S to the lower-end HMDs from the 2000 study, there is a clear drop in price and increase of FOV.

In contrast, the cost of cardboard VR devices typically ranges from $8.50-20 USD. The 2014 Google Cardboard is capable of displaying a ~65.5° FOV, while the second-generation Google Cardboard, released in 2015, has an ~80° FOV [44]. Since the smallest non-cardboard HMD FOV was 39.6° in the 2020 comparison [32], we felt it appropriate to compare the Google Cardboard's full FOV (~65.5°) to half of its FOV capability (~32.5°) as the half FOV is close to the low-end 2020 FOV sizes.

2.2 Effects of FOV in VR

The effects of FOV in VR has been studied for decades, yielding positive and negative results for a diverse range of experiences. A larger FOV positively affects immersion and presence [5, 15, 31, 39]. A larger FOV can also help navigation, wayfinding, and memory of the VE by improving spatial awareness [5, 31]. Caluya et al. [8] tested the effects of FOV on spatial memorization and found while FOV did not affect users' memorization performance, a larger FOV reduced physical strain, giving an ergonomic advantage. Wider FOVs have also been linked to greater self-motion perception, vection, which at least partly depends on peripheral vision motion cues [15]. Kline and Witmer [23] studied the effects of FOV on distance perception and found users tend to underestimate distances but had more accurate judgement with a wide FOV, while over-estimating with a small FOV.

Conversely, it has also been thoroughly documented that a wider FOV increases susceptivity to cybersickness [15, 27, 31]. One reason for this is the user's peripheral vision system is more sensitive to flicker, which increases cybersickness onset; a wider FOV increases the amount of flicker perceived by users, and thus cybersickness [27]. Similarly, a wide FOV can increase postural disturbance, in turn yielding cybersickness [15, 31]. An increased FOV can also negatively impact a user's balance because their center-of-balance becomes more dispersed [15].

To combat cybersickness, some applications restrict FOV to completely block the peripheral view, reducing user peripheral awareness [10]. Cao et al. [10] proposed granulated rest frames to reduce cybersickness without completely blocking the peripheral view. This used granulated dots placed in the peripheral view, leveraging human ability to detect objects as a whole, even if they are partly occluded (amodal completion). Granulated rest frames improved visual search performance compared to a restricted FOV, but future work is needed to determine their effects on cybersickness. Our work uses FOV restrictors in the form of black bars around the edges of the user's view.

2.3 FOV and Search Tasks

A wider FOV is well-known to improve task completion and target discovery [2, 4, 38, 41]. The effects of FOV on search performance is stronger when users do not have prior knowledge of the target's location; a wider FOV is more beneficial without prior knowledge [9, 16]. Generally, a wider FOV tends to improve search performance [2, 14, 16, 25, 33, 37, 41]. Trepkowski et al. [41] found a wider FOV improved search performance for text and symbol search tasks using the HoloLens[3]. Conversely, neither Butkiewicz and Stevens [7] nor Kishishita et al. [22] found FOV significantly affected target search time. In fact, Kishishita et al. [22] found a wide FOV could even hinder search performance if in-view labelling was present.

Previous studies support that a wider FOV also reduces task error rate [4, 37, 41]. For example, Ragan et al. [37] report that larger FOVs yielded lower error rates and better performance in a threat search and identification task. Conversely, Ens et al. [16] found no significant effects of FOV on selection task error rate but recorded fewer errors with smaller FOVs overall.

Other studies have revealed that a larger FOV tended to result in users developing less natural search patterns [2, 9, 14, 38]. On the other hand, a smaller FOV yielded increased head movement, wider search paths, and movement time [2, 9, 14]. Consequently, smaller FOVs help users notice more targets resulting in fewer errors, since they had to scan their surroundings more [7, 16, 38].

Previous studies have also studied the effect of FOV on mental workload. Kruijff et al. [25] found users perceive tasks as less difficult with wide FOVs. Similarly, Kishishita et al. [22] found no significant effects of FOV on mental workload. In contrast, Blattgerste et al. [4] compared eye- and head-gaze selection under three FOV sizes (36°, 60°, and 90°). NASA-TLX scores, a common workload measure [17, 18], were lowest (best) with the large 90° FOV condition for both selection techniques. Similarly, Covelli et al. [14] report increased workload and stress with a smaller FOVs. These differing results could be explained due to different experiment scenarios. Covelli et al. [14] conducted their experiment using a pilot simulation, while Kruijff et al.'s [25] participants walked through a college campus and Kishishita et al. [22] studied a tourism scenario. Nevertheless, there is some inconsistency in results warranting further investigation.

Notably, Ragan et al. [37] used a single high-fidelity VR system to simulate mixed reality (MR) systems with different experimental conditions of equal or lesser fidelity. MR simulation has been used and verified by many other researchers to compare different FOVs in AR and VR with a single VR system [4, 16, 22, 23, 38]. We also use this method in our study.

