Pushing the Limits? Frame Rate Benefits to Players for up to 500 Hz in First Person Shooter Games

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ABSTRACT

Computer games – and computer game players – often drive technology improvements, with graphics cards and monitors pushing the limits of display technologies. High frame rates, in particular, promise to provide lower latencies and smoother game visuals to gamers, especially important for competitive first person shooter (FPS) game players. What is not well-known is to what extent gamers benefit from ultra-high frame rates in terms of player performance and quality of experience. This paper studies the effects of frame rates – especially high frame rates – on FPS game players. A custom FPS game was developed to allow for consistent delivery of frame rates from 7 f/s to 500 f/s, while recording objective (performance) and subjective (smoothness) measures. Analysis of data from a 44-person user study shows player performance (e.g., score) improves sharply from 7+ f/s, but levels out after about 90 f/s. However, users perception benefits over the full range of frame rates studied, rising sharply from 7+ f/s, but continuing to improve through the top 500 f/s.

CCS CONCEPTS

• **Applied computing** → **Computer games**; • **Human-centered computing** → *User studies*; Laboratory experiments.

KEYWORDS

First Person Shooter, FPS, High Refresh Rate, Framerate, Frame Rate, 500 Hz, Latency, QoE, Quality of Experience, Visual Perception

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1 INTRODUCTION

Computer games continue to drive many advances in computer technologies, with improvements to hardware and supporting software enhancing both immersion and player performance [6]. In first-person shooter (FPS) games, precision and responsiveness are essential, and high frame rate monitors driven by powerful GPUs are sought out by competitive esports players [11]. High frame rate monitors provide smoother animations and reduce input latency, potentially boosting player experience and performance.

Higher frame rates improve visual smoothness by capturing smaller position changes and making transitions between frames appear smoother. They also reduce system latency, allowing players to see actions sooner and react more quickly, such as spotting an opponent emerging from cover earlier.

Despite the availability of high-end gaming systems for consumers, the extent to which high frame rates affect player performance and QoE in FPS games remains under-explored. Understanding the impact of high frame rates on performance and experience can help: 1) system developers to focus on technologies that matter, and 2) players to decide on system upgrades or settings in order to get systems with frame rates that matter.

To study the effects of high frame rates on FPS game players, we designed and implemented a bespoke FPS game (*Lead Rush*) that focused on core FPS game elements while controlling frame rates to be consistent up to 500 f/s. Participants played Lead Rush for about 2 dozen short game rounds at different frame rates, while recording performance metrics (e.g., shots fired, shots hit) and users' perceptions of game smoothness. This approach allows analysis of the impact of frame rates on both player performance and player quality of experience (QoE).

The rest of this paper is organized as follows: Section 2 provides background and research related to our paper; Section 3 outlines our methodology – assessing the effects of frame rate through a user study; Section 4 analyzes the results from the user study; Section 5 discusses our key findings and their implications; Section 6 identifies some study limitations; and Section 7 summarizes our conclusions and suggests possible future work.

2 RELATED WORK

This section summarizes studies related to our work in three areas: frame rates and visual quality, frame time variability, and frame rates and FPS games.

Frame Rate and Visual Quality: The relationships between frame rate media quality has been studied for various video media. Early work by Apteker et al. [1] analyzed the influence of network bitrates on video playback rates. They found that degrading quality of service in a video reduced bitrates in playback frame rates. Mazhar and Abdalla [10] studied the tradeoff between frame rate and resolution and concluded that at least 20 frames per second were needed for high-motion sequences, but 15 frames per second may be acceptable for low-motion sequences. Across both studies, playback rates for video content impacted performance and quality.

Ou et al. [12] found that video quality decreased as frame rates dropped, following an inverted exponential trend, with faster motion content degrading more quickly. They proposed a model to predict quality based on motion, frame differences, and contrast, emphasizing the need for higher frame rates to maintain quality in dynamic content.

Zadtootaghaj et al. [16] developed a QoE model for cloud gaming that focused on the relationship between bitrates and framerates. They concluded that for lower bitrates, opting for a frame rate of 25 f/s was advisable to minimize blockiness in the video. However, at frame rates below 25 f/s, video quality significantly deteriorated due to jerkiness, which could potentially lead to fatigue or other adverse effects over time.

