# The Effects of Frame Rate Variation on Game Player Quality of Experience

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## ABSTRACT

For gamers, high frame rates are important for a smooth visual display and good quality of experience (QoE). However, high frame rates alone are not enough as variations in the frame display times can degrade QoE even as the average frame rate remains high. While the impact of steady frame rates on player QoE is fairly well-studied, the effects of frame rate variation is not. This paper presents a 33-person user study that evaluates the impact of frame rate variation on users playing three different computer games. Analysis of the results shows average frame rate alone is a poor predictor of QoE, and frame rate variation has a significant impact on player QoE. While the standard deviation of frame times is promising as a general predictor for QoE, frame time standard deviation may not be accurate for all individual games. However, 95% frame rate floor -– the bottom 5% of frame rates the player experiences — appears to be an effective predictor of both QoE overall and for the individual games tested.

## CCS CONCEPTS

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

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## 1 INTRODUCTION

Computer games are one of the world's most popular forms of entertainment, with global sales increasing at an annual rate of 10% or more [21]. The increasing popularity of computer games drives development of new computer hardware, such as processors and graphics cards, to support the latest game innovations and to provide better player experiences. A key factor to the player experience is the frame rate where, generally, a higher frame rate is preferred over a lower frame rate. However, high average frames rates alone do not ensure a good experience since variation in frame rates can degrade the player's experience even while the average stays high. And, unfortunately, frame variation is a challenge that may be faced by most game systems as new games and the demands of their players continually push the graphics and processing capabilities of today's systems.

Frame rate is a well-known metric which denotes how many times the pictures are displayed to the screen in a second. For example, 30 f/s means 30 pictures are displayed each second. Figure 1 depicts two sets of frame rates, where the top set has a lower frame rate and the bottom a higher frame rate. Generally, with a higher frame rate, the game appears visually smoother and more responsive to player input than it does with a lower frame rate. Also depicted in the figure is *frame time* – the time interval between consecutive frames being displayed on the screen. The higher the frame rate, the shorter the frame time.

There have been numerous studies that have examined the effects of frame rates on users passively watching streaming video [4, 6, 14, 15, 23]. These studies have generally found that a decrease in average frame rate results in a modest decrease in user satisfaction. However, passively watching video, even in its most interactive form such as during a videoconference, does not have the same interaction requirements as do computer games. There are some, albeit fewer, studies that have examined the effects of frame rates on users actively engaged in playing computer games [7–9, 18]. These studies have generally found that a decrease in average frame rate has a marked decrease on both player performance and game enjoyment, and that actions that require more precise, faster response, such as shooting, are more impacted by degradations in average frame rates. While informative, these studies have only examined the average frame rate, with no consideration for frame rate variation over the video or game.

Figure 2 depicts frame variation, showing a game with a consistent frame rate on the top versus a game with an inconsistent frame rate on the bottom. With a consistent frame rate, the frame time is constant resulting in the pictures being refreshed regularly. In contrast, when there is frame rate variation, the frame time is not the same for each picture displayed and frame times can be longer or shorter than the frame time average. Frame rate variation can make the game appear visually choppy with irregular visual feedback to player input.

Variation in frame rate is common with computer games, particularly for games on a PC. PC computer games run on systems with a range of processing and display capabilities. The diversity of PC hardware means a game with a smooth frame rate on one game system may struggle to consistently render and display frames at the same rate on another. Despite the pervasiveness of frame rate variation in PC games, to the best of our knowledge, there is no quantitative understanding of the effects of frame rate variation on the quality of experience (QoE) of computer games players.


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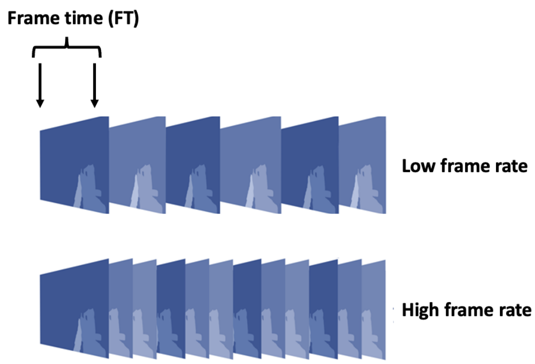