2.4 Out-of-View Search and Dynamic Target Selection

Our study includes both out-of-view and moving targets, to be more representative of the kinds of "real" search tasks common in VR (notably games). Out-of-view target search in VR and AR often includes labels or visual cues to direct users to each target's location. The combination of FOV size with different label types and visual cues affects user search performance [20, 22, 25]. Although a narrow FOV hinders search performance, proper use of labels ameliorates this issue [25]. Kishishita et al. [22] found in-situ labelling yielded better search time, lower error rates, and higher target discovery rates. Overall, the impact of FOV was reduced by leader lines [22]. Similarly, Hu et al. [20] found that visual cues placed in the peripheral vision were more effective

[1] https://www.vive.com/ca/
[2] https://www.oculus.com/rift-s/
[3] https://www.microsoft.com/en-us/hololens

than moving arrows because they provided an better balance between obtrusiveness and persistence. However, these peripheral cues are overlayed on the display, which can be sub-optimal for narrow FOV HMDs. Therefore, Hu et al. [20] suggest moving arrows with a trail or tail to for narrow FOV conditions.

Compared to static target selection, few studies have been conducted on dynamic or moving target selection in VR. Yet, dynamic target selection is a common task, for example, in gaming applications [11] and encompasses two fundamental user tasks: search and selection. Even in 2D user interface research, and despite the prevalence of such tasks in many interactive systems, this area is relatively underexplored [21, 29]. Li et al. [30] evaluated dynamic target selection performance in VR with varying feedback mechanisms, including visual, audio, haptic, and combinations of all three, and varying target movement speed. Target speed had a significant impact on performance; faster target speeds yielded lower target selection accuracy.

Cashion et al. [11] compared four selection techniques for dense and dynamic target selection in a 3D environment. They compared raycasting, and three progressive refinement techniques SQUAD [24], Zoom [3], and Expand [11]. Overall, raycasting was best at selecting high-density, slow-moving targets while Expand was best for high-density, high-speed target selection.

Overall, there is relatively little work on dynamic target selection in VR, particularly with out-of-view targets. Moreover, the effects of field of view have yet to be studied in this context. Given that FOV has significant effects on search and selection tasks with *stationary* targets, we aim to improve understanding on how it these effects are impacted under dynamic target conditions.

3 Methodology

We conducted a remote user study using a cardboard VR device sent to participants, to minimize contact during the COVID-19 pandemic. Our objective was to determine the effects of FOV on moving vs. stationary out-of-view target search and selection.

3.1 Participants

We recruited 20 participants (5 female, 14 male, 1 non-binary) ages 18-50 (M = 24.75 years, SD = 8.12 years) by online recruitment by email and through a study recruitment Facebook page. Thirteen participants had little to no experience using VR HMDs, while 19 had little to no experience using a Google Cardboard. Three participants described themselves as novice VR users; four described themselves as VR experts. All participants had normal or corrected-to-normal vision except one who had uncorrected vision. Fourteen of the participants play video games that require a controller at least once a month.

3.2 Apparatus

3.2.1 Hardware

We sent participants a Google Cardboard VR device, ordered directly from Amazon. All participants used the POP! CARDBOARD 3.0 by Mr. Cardboard [35]. See Figure 1.

Figure 1: Google Cardboard kit by Mr. Cardboard with head strap.

The device has a measured total 70° FOV, a stereoscopic FOV of 65°, and can accommodate a smartphone of up to 3.3” wide [35]. FOV may vary depending on eye-to-lens distance and screen size. The cardboard viewer has a cut-out on the bottom to provide access to the smartphone’s touchscreen for input. The viewer also included a headband and internal nose padding for comfort.

Participants used their own Android smartphone running OS 7.0 or higher as the HMD. Out of the 20 smartphones, all had screen sizes 5” or greater, with 70% with 6” or greater screen size. There were eight different resolutions: four ranging from 1920-2400 × 1080 px and four ranging from 2560-3200 × 1440 px. The PPI of the devices varied as follows: 50% had 400-445 PPI, 40% had 500 PPI or higher, 10% had 395 PPI, and the highest PPI was 576. Most (80%) of the devices had a refresh rate of 60 Hz, while three devices refreshed at 120 Hz and one device at 90 Hz.

The smartphone acted as the display, computing device, and its internal sensors were used to detect head motion. Participants could change the viewport orientation with 3 DOF head rotation. Tapping the touchscreen through a finger hole on the bottom of the HMD issued a “click” event (that ended a search trial).

3.2.2 Software

We developed a VR system using Unity 2019.2 and the Google VR SDK for Unity v.1.2.00. with the Google VR Android v.1.18.4 package. The VE presented a room provided by the Google VR SDK. The environment contained blue, purple, and pink cubes placed around the room and a block texture on the walls to provide additional depth information to the participants. The area of the room where targets could spawn was 19 x 8.2 x 10.35 meters, and we positioned the camera 3.66 meters above the floor. The smartphone motion sensors were used to facilitate head motion in the scene. The environment is seen in Figure 2.

Figure 2: Virtual environment used in the experiment, depicting a trial with six targets in view. The instruction text indicates participants must find and select the target labelled ‘W’.

The environment contained between 2 and 26 floating white cubes of 0.5m size, as seen in Figure 2. Each cube face had a designated bright pink letter with a darker outline to make each target distinguishable and eas9y-to-read. Each trial, the software assigned a unique, random letter to each cube, thereby randomly generating a letter for the participant to find; the software displayed text in the centre of the screen to indicate which letter was the target for that trial. The cube positions were generated randomly such that no cube occluded another relative to the participant’s viewpoint, and the intended correct target always instantiated outside of the FOV. Target positions were different every time the program ran, thus no participants were presented with the same target locations. Targets were either static (i.e., stationary) or dynamic (i.e., moving), depending on the condition.