Frame Time Variation & Adaptive Displays: Player input in twitch genres like FPS games relies on real-time visual cues, making frame rate and inter-frame variability critical. Klein et al. [7] found that deviations from the average frame time affected perceived motion smoothness, with minimal extra impact. Liu et al. [9] showed that increased frame time variability – induced by higher CPU load in Valorant, Rocket League, and Strange Brigade – reduced the quality of experience.

Technologies like VSync and G-Sync help mitigate these effects. Lee et al. [8] demonstrated that a higher server tick-rate and VSync improved player accuracy, while Watson et al. [14] observed that G-Sync enhanced performance in Battlefield 4.

Xu et al. [15] developed a QoE model from four studies over 11 games considering frame rate and frame time variations. They found that frame time variability and interruption severity were strong predictors of player experience, accounting for roughly 90% of gaming quality variance, though average frame rate did not always predict satisfaction accurately.

Denes et al. [5] developed a model to optimize motion quality by adjusting monitor refresh rates and resolutions based on motion speed. Their experiments, ranging from 50 Hz to 165 Hz, showed that adaptive refresh rates provided smoother visuals than fixed rates, especially for fast-moving content. The study highlighted that balancing refresh rate and resolution improved performance, with practical applications for G-Sync monitors and VR/AR headsets for better visual quality with hardware limits.

Impact of Frame Rate on FPS Games: Claypool and Claypool [2] examined how varying frame rates impact player performance through the lenses of first person, third person, and isometric avatar perspectives. Generally, when the frame rate dropped below 15 f/s, users performed worse, especially in tasks that required quick, precise actions like shooting in games. The negative impact on performance was more noticeable for actions needing fast, accurate responses compared to tasks that can handle a bit of delay, like moving around in the game. In a comparative study between frame rate and resolution, Claypool et al. [3, 4] found that frame rate had a greater impact on player performance and perceived game quality than did resolution. They also observed that for video playback, the situation was reversed: resolution was more important to viewers than frame rate.

Spjut et al. [13] studied the effects of latency and display refresh rates on FPS performance using skilled esports athletes. They found that lower latency significantly improved task times for both single-click ("1-hit") and tracking tasks. While higher refresh rates (120 f/s to 360 f/s) helped, their impact was greater for tracking tasks requiring sustained aim and less critical for single-click actions. The main benefit of higher refresh rates is their ability to reduce latency, which is important in competitive gaming.

Our current paper: extends previous research by focusing on ultra-high framerates, up to 500 f/s in a genre popular with previous studies and esports players – an FPS game. Unlike prior studies that adjusted input latency – an aspect inherently tied to frame rate – our research isolates frame rate as the primary factor of interest and evaluates the effects of frame rate on objective performance metrics (e.g., accuracy, score), subjective QoE (smoothness), and player behavior (e.g., mouse movement).

3 METHODOLOGY

To investigate the effects of frame rate in a first-person shooter (FPS) game, we conducted a user study using a custom FPS game called *Lead Rush*. The game was modified to fit our study, running each round at a controlled framerate while recording objective player performance and subjective Quality of Experience (QoE).

3.1 Game Description

Lead Rush[1] is a first-person shooter game developed in Unity 2023 to run at ultra-high frame rates (1500+ Hz). It features procedural animations, positional audio for gunplay, and a configurable experimental harness for data collection. A logging system was added to record performance metrics.

The game involves controlling an avatar to shoot and destroy a single enemy at a time while avoiding contact. Enemies are red floating orbs that require 5 hits to destroy. The orb moves toward the player, navigating around obstacles. If it collides with the player, both are eliminated, and the player respawns at the starting position. After an orb is destroyed, a new one respawns in 100 milliseconds.

The orb's respawn location is dynamically set within a torus-shaped area, 4 to 6 Unity meters from the player, avoiding blocked areas. The orb oscillates on the Y-axis between 0.9 and 1.1 Unity meters and moves at 3.1 meters per second, slightly faster than the player's 3 meters per second. Unity Navmesh[2] is used for navigation.

The game provides visual and audio cues for enemy direction and proximity. Yellow bars flash along the screen edges, growing brighter as the enemy gets closer. Positional audio indicates enemy location, with distinct sounds for hits, destruction, and shooting.