**Figure 1: Frame rate**

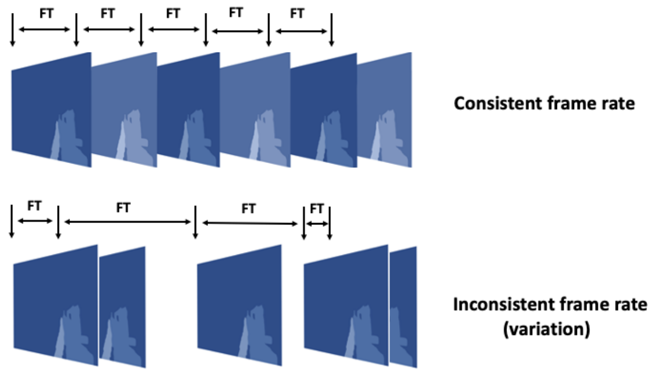


**Figure 2: Frame rate variation**

A quantitative understanding of the effects of frame rate variation can be helpful for: (1) *players* to make informed decisions on computer system upgrades and for adjustments to game display settings; (2) *game developers* to implement display-related optimizations where appropriate to provide better experience for game players; and (3) *computer system developers* to provide frame rate variation targets while improving computer processors and graphics cards and their software. Frame rate variation may be of particular interest in cloud-based game streaming where game frames are rendered as video in the server and streamed across a network to the client. In such systems, there is additional likelihood for frame rate variation since the network has variations in delivery times and rates.

This paper presents the results of a user study that measures the impact of frame rate variation on game player QoE: Section 2 describes previous work on frame rate and frame rate variation related to this paper; Section 3 details our methodology, including games and user study design and execution; Section 4 gives participant demographic information and analysis of QoE versus frame rate variation from the user study; Section 5 discusses the implication of the study results; Section 6 mentions some limitations of our study; and Section 7 summarizes our conclusions and possible future work.

## 2 RELATED WORK

This section describes related work in two main areas: frame rates and video streaming (Section 2.1) and frame rates and games (Section 2.2). The specific methodologies of each paper vary, but these works generally all measure QoE via user questionnaires similar to what we do in our study.

### 2.1 Frame Rates and Video Streaming

Previous studies have examined the effects of frame rate and frame rate variation on users passively watching streaming video [6, 14–17, 20].

Ou et al. [17] investigate frame rate variation on perceptual experience and find that perceived degradation due to frame rate variation is largely independent of video content. Chen and Thropp [6] conduct a comprehensive survey of the effects of frame rates on human performance. They conclude that 10 f/s is acceptable and 15 f/s is sufficient for performance, and 5 f/s is acceptable and 10 f/s is preferable for experience. Madhusudana et al. [14] study the relationship between frame rate, video content and viewer experience. They find that increases in frame rate lead to higher perceived quality, but with diminishing returns beyond 60 f/s. Also, the preference for higher frame rates is not ubiquitous but depends on the video content. McCarthy et al. [15] test the importance of frame rate versus resolution to viewer experience and find that high motion does not imply the need for high frame rates when the videos are viewed on small screens. Users generally prefer high resolution to high frame rate. Ou et al. [16] investigate the impact of temporal variation of frame rate and quantization stepsize on the perceptual video quality. Similar to our work, they propose models to predict the perceptual quality of video with varying frame rate and quantization stepsize. They conclude that under the same average frame rate, the perceptual quality for a video with a constant frame rate is higher than the same video with frame rate variation.

While helpful for understanding the impact of frame rates on viewer experience while watching videos, these papers study video streaming where users are predominantly passively watching the content with little to no interaction, unlike in computer games where players are reacting to the video display making several actions per second in response to what they see.

### 2.2 Frame Rates and Computer Games

Previous studies have analyzed the effects of system and game configurations on player performance and QoE, generally focusing on frame rate as an independent variable in their analysis [7, 9, 18, 19, 22].

Spjut et al. [19] show a reduction of 30 milliseconds of latency benefits first-person targeting tasks more than frame rates above 60 f/s. Claypool and Claypool [7] show that player actions that require precise, rapid response, such as shooting, are greatly impacted by degradation in frame rates below 30 f/s for first-person shooter games. As a comparison, Claypool et al. [9] find frame rate has a marked impact on both player performance and game enjoyment while frame resolution has little impact on performance and some impact on enjoyment for first-person shooter games. Slivar et al. [18] analyze the impact of different game types and video adaptation strategies on QoE in cloud gaming. They find that lowering frame rates down to 25 f/s does not significantly degrade the gaming experience regardless of the game. They also find first-person shooter games are more sensitive to degradations in frame rate. Zadtootaghaj et al. [22] investigate the impact of frame rates and bitrates on QoE and find that there is no significant difference in quality ratings and performance ratings between 25 f/s and 60 f/s.