Stationary targets were dispersed throughout the VE 180° in front of the participant’s position. Stationary targets never moved and remained fixed in their initial randomly generated position. Conversely, dynamic targets floated in space 180° in front of the participant and moved at a constant speed of .75 m/s. The dynamic targets moved in a constant direction with a fixed upright orientation until they collided with an invisible boundary at the edge of the environment. After colliding, they bounced off mimicking light reflection.

We also displayed a small white ring cursor in the centre of the display to indicate where the participant's head/gaze was directed. For this work, we treat head-directed and gaze-directed as synonymous following common practice [12, 28, 40, 42, 43] and refer to the participants' gaze from this point forward. The cursor radius expanded when its center overlapped a cube as seen in Figure 3. We also displayed instruction text, indicating which target to select next, below the ring cursor, attached to the camera, so it was always in the participant's view.

Figure 3: Instruction text and ring visual cue before (left) and after (right) interacting with a selectable target.

Depending on condition, the scene was either presented with the full (~65°) stereoscopic field of view (see Figure 2), or half (~32.5°) stereoscopic field of view. Given the size of the virtual environment, we restricted the FOV both horizontally and vertically to cut off all peripheral vision and strengthen the effect FOV has on visual search performance. If the FOV was only restricted horizontally or vertically, participants would be able to view the room either from floor-to-ceiling or wall-to-wall while facing forward. To restrict FOV, we attached black bars to the camera position, overlaying the screen edges, and dynamically resizing based on the device screen size so they cut the viewing window by 50% of its original size (see Figure 4).

Figure 4: Half ~32.5° FOV version of scene shown in Figure 2.

The software also recorded several dependent variables. These included search time and error rate, among others. The software sent the dependent variables by email to us in real time.

3.3 Procedure

We conducted the experiment fully remotely due to the ongoing COVID-19 pandemic. We posted an ad on a Facebook page advertising experiments to prospective participants. Interested respondents contacted us by email; we pre-screened them for an appropriate smartphone by first sending them a link and instructions to install all necessary software (including the Cardboard VR app, and our VR app) on their smartphone. After confirming the study would work on their device, we asked for their mailing address, which we used to directly order the Cardboard to them from Amazon. Prior to the arrival of the Cardboard device, we sent them detailed instructions and all necessary information to complete the study independently. On request, a researcher was on standby via Discord or Zoom while they performed the study, in case participants had any issues.

To begin, participants read through the given instructions, which stated how to operate the Cardboard, a step-by-step explanation of the experiment procedure, and what was expected of participants during the experiment. After this explanation, the participant signed a consent form provided in the instructions. After providing consent, participants completed a demographic questionnaire via Qualtrics. Prior to starting the experiment, we asked them to silence all phone notifications, close any running applications, and be seated in a non-distracting environment.

We included a participant ID number and a counterbalancing order letter with the instructions. After the setup process, participants ran our VR application and entered the participant ID number and pressed one of four labelled buttons for their assigned counterbalancing order. After selecting a button, participants completed four target acquisition trials in each of the four practice conditions. Upon completing the final practice trial, the software presented a button to start the actual experiment, immediately taking them to the first study condition.

The experiment consisted of four conditions with 81 individual trials each. We labelled each target with a letter of the alphabet to uniquely identify it, and always displayed text instructions in the participant's view, specifying which letter target to search for. Each trial required participants search for the indicated target (see Figure 3) and select it as quickly and accurately as possible. To search for a target, participants directed their gaze at the target by moving/rotating their head. Selecting it required centering the ring cursor on the target and tapping on the smartphone screen through the Google Cardboard cut-out finger hole. The trial ended regardless if participants successfully hit the target or not; in either event, the next trial would commence, and the software logged the result of the completed trial as a hit or miss.

After completing each condition, participants removed the HMD and filled out an online NASA-TLX questionnaire [17] for the condition they had just finished. After completing the questionnaire, participants put the HMD back on and selected a "continue" button to proceed to the next condition. This process was repeated for the next three conditions. Participants took between an hour to an hour and a half to complete the entire experiment, excluding optional break time. Upon completion of the entire experiment, they also had the option to provide any comments they had on the experiment or Cardboard VR in general. As compensation, they were allowed to keep the Cardboard and received a $10 Amazon gift card by email.

3.4 Design

The experiment employed a 2 × 2 × 9 × 9 within-subjects design with the following independent variables and levels:

- ***FOV***: Full (~65°), Half (~32.5°)
- ***Target Movement***: Static, dynamic
- ***Target Count***: 2, 5, 8, 11, 14, 17, 20, 23, 26
- ***Trials***: 9

We counterbalanced the ordering of FOV and target movement according to a balanced Latin square, and randomized target count order. Target count indicates how many targets were visible in a given trial and ranged from 2 to 26. We included this factor to assess if the measured search time increased linearly with the number of distracters, as is typical in visual search tasks [33].

Participants completed nine trials per target count, for a total of 2 × 2 × 9 × 9 = 324 trials per participant, or 6480 trials in total.