Figure 1 shows a screenshot of *Lead Rush*. The yellow bar at the top indicates the enemy is in front. Hit markers appear on

[1] Lead Rush GitHub: https://github.com/Tokey/Lead-Rush
[2] Unity Navmesh: https://docs.unity3d.com/ScriptReference/AI.NavMesh.html

successful hits (yellow) and kills (red), though these are not shown in the figure. Lead Rush gameplay video[3] shows two rounds of gameplay. It demonstrates the gameplay mechanics, enemy AI, gunplay, animations, and UI elements in action. Each round ends with a window asking about visual quality via a slider to gather player feedback.

Figure 1: Lead Rush in-game screenshot.

The study used a fully automatic assault rifle with a 750 rounds/minute fire rate. Hits are detected via hitscan, and the gun features procedural recoil, sway, camera shake, and aim-down sight animations. A green laser assists aiming. The weapon has unlimited magazines of 31 bullets each and reloads automatically or manually ('R'), with a 2-second reload animation.

Players earn 10 points per hit and 100 points per kill but lose 100 points per death. Scores can drop below zero.

3.2 Experimental Harness

The game consists of 1-minute rounds played at different frame rates. For this study, we used twelve frame rates – 7, 15, 30, 45, 60, 75, 90, 120, 165, 240, 360 and 500 frames per second – each played twice for a total of 24 main rounds. Prior to the main rounds, participants played 2 practice rounds, each a minute long, with the first at 500 f/s followed by a second round at 7 f/s. The order of the main rounds was arranged using a Latin square to balance frame rate conditions across sessions.

A session ID tracked each row of the Latin square. After a user completed a session, the session ID was incremented and saved to a file. For a new session, the ID was read from the file, and the corresponding row of the Latin square used to determine the sequence of rounds.

After the round ended, players were asked a question regarding their experience for that round:

- *Rate the Smoothness of the Round* - 1 (Very Choppy) to 5 (Very Smooth) via a slider.

The game generated logs to track player actions, performance metrics, and enemy interactions, which were used in our analysis.

3.3 User study procedure

The user study procedure, approved by the university's institutional review board, began with recruitment through departmental emails and advertisements on an official Discord playtesting channel. Participants selected from availability time slots using Slottr. Before participating, they were provided with a consent form outlining the study details and completed an optional demographic survey. A reaction time test was conducted, followed by two practice rounds - one at 500 fps and another at 7 fps - to familiarize participants with the smoothest and choppiest frame rates and the QoE question presented after each round. Participants then completed 24 main rounds. Log files from each session were collected and backed up by the study proctor. Each session lasted approximately 30 minutes, and participants were entered into a raffle for a $25 Amazon eGift card, with an additional $10 eGift card awarded to the highest scorer.

3.4 Hardware

The participant's computer was a high-end gaming PC: an ALIENWARE AW2524H monitor overclocked to 500 Hz, 1920 x 1080 pixels, an Intel Core i9-11900K CPU, 32 GB DDR4 RAM, an NVIDIA 4070 Super FE GPU, a Samsung 970 Evo SSD, and a Logitech G502 mouse. This allowed Lead Rush to run consistently at extremely high frame rates.

The NVIDIA Reflex Analyzer was used to measure the local latency of our system. For the purposes of latency measurements only, *Lead Rush* was modified to display a color-changing box on the side of the screen upon mouse click. The mouse was connected to the monitor, and the game was played through 12 rounds with our 12 set of frame rates.

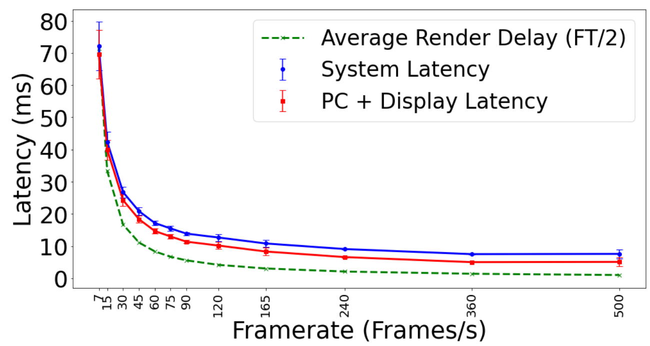

Figure 2: Latency of Lead Rush using NVIDIA Reflex Analyzer.