Although not for a game, Watson et al. [20] study frame time and frame time variation on game-like task performance in a virtual environment (VR). They show deviations up to 40% of the average frame time does not affect task performance, and acceptable average frame times are below 50 ms (20 f/s). However, at a frame time often considered a minimum for immersive VR, frame time variations do produce significant effects on closed-loop task performance.

While helpful for ascertaining the impact of average frame rate, these papers do not specifically deal with variation in frame rate and also predominantly only study first-person shooter games.

## 3 METHODOLOGY

We assess the effects of frame rate variation on player QoE via a user study were participants played games with controlled amounts of variation.

### 3.1 Game Selection

Since the effects of frame rate variation on player quality of experience may depend upon the visuals (e.g., camera perspective and scope) and type of player input (e.g., continuous or discrete), we chose three games for study that vary along these dimensions, listed in Table 1. Rocket League and Strange Brigade provide a third-person camera perspective as the player sees the avatar they are moving, while the Valorant player has a first-person view of the world. Rocket League takes place in a large, indoor virtual arena, Valorant is also indoors but in a small room, while Strange Brigade is in a large outdoor room. All three games have the players move their avatars with continuous input (i.e., holding keys down to move), while Strange Brigade and Valorant also have discrete input for shooting.

Each player does the same task/mission in each game. In Rocket League, players try to score goals by driving a car that acts as a soccer player, with the aim to score more goals than the opponent. In our user study, the gameplay was 1v1 with the user playing against a computer-controlled opponent (a bot). In Valorant, players fight opponents using a variety of projectile weapons. In our user study, the gameplay was in a tutorial where players planted a "spike" then defended it against computer-controlled opponents. In Strange Brigade, players explore a fictional world and fight enemies with different weapons. In our user study, the gameplay was restricted to a single area where players continually shot and killed waves of zombies.

### 3.2 Frame Rate Variation

Our participants played on a gaming PC with more than sufficient processing and graphics capabilities to support the games, providing for high stable frame rates for the base condition. The PC has an NVIDIA GeForce RTX 2080 graphics card, 11th Gen Intel Core I9-11900k @ 3.50 GHZ CPU, Samsung SSD 70 EVO Plus 2 TB disk driver, 32 GB RAM running Microsoft Windows 10 Pro. The PC is equipped with a gaming mouse: a Logitech G502, 12k DPI with a 1000 Hz polling rate; and a high refresh rate monitor: a 25" Lenovo Legion, 1920x1080 16:9 pixels @ 240 Hz with AMD FreeSync (Gsync compatible) and a 1 ms response time. The chosen hardware represents a state-of-the-art PC that someone interested in playing games may have.

To measure local input latency, we used a 1000 f/s camera (a Casio EX-ZR100) to video capture the moment that a user presses the mouse button and the resulting screen output. We inspect the video frame-by-frame to get the time when the mouse was clicked ($t_1$) and the time when the result was visible ($t_2$). The local latency is then $t_2$ - $t_1$. We repeated the test 5 times and take the average as the local latency: the local was 17.7 milliseconds with a standard deviation of 2.3 milliseconds, low, as is typically desired by gamers.

Each game is tested with two target frame rates: 60 Hz and 120 Hz, chosen since 60 Hz is a typical update rate for many game engines and monitors and 120 Hz helps assess higher-end game systems that are also more likely to be used in the future. The frame rate is capped using Rivatuner Statistics Server (RTSS) [11] – a multi-function tool that support frame rate limiting.

In order to induce different amounts of frame rate variation, we added extra load for the CPU via an infinite Fibonacci number counter written in Python. The counter runs as a separate process infinitely computing sequences of numbers (i.e., it is CPU bound) and so competes for use of the CPU with the game. By controlling the number of counters running simultaneously with the game, different amounts of frame rate variation can be observed in the display.

We use Presentmon [10] – a lightweight tool that captures performance metrics for graphics applications – to record the time between frame displays while the games are running. Figure 3 depicts frame time versus time in game for Rocket League running at 120 Hz with no counters. The x-axis shows the game time from 22 to 30 seconds and the y-axis shows the frame time (the time between changes in the display) in milliseconds. Figures 4 and 5 depict the same data but with 4 and 8 counters running, respectively. From the graphs, the variation in frame time with no counters running alongside the game (the base system) is small, with marked increases in frame variation with 4 counters and even greater increases with 8 counters.

### 3.3 User Study Procedure

The user study was conducted in a dedicated, on-campus computer lab.