There were six dependent variables: search time (s), error rate (%), FOV entries (count), time-in-FOV (s), target entries (count), and time-on-target (ms). Search time was the time from the previous target selection to the current target selection, and thus was the total search and selection time for a target. Error rate represented the percentage of target selections for a given condition that occurred with the curser outside of the target. FOV entries and target entries were inspired by selection accuracy metrics proposed by MacKenzie et al. [34]. FOV entries is the number of times the target entered the FOV in each trial. A higher number suggests that participants didn't immediately notice the target, continued to search, with the target leaving and entering the FOV before they eventually found it. Target entries is the count of times the curser overlapped the target prior to selection. Time-in-FOV is the amount of time (in seconds) the target was in the user's FOV before selection. Time-on-target indicates the total time (in milliseconds) a participant's gaze overlapped the target.

Our experiment design was influenced by MacKenzie's past work [33] that examined the linear relationship between search time and number of items. Our goal was to explore how targets being out-of-view or in motion would influence this relationship.

4 Results

We treated data points outside of ±3 *SD*s from the mean search time as outliers, removing 203, or 3.15% of the data set, by this criterion. Most outliers were significantly longer search times for their respective condition. However, 100 outliers were most likely mis-clicks – trials with accidental second taps of the screen after a trial, yielding very low selection time and a time-in-FOV of zero.

We performed a one-way ANOVA with condition order as the independent variable. The results were not significant, suggesting counterbalancing was effective. We also plotted the mean selection times for all 81 trials for each target count condition and overall, to determine if condition order affected performance due to fatigue, mental demand, learning, etc. Participants did not perform notably better or worse as a function of time.

We used Mauchly's test of sphericity and repeated measures ANOVA (RM-ANOVA) on each dependent variable. Where sphericity was violated, we report the Greenhouse-Geisser corrected tests. All significant effects of factors with more than two levels were followed up with pairwise comparisons using Bonferroni adjustment. Significant pairwise differences are visualized in results graphs as lines between conditions. For space reasons, we only report *significant* main and interaction effects.

4.1 Search Time

Mean search times are summarized across the four conditions in Figure 5. We analyzed search time using a RM-ANOVA, which revealed significant main effects of FOV ($F_{1,19} = 262.85$, $p < .001$, $\eta_p^2 = .93$), and target movement on search time ($F_{1,19} = 82.43$, $p < .001$, $\eta_p^2 = .81$). Both a wider FOV and static targets improved search performance, yielding lower search times. See Figure 5.

ANOVA also revealed a significant main effect of target count on search time ($F_{8,152} = 36.46$, $p < .001$, $\eta_p^2 = .66$). Post hoc tests using Bonferroni adjustment, revealed significant differences between low target counts (3, 5), medium target counts (8, 11, 14, 17), and high target counts (20, 23, 26). As seen in Figure 6, search times generally increased with target count. We modeled the relationship between search time and target count and found it to be highly linear (lowest $R^2 \approx 0.85$ for Half-Dynamic), regardless of target movement or FOV size. These results suggest that neither target movement nor FOV have much effect on the expected linear relationship, contrary to our H3.

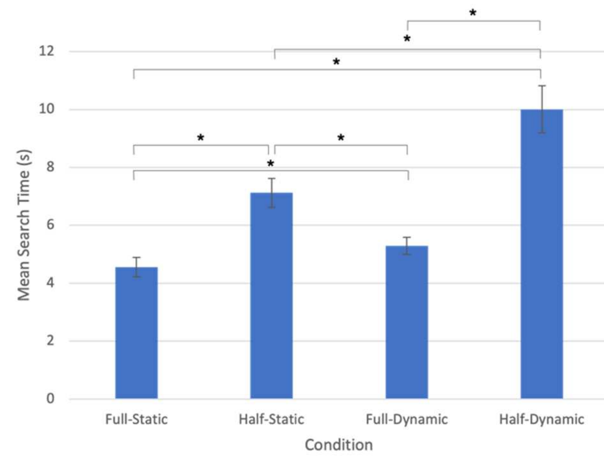

Figure 5: Mean search time by condition. Error bars show 95% CI.

We found a significant interaction effect between FOV and target movement on search time ($F_{1,19} = 28.85$, $p < .001$, $\eta_p^2 = .6$), indicating the effect of FOV was influenced by target movement. A second significant interaction between target movement and target count was found ($F_{8,152} = 3.13$, $p = .003$, $\eta_p^2 = .14$). We followed up this interaction with simple effects analysis. A significant simple effect of target count on static movement was found ($F_{16,4} = 6.61$, $p = .04$, $\eta_p^2 = .96$). Subsequent pairwise comparisons showed a significant difference in search time between all target counts except high target count (17, 20, 23, 26) pairs. A second simple effect of target count on dynamic target movement was found ($F_{16,4} = 28.88$, $p = .003$, $\eta_p^2 = .99$). Pairwise comparison revealed a significant difference between all target counts that were not sequentially adjacent to each other. As seen in Figure 6, the effect of target count on search time was more prominent in the dynamic target movement conditions. There was no significant interaction between FOV and target count.