Figure 2 presents a comparison of system latency, PC + display latency, and the estimated average render delay across different frame rates. The data was measured using NVIDIA GeForce Experience (Version 3.28.0.412 - Experimental) and reported as means with 95% confidence intervals. The blue line shows the system latency, which is the total time taken for the computer to process an input and display the corresponding action on the screen. The red line represents the PC + display latency, a component of system latency, measured from when the OS registers the click to when the display updates. The green dashed line shows the estimated average render delay (FT/2), where FT is the frame time for a given frame rate. The plot shows our PC provides consistent control of the frame rate for the full range (7 - 500 f/s) with small system and display latencies on top of the average frame time latency. The recorded

[3]Lead Rush gameplay video: https://www.youtube.com/watch?v=Lakj7qhED1c

frame rates were close to the intended values, with minimal deviations. Lower frame rates (7 to 75 fps) had standard deviations of 0.00 to 0.01, while higher rates (90 to 500 fps) showed slightly more variation, with deviations from 0.02 to 0.15. This shows the hardware maintained the intended frame rates.

4 ANALYSIS

This section provides the participant demographics, followed by an analysis of player experience, performance and behavior.

4.1 Demographics

A total of 44 players participated in the study. Table 1 summarizes their demographics. Numeric values are means with standard deviations in parentheses. The average participant age was about 21 years (M = 21.6, SD = 5.5), ranging from 18 to 38 years old, with the majority identifying as male (68%). Participants rated their experience in general gaming and FPS games with a mouse and keyboard on a scale from 1 (low) to 5 (high). On average, participants had moderate gaming experience (M = 3.3, SD = 0.9) and moderate FPS experience (M = 2.9, SD = 1.1) and enjoyed playing games (M = 4.4, SD = 0.7). Reaction times were quick (M = 196.5 ms, SD = 72.0), typical of experienced gamers.

4.2 Player Experience

Figure 3 shows the QoE scores for all players over all rounds, with means bounded by 95% confidence intervals. The graph on the left shows QoE versus frame rate on the x-axis and the graph on the right shows the same QoE data, but plotted versus frame time on the x-axis. From the graph on the left, there is a sharp increase in QoE as frame rates go from 7 f/s to about 90 f/s then a noticeable flattening of the QoE trends from 120 f/s to 500 f/s. From the graph on the right, the trend in decreasing QoE scores with an increase in frame time is fairly linear across all frame rates, albeit with a curve from 13 ms to 142 ms. Note, in both graphs, while the QoE trends have flattened, there appears to be a slight upward slope even at the highest frame rates – a slight increase in QoE at the right edge of the left graph from 165 f/s to 500 f/s and a slight decrease in QoE at the left edge of the right graph from 2 to 13 ms. This suggests that users are able to notice the smoother experience afforded by the highest frame rates.

4.3 Player Performance

Figure 4 shows the aggregated player scores for all players averaged across all rounds with a 95% confidence intervals. The left graph shows score versus frame rate and the right graph shows the same data but versus frame time. From the graph on the left, player performance rises sharply from 7 f/s to 60 f/s and then flattens, showing almost no change from 60 f/s to 500 f/s. This is evident in the flat trend on the left side of the right graph. Also in the right graph, the decrease in player score is nearly linear as frame times increase from 22 ms to 142 ms. In comparison to the QoE analysis (Figure 3), the benefits for high frame rates to player performance level out a bit earlier compared to player QoE (60 f/s versus 90 f/s). Moreover, while there was a slight upward trend in QoE as frame rates continue to climb above 90 f/s with means increasing all the way through 500 hz, there is no visual trend in score performance for the same range. Note, accuracy analysis followed similar trends as for score, but is not shown here due to space constraints.

4.4 Player Behavior

This subsection analyzes the effects of frame rate on player behavior, here focusing on mouse movements. Figure 5 shows an analysis of the mouse movements, computed as the total degrees moved averaged across all users and all rounds with 95% confidence intervals, plotted versus frame rate (graph on the left) and frame time (graph on the right). The trends in mouse movements follow the trends in performance, with an increase in mouse movements as frame rates increase (and corresponding decrease in mouse movements as frame times increase) the difference in mouse movements for low frame rates compared to high frame rates is not as large as the corresponding differences in scores. This suggests players are trying to do about the same actions (moving the mouse to aim) across all frame rates, but with the previous performance data (Figure 4) showing the impact that frame rates have on performance. From the graph on the right of Figure 5, there is a slight upward trend in mouse movements even as frame rates go from 90 f/s to 500 f/s (corresponding to a slight decrease on the left edge of the graph on the right), suggesting the higher frame rates incentivizes more mouse movements. In addition, the trendline in the graph on the right shows a nearly linear relationship across the full range of frame times – 2 ms to 143 ms – suggesting player behaviors (actions) have not saturated at lower frame rates (e.g., 90 f/s) even if performance may have (e.g., score in Figure 4). Note, while there could have been an increase in mouse movement values recorded due to mechanical "noise" in readings from the mouse (i.e., small variations in readings even if the mouse does not move) that accumulate more at higher frame rates, this was not the case here – repeated readings of a still mouse at 500 f/s found all readings to be zero.