The final user study procedure was informed by a pilot study with 3 volunteers. The pilot study results helped adjust the amount of frame variation induced (i.e., the number of counters used for each game), round length, total number of rounds and user instructions.

Players started with a practice round without any counters – users were told the first round was practice and data from this practice round was discarded. The frame rate variation has four (4) conditions for each target frame rate (60 Hz and 120 Hz) based on the number of counters: a "perfect" condition without any counters, a "noticeable" condition where the counters cause frame rate variation that is just noticeable to players, a "severe" condition where the

**Table 1: Games selected for our user study**

| Game | Camera Perspective | Visual Scope | Input |
|---|---|---|---|
| Rocket League [1] | Third-Person | Indoor Broad | Continuous |
| Strange Brigade [2] | Third-Person | Outdoor Broad | Continuous and Discrete |
| Valorant [3] | First-Person | Indoor Limited | Continuous and Discrete |

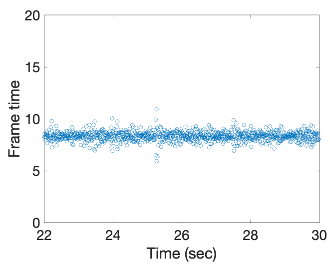


**Figure 3: Game with no counters**

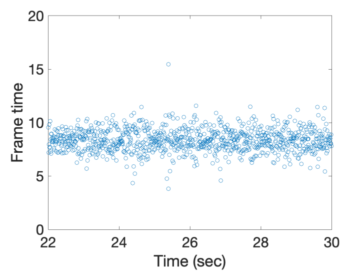


**Figure 4: Game with 4 counters**

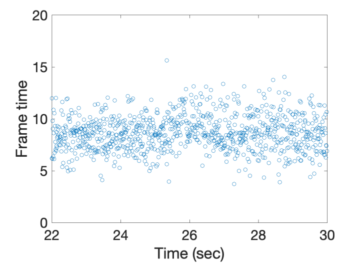


**Figure 5: Game with 8 counters**

counters cause severe frame variation but the game is still barely playable and one "mid" point between "noticeable" and "severe". The four conditions and the corresponding number of counters for each game is shown in Table 2. The numbers of counters are the same for Valorant and Strange Brigade but are somewhat higher for Rocket League due to differences in gameplay and the game's processing load.

In addition, there are three (3) additional rounds where the number of counters varies during the game. These "chaos" runs are meant to provide frame rate variations that arise due to varied gameplay load and systems that may not be able to meet them. For the first chaos condition, the number of counters switches randomly every 1-2 seconds between the lowest and highest number of counters in Table 2 for each of game. The second chaos condition is the same, but the switching is more frequent at 0.25-0.5 seconds. For the third chaos condition, the number of counters switches randomly every 4-6 seconds across all counters for each game.

Users were invited to participate in the study based on their familiarity with the three games in Table 1 and overall gaming experience, favoring participants that played games regularly and had played our three games over those that did not.

For each participant, the order of the games, the base frame rates and the counter conditions were randomly shuffled. For each game, users first played all rounds at the same target frame rate (either 60 Hz or 120 Hz) and then proceeded to the rounds with the other target frame rate, with the number of loaders randomly shuffled. All rounds were completed for one game before proceeding with the next.

Each game round lasted for 1 minute. After each of the round, a survey popped up to assess the players' experience via two questions: a) a Mean Opinion Score (MOS) "Please rate your experience" with a text box for a 1.0 to 5.0 point numeric entry, shown along with scale: Excellent, Good, Fair, Poor, Bad; and b) a yes/no question "Is the experience acceptable?". After completing the survey, the next round would commence when the user was ready, allowing the users to rest as long as needed before starting the subsequent round.

In summary, we had a within-subjects design. For each game, users first played a practice round. Then, for 2 different frame rates (60 Hz and 120 Hz), users repeatedly played the same game round with 7 different conditions: 1 perfect condition, 3 constant variation conditions, and 3 chaos conditions. After completing all the game rounds, users were given an additional questionnaire with demographics questions about overall gamer experience – average time spent playing games and self-rated expertise with computer games. It took each user about 60 minutes to complete all the tasks in the study. A user study proctor was available for questions and trouble-shooting for the duration.