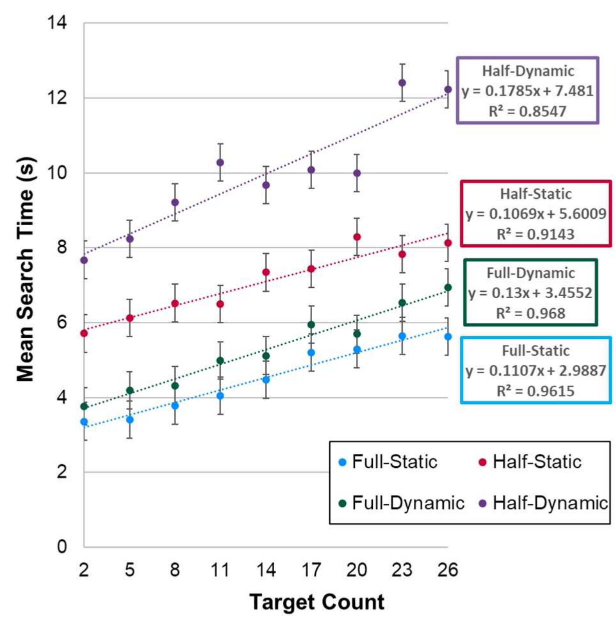

Figure 6: Mean search time by condition, and target count. Dotted lines show linear regression. Error bars show 95% CI.

4.2 Error Rate

Next, we analyzed error rate across the four study conditions. A RM-ANOVA revealed significant main effects of FOV ($F_{1,19}$ =

7.68, $p = .012$, $\eta_p^2 = .29$), and target movement ($F_{1,19} = 28.98$, $p < .001$, $\eta_p^2 = .6$). As seen in Figure 7, dynamic targets and the full FOV condition yielded more errors while target movement had a larger influence on error rate than FOV. A significant interaction between FOV and target movement was found ($F_{1,19} = 9.76$, $p = .006$, $\eta_p^2 = .34$), indicating the effect of FOV on error rate was influenced by target movement.

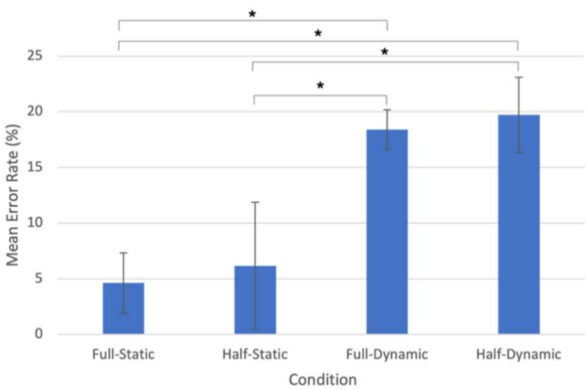

Figure 7: Error rate (%) by condition. Error bars show 95% CI.

4.3 FOV Entries & Time-in-FOV

FOV entries represent the number of times the target entered the FOV before being selected. A higher number suggests participants had a hard time finding the target. See Figure 8.

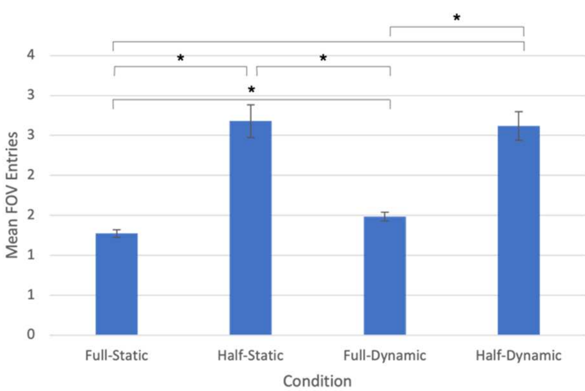

Figure 8: FOV entries by condition. Error bars show 95% CI.

RM-ANOVA revealed a significant main effect of FOV on FOV entries ($F_{1,19} = 197.02$, $p < .001$, $\eta_p^2 = .91$). The half FOV yielded significantly more FOV entries than the full FOV (see Figure 8). When addressing the impact of target count, Mauchly's test indicated sphericity was violated ($\chi^2_{35} = 56.73$, $p = .014$), and so we report Greenhouse-Geisser corrected tests, ($\varepsilon = .61$). We found a significant main effect of target count on FOV entries ($F_{4.88,92.68} = 3.61$, $p = .005$, $\eta_p^2 = .16$). Follow-up pairwise comparisons revealed a significant difference between target counts 3 and 23 ($p = .002$), and 8 and 23 ($p = .028$). A significant interaction between FOV and target movement was found ($F_{1,19} = 4.68$, $p = .044$, $\eta_p^2 = .2$). As seen in Figure 8, the effects of FOV on FOV entries is more pronounced with static targets.

Time-in-FOV indicates the total time the target was in the FOV before being selected. A higher number suggests participants had difficulty selecting the target, e.g., once it is found and identified. Mean time-in-FOV across conditions is seen in Figure 9.

RM-ANOVA revealed significant main effects of FOV ($F_{1,19} = 52.41$, $p < .001$, $\eta_p^2 = .73$), and target movement ($F_{1,19} = 35.12$, $p < .001$, $\eta_p^2 = .65$). As seen in Figure 9, targets were in the FOV longer with half FOV, and dynamic targets. The main effect of target count was significant ($F_{8,152} = 17.91$, $p < .001$, $\eta_p^2 = .49$).