5 DISCUSSION

While frame rates of 60 f/s are common among PCs and similar devices, many gamers seek systems with higher frame rates – 120 f/s, 144 f/s and even 240 f/s. This is especially true for serious gamers that push for technologies that improve their experience and provide a competitive edge. In particular, FPS game players often drive technology improvements given the prevalence of FPS games in esports.

Our study results for a FPS game played over a wide range of frame rates (7 f/s to 500 f/s) show that increasing frame rates does help player performance up to a point – specifically, performance at low frame rates can be markedly improved by increasing the frame rate. On the other hand, increasing frame rates above 90 f/s does not noticeably improve player score nor accuracy. This is likely because there are diminishing returns to performance with the reduced latency afforded by ultra-high frame rate displays. However, even with the lack of benefit to performance, frame rates higher than 90 f/s *do* seem to improve player experience, with our data showing a slight upward trend in player perception of smoothness in the game all the way to 500 f/s.

We conjecture that in an FPS game, such as Lead Rush, how readily a player discerns the frame rate – low or high – is largely impacted by the movement of their mouse. The more a player moves

Table 1: Participant demographics.

Users	**Age**	**Gender**	**Gaming Skill** (1-5)	**FPS Skill** (1-5)	**Reaction Time** (ms)	**Likes Games** (1-5)
44	21.6 (5.5)	♂30 ♀12 ☿2	3.3 (0.9)	2.9 (1.1)	196.5 (72.0)	4.4 (0.7)

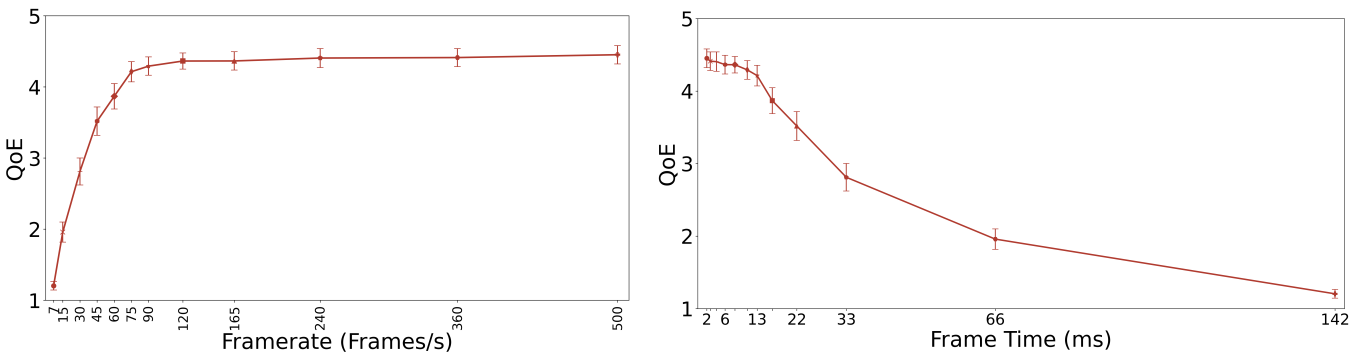

Figure 3: Player experience (QoE) – mean and confidence interval – versus frame rate (left) and frame time (right).