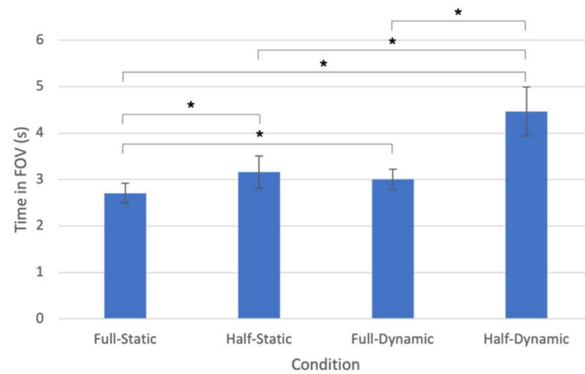

Figure 9: Mean time in FOV by condition. Error bars show 95% CI.

Pairwise comparisons revealed significant differences between low target counts (3, 5, 8), high target counts (23, 26), and all other target counts. We found a significant interaction between FOV and target movement ($F_{1,19} = 14.41$, $p = .001$, $\eta_p^2 = .43$), revealing the influence of FOV on time-in-FOV was stronger with dynamic targets (see Figure 9). When investigating the target movement and target count interaction, Mauchly's test indicated sphericity was violated ($\chi^2_{35} = 70.8$, $p < .001$), so we used Greenhouse-Geisser correction, ($\varepsilon = .53$). We found a significant interaction between target movement and target count ($F_{4.21,79.89} = 3.17$, $p = .017$, $\eta_p^2 = .14$). There was a significant effect of target count on dynamic target movement ($F_{16,4} = 11.98$, $p = .014$, $\eta_p^2 = .98$). Pairwise comparisons revealed significant differences between all non-adjacent target counts, with full FOV, and a significant difference between all targets counts and the lowest and highest target counts (3, 23, 26) with half FOV. Overall, the effect of target movement on time-in-FOV was influenced by target count; time-in-FOV increased more prominently with a higher target count and dynamic targets.

4.4 Target Entries & Time-on-Target

Target entries indicate how often the cursor hit the target prior to selection; higher numbers may indicate difficulty in acquiring the target. RM-ANOVA revealed a significant main effect of FOV ($F_{1,19} = 41.53$, $p < .001$, $\eta_p^2 = .69$), and target movement on target entries ($F_{1,19} = 114.98$, $p < .001$, $\eta_p^2 = .86$). As seen in Figure 10, smaller FOV and dynamic targets yielded more target entries. A significant interaction between FOV and target movement was found ($F_{1,19} = 9.59$, $p = .006$, $\eta_p^2 = .34$). The effect of FOV was stronger with dynamic targets. Overall, the half-dynamic condition had the highest target entries. See Figure 10.

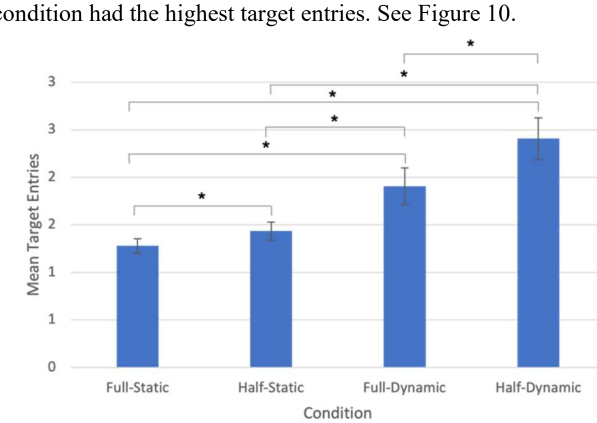

Figure 10: Target entries by condition. Error bars show 95% CI.

Time-on-target is similar, and represents how long the cursor was on the target, in total, before selection. The mean time-on-target scores are seen in Figure 11. RM-ANOVA revealed significant main effects of both FOV ($F_{1,19} = 23.58$, $p < .001$, $\eta_p^2 = .55$), and target movement ($F_{1,19} = 4.88$, $p = .04$, $\eta_p^2 = .2$), on time-on-target. As seen in Figure 11, time on the target was shorter with the full FOV, and with dynamic targets.

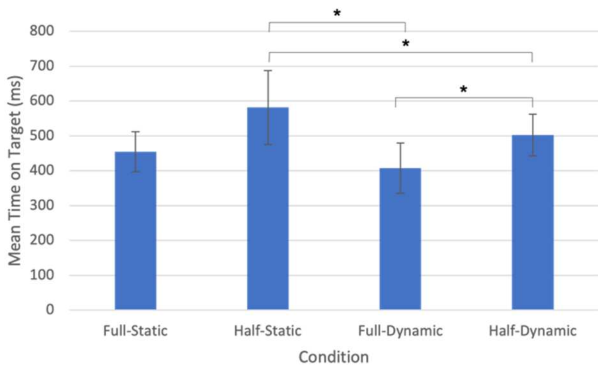

Figure 11: Mean time on target. Error bars show 95% CI.

4.5 Workload

We also asked participants to rate their perceived workload after each condition using the NASA-TLX questionnaire [17]. As seen in Figure 12, and contrary to our objective results above, the resulting scores suggest target movement more strongly influences perceived workload than FOV size. Both static target conditions were rated lower in all categories regardless of FOV. Participants perceived Half-Dynamic had the highest workload in all categories, while Full-Static condition was perceived as the least demanding in all categories across all conditions.

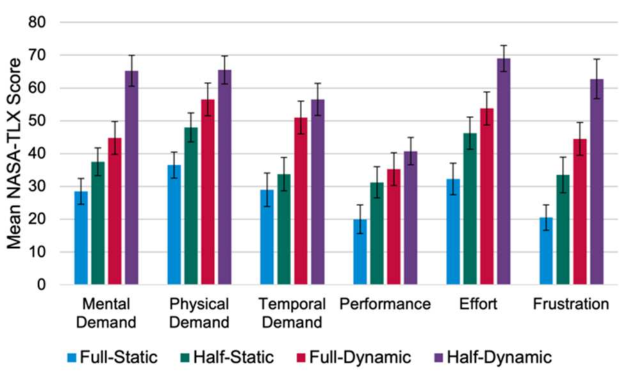

Figure 12: NASA-TLX scores by condition. Error bars show ± SD.

5 Discussion

Overall, full FOV conditions offered faster mean search times regardless if targets were static or dynamic (see Figure 5). Overall, full FOV conditions offered faster search times regardless if targets were static or dynamic (see Figure 5). This aligns with past findings [2, 14, 16, 25, 37, 41] and supports our hypothesis H1. Similarly, static targets were found more quickly, reflected in faster search times regardless of FOV, supporting H2. The Full-Static condition yielded the lowest search time of all conditions. Comparably, the Half-Dynamic condition had the highest mean search times of all conditions. Overall, these results support H1 and H2 and were expected. A wide FOV permits users to search a larger space and see more targets at any given time, allowing them to react faster in selecting them. Likewise, stationary targets are easier to locate, identify, and keep track of.

As seen in Figure 5, the mean search time of Half-Static was much higher than Full-Dynamic. This suggests FOV may have a greater influence on search time than target movement. This observation is reinforced by comparing the difference of mean search times of the FOV and target movement conditions independently. There was a larger difference in mean search time between the full and half FOV conditions than the static and dynamic conditions. It is possible FOV is a better determinant of search performance than target movement because a smaller FOV poses a larger hindrance on search performance and is generally seen as a disadvantage while moving targets can sometimes aid in search; for instance, a target could move into the user's FOV without the participant having to move themselves.

We used linear regression to model the relationship between search time and number of targets for each FOV/target movement condition. The advantage of such models is to provide a predictor of times for sample sizes not actually tested. As expected, target count had a significant impact on search time; as seen in Figure 6, as the number of visible targets increased, search time increased. This aligns with past literature on visual search [33]. Previous studies have shown that the relationship between mean search time and number of items in a set is highly linear [13, 19, 26, 33]. This result is apparent in all four conditions regardless of FOV and target movement. Thus, we reject our H3; even with the Half-Dynamic condition, the relationship was still linear. However, the R^2 value for the regression models for both of the half FOV conditions was lower than the full FOV conditions (see Figure 6). Moreover, we attempted to model these with a polynomial regression, and found slightly higher R^2 values for the half FOV conditions, with the curve "bending" slightly upward with higher target count. This might suggest that with a higher number of targets in the set, the half-FOV conditions might eventually become non-linear. This is a topic for future study.

Overall, the dynamic target conditions yielded substantially higher error rates than static targets (see Figure 7). This was expected and indicates that moving targets are more difficult to select as participants more consistently selected the space around the target. These results align with past work stating faster target speeds yielded lower target selection accuracy [30]. This increased selection difficulty increased search time as participants required more time to line up and perform a selection. Past work has been divided on the effects of FOV on error rate; there has been recorded findings of a wider FOV lowering error rate [4, 37, 41], while other past work found no significant effect of FOV on error rate [16]. Our results did not show a significant effect of FOV on error rate, therefore the effects of FOV on error rate are inconclusive in our study.

The FOV entries results show the target entered the full FOV more on average than the half FOV (see Figure 8). This suggests the target was less noticeable in the full FOV condition as it left and re-entered the participant's FOV more often, i.e., they missed it and continued to search more with a full FOV than the half FOV. This observation is in line with previous results that found users are more thorough and less sporadic in their search when given a smaller FOV [2, 9, 14], resulting in users noticing targets more often [7, 16, 38]. While targets entered the full FOV more often on average, the mean time-in-FOV shows that, on average, targets were inside the FOV longer with the half FOV conditions (see Figure 9). This supports our previous observation that a smaller FOV increases the difficulty of search tasks as participants needed more time to line up and select the target.

The mean target entries reveal on average, the participant's gaze re-entered the target more often given a smaller FOV and/or dynamic targets, with target movement being the more substantial factor. These results align with past work [30] by supporting the finding that moving targets reduce selection accuracy; it is more difficult for participants to line up the curser to the target and remain on the target. Similarly, on average, the participant's gaze spent less time on the target in the full FOV condition. This suggests that a larger FOV makes search faster and more accurate since the participant's gaze is entering and remaining on the target less often. This aligns with past work that found a wider FOV led to faster completion times and target discovery rates [2, 4, 37, 40].