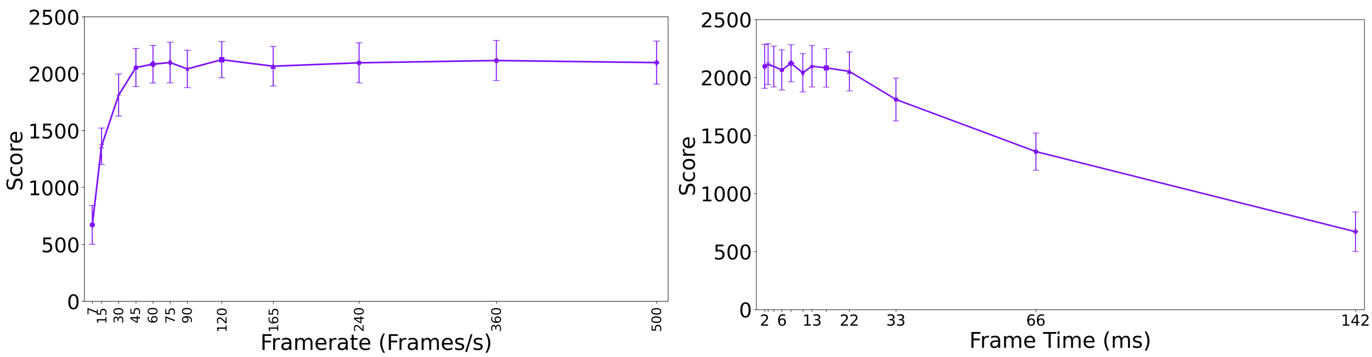

Figure 4: Player performance (score) – mean and confidence interval – versus frame rate (left) and frame time (right).

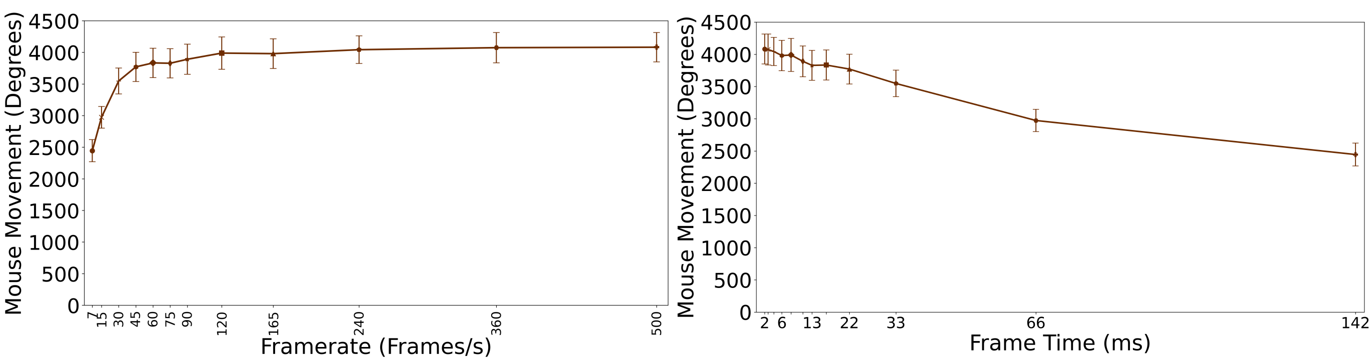

Figure 5: Player actions (mouse movement) – mean and confidence interval – versus frame rate (left) and frame time (right).

the mouse, the more the first person perspective camera moves and the more likely a player notices the frame rate – choppy for a low frame rate (e.g., 7 f/s) and smooth for a high frame rate (e.g., 500 f/s).

To test this, Figure 6 shows the correlation between perceived smoothness and mouse movement. The y-axes are the QoE scores and the x-axes are the total mouse movements (in degrees) in a round. Each point is the average for 10 equal clusters of mouse movements. The extremes are shown – the left graph has values for 7 f/s and the right graph has values for 500 f/s. The lines are linear trends with the coefficient of determination (R^2) shown.

At 7 f/s (left), the trend line shows a negative slope, suggesting that as players moved the mouse more, they became more aware of the choppiness, resulting in lower QoE. Conversely, at 500 f/s (right), the trend line is positive, indicating that players that moved the mouse more perceived more smoothness, resulting in a higher QoE.

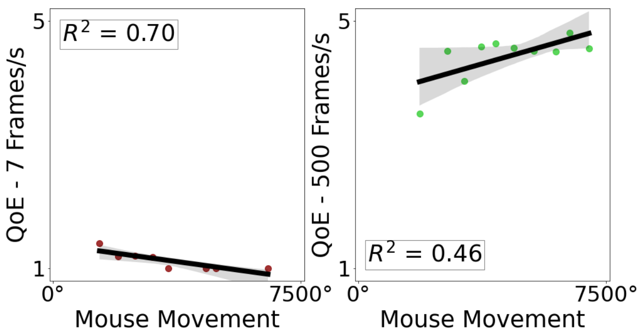

Figure 6: Correlation of QoE with mouse movement for 7 f/s and 500 f/s.