5.1 Participant Feedback

The NASA-TLX results indicate target movement was considered to have a more significant impact on mental workload than FOV size. Both dynamic target conditions received worse scores in each category (see Figure 12), indicating that participants felt that moving targets posed a more demanding task. However, within the same target movement condition, the full FOV conditions scored better than the half FOV conditions. Globally, these results suggest that a larger FOV and stationary targets were perceived as less difficult by participants, with target movement the more critical factor. Unlike past work that found no effect of FOV on perceived workload [22, 25], our findings align with Blattgerste et al. [4] who found lower NASA-TLX scores are associated with larger FOVs. Likewise, our results are similar to those of Covelli et al. [14] who report increased workload and stress with a smaller FOV. Overall, our results suggest participants perceived tasks with a smaller FOV and/or moving targets as more demanding, frustrating, and requiring more effort to perform.

Finally, we also gathered subjective qualitative feedback from participants once they completed all conditions, asking their opinion of the search tasks and Google Cardboard VR. Multiple participants stated the full FOV made search easier, as did static targets. Other participants noted that the half FOV was more tiring, as it required more head movement. These comments support our NASA-TLX results. Interestingly, one participant reported that they found dynamic targets easier to find as they didn't need to look around as much. Conversely, another participant found dynamic targets harder to find because they kept losing track of visible targets. Participants also reported negative effects (e.g., finger strain, eye strain, dizziness, and nausea) from using the Google Cardboard for an extended period of time. Almost half the participants reported accidental screen taps by double tapping the screen or from finger twitches. This accounts for the 100 mis-clicks that were removed as outliers. Participants who had previous experience in VR reported the experience of the Cardboard VR felt similar to higher-end HMDs but was not a suitable replacement; multiple participants stated the Cardboard was uncomfortable to wear and the image was not clear.

5.2 Limitations

Due to the ongoing COVID-19 pandemic, we had to conduct this study remotely making it more difficult to ensure the accuracy of our data as no researcher was present during the experiments. We had to put greater trust into participants to complete the study accurately and to the best of their abilities. As well, participants used different phone models with diverse screen sizes, potentially causing a varied experience among participants with slightly differing FOVs. These factors likely introduced greater variability in our data than we would expect in a lab-based study. That said, there is some advantage of this approach, in that it enhances the external validity of the experiment. In other words, we reliably detected significant differences, but they likely apply to a broader set of people, situations, and technology setups due to the variance in the technical setups used in the study.

As participants mentioned, the quality and comfort of the Cardboard was not on par with current HMDs. While we don't expect this to drastically change results, it would be worth repeating the study with a high-end HMD (e.g., Oculus Quest).

5.3 Future Work

In future work, we will explore search and selection performance with varying target speed to determine the impact of target movement speed in such tasks. We would also like to investigate dynamic, out-of-view target search in more complex (more natural) VEs. For example, dynamic objects could be part of the environment, and the cognitive load of the task and perceived workload may increase. Past studies have shown FOV does not influence perceived workload [22, 25]. However, a dynamic environment and moving targets may yield different results.

We would also like to investigate the effects of dynamic targets on user search patterns. Past research suggested a larger FOV resulted in less natural search patterns [2, 14, 30, 38], and a narrow FOV made users more thorough and deliberate in their search [7, 16, 38]. It would be valuable to investigate whether the inclusion of dynamic targets would influence user search patterns in a way that contends with these past findings.

We would like to use the design of this study and modify it to determine under what conditions the relationship of search time and number of visible items diverges from linearity. This would involve comparing greater variations of target speed, FOV sizes, and number of visible items. We would like to investigate at what number of visible items does this established linear model break.

Lastly, as our study was conducted on Google cardboard, we would like to investigate whether our results could be generalized to modern, commercial HMDs. Modern HMDs provide higher graphical fidelity, greater FOV capabilities, and improved selection techniques (e.g., tracked controllers, gaze-based selection using eye tracking technology). These factors could influence selection performance and perceived workload.

6 Conclusion

Visual search is common in VR and is affected by many factors including FOV and target speed. Our results add to a body of literature on FOV and target search. While past research on FOV generally suggests that wide FOVs are preferable, these studies were all conducted on stationary targets that were either in-view, or with view-direction aids [16, 25, 37]. Yet, static in-view target search/selection is likely the exception rather than the norm in many VR applications. Our study is, to our knowledge, the first to systematically investigate the effects of FOV on dynamic, out-of-view visual search. Our results suggest that, as expected, moving targets are more difficult to acquire than stationary ones, and harder to find still with a smaller field of view.

A key finding is that the target set size seems to increase search time linearly regardless of dynamic/small-FOV conditions. However, this is a topic for future work, as the maximum number of targets we used in any trial was 26; it is possible for larger target sets that these models become nonlinear. Such a result would have important implications for the design of virtual environments with large numbers of searchable/selectable objects.

Our results also suggested FOV as a more substantial factor of search performance than target movement. Conversely, target movement showed to be a more significant factor of perceived workload than FOV. FOV and target movement did not affect the linear relationship between search time and number of visible items. Overall, these results are encouraging and motivate us to further explore dynamic target search in 3D environments.

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