We do the same analysis for all frame rates and compute the slopes (QoE versus mouse movement) for the trendlines. Figure 7 shows these slopes with the y-axis the slope – QoE change per 10k degrees of mouse movement. The slopes follow the expected relationship – low frame rates have a negative slope meaning moving the mouse more reveals the choppiness, while as frame rates get ultra high, moving the mouse mores allow users to perceive more smoothness.

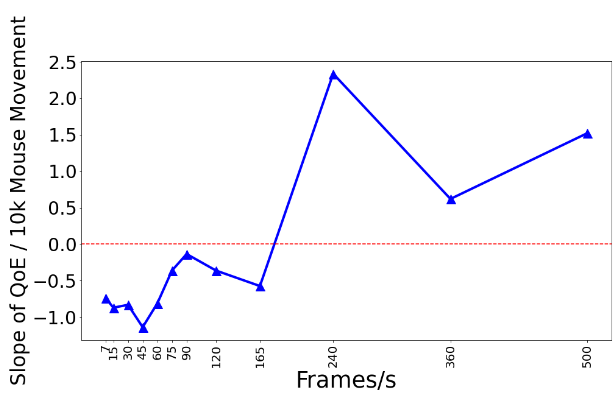

Figure 7: Slope of QoE and 10k total mouse movement with frame rate.

The slope, intercept, and R^2 values for the correlation between QoE and mouse movement varied across frame rates, with differences observed at 240 and 500 f/s. Higher skill players had greater total mouse movement compared to lower skill players, indicating that frame rates may affect skilled players differently.

6 LIMITATION

Our study is designed to achieve consistent, fixed frame rates in order to assess the effects of frame rate precisely. In practice, for many games and game systems, the frame rates fluctuate due to factors such as system load, network conditions, and game-state complexity, which may outweigh or even mitigate the fixed frame rate effects in our study.

Our game was also deliberately focused on only the gameplay core to a FPS game – moving and shooting in combat with a single enemy. However, most commercial FPS games are more complex, with diverse mechanics, environments, and player interactions that can influence performance and experience. Our study also only used a fully automatic rifle, while most FPS games offer weapons with different characteristics (e.g., firing rates, damage, bullet spread), allowing players to adjust their strategies with frame rate. More precise weapons (e.g., sniper rifles) may be more sensitive to lower frame rates and, possibly, may benefit from higher frame rates.

Our study relied upon users providing truthful responses to a smoothness question after only one minute of gameplay, before the frame rate switches in the next round. That was deemed long enough in our pilot tests, but in actual games, users may become acclimated to a given frame rate when playing for a longer time, possibly adjusting the QoE scores up or down from those we record.

7 CONCLUSION

Higher frame rates provide for a smoother visuals and lower input latency, but likely have diminishing returns as technologies push the limits of human perception and performance. This study explores the effects of frame rate on player experience, performance, and behavior using a bespoke first person shooter (FPS) game, Lead Rush. Lead rush provides core FPS gameplay and is specifically designed and implemented to provide consistent, frame rates from a low of 7 f/s to an ultra-high 500 f/s. A total of 44 participants each played 24 one-minute rounds of Lead Rush at 12 different frame rates, ranging from 7 f/s to 500 f/s, with objective data collected on player performance (e.g., score) and subjective data gathered on player quality of experience (e.g., perceived smoothness).

The results show that player performance improves sharply from 7 f/s through 90 f/s, but sees little benefit for frame rates higher than 120 f/s. Player smoothness-based QoE also has a dramatic rise from 7 f/s through 90 f/s, but *also* increases slightly through the full range of frame rates tested (i.e., up to 500 f/s). Perception of low and high frame rates is likely enhanced by more frequent mouse movements, with higher skilled players moving the mouse more than lower skilled player. These results can help inform esports researchers towards systems that have both real and perceived benefits, and provide players guidance for system purchases and upgrades.

Future research could look at how ultra high frame rates affect other game genres that need precise timing, like racing, rhythm, or fighting games, to better understand impact on player experience, performance, and behavior. Display sizes may have a confounding effect on frame rates, too, so studies with larger monitors with higher resolutions as well as smaller monitors with lower resolutions could be worthwhile.

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