**Table 2: Number of counters**

| Game | Perfect | Noticeable | Mid | Severe |
|---|---|---|---|---|
| Rocket League | 0 | 14 | 17 | 20 |
| Strange Brigade | 0 | 13 | 14 | 15 |
| Valorant | 0 | 13 | 14 | 15 |

In summary, the procedure each user followed was:

(1) Submit a screener to provide familiarity with the games.
(2) For invited participants, arrive at the dedicated lab at a scheduled time and sign a consent form.
(3) Adjust the computer chair and monitor so as to be comfortably looking at the center of the screen.
(4) Read the instructions regarding the first game (randomly chosen).
(5) Play a practice round.
(6) Randomly get a target frame rate (60 Hz or 120 Hz).
(7) Repeatedly play the same game round with 7 conditions: 1 perfect condition, 3 constant variation conditions, and 3 chaos conditions. After reach round, fill out a corresponding QoE survey.

**Table 3: Participant demographic information**

| Users | Age (yrs) | Gender | Gamer Self-rating |
|---|---|---|---|
| 33 | 20.1 (2.0) | 26 ♂ 6 ♀ 1 unspecified | 3.6 (1.2) |

(8) Repeat the previous two steps for each frame rate.
(9) Repeat the previous five steps for each game.
(10) Complete a final demographics questionnaire.

The study design was approved by our university's Institute Review Board (IRB). Study participants were solicited via university email lists. Thirty-three (33) users were recruited and participated in total. All users were eligible for a $15 USD Amazon gift card upon completion of the study, and many users received playtesting credit for relevant classes in which they were enrolled.

# 4 ANALYSIS

This section first provides summary demographics for the 33 participants (Section 4.1) and overall Quality of Experience (QoE) scores (Section 4.2). Then, the main results relating QoE to frame rate variation are analyzed: frame rate average (Section 4.3), frame time standard deviation (Section 4.4), frame rate floor (Section 4.5), and acceptable quality thresholds (Section 4.6).

## 4.1 Demographics

Table 3 summarizes the demographic information for the 33 user study participants. Gamer self-rating is in response to the question "rate your experience as a gamer" on a five-point scale, 1-low to 5-high. For age and gamer self-rating, the mean values are given with standard deviations in parentheses. Participants ranged from 18-26 years old but with the large majority of typical college age (18-22). Gender breakdown was predominantly male (26 males, 6 females, 1 unspecified) but aligns with our sample pool of university students that skews male. User self-rating of experience playing computer games skewed slightly above the mid-point (mean 3.6). Most participants majored in Robotics Engineering, Computer Science, or Game Development.

Participants indicated their familiarity with the games under test in the pre-screening questionnaire. The number of users familiar with each game was 22 for Rocket League, 19 for Valorant and 0 for Strange Brigade.

## 4.2 Overall QoE

This section presents the overall QoE distribution of the three games.

Figure 6 depicts the distribution of all QoE scores for each game with a box: Valorant in blue, Strange Brigade in pink, and Rocket League in green. From the graph, for all three games, the QoE ratings cover the range from 1 to 5, with most of QoE ratings above 3. However, the distributions vary somewhat (Valorant M=3.9, SD=1.1, Strange Brigade M=4.1, SD=0, and Rocket League M=3.6, SD=1.1), and a one-way analysis of variance (ANOVA) test shows that there is a statistically significant difference between the mean QoE values for each game, F(X, Y) = 23.12, $p < 0.001$. Pairwise t tests with a Bonferroni correction show that there is no significant difference

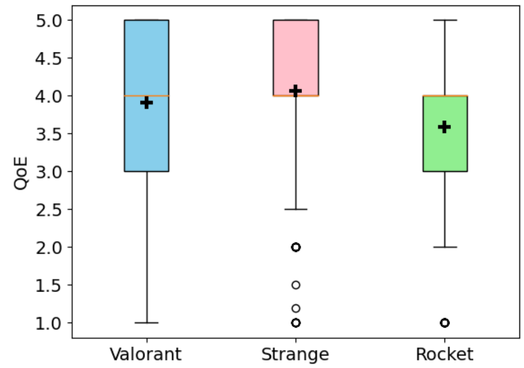


**Figure 6: QoE boxplot**

between Valorant and Strange Brigade (t = -2.08, p = 0.04), but there is between Valorant and Rocket League (t = 4.32, $p < 0.001$) and Rocket League and Strange Brigade (t = 6.92, $p < 0.001$). We use these differences as motivation to assess not just how well our models predict overall QoE but also how well they predict the QoE for individual games.

## 4.3 Frame Rate Average

This section analyzes the correlation between frame rate average and QoE.

The QoE values are grouped by one of the 9 possible frame variation conditions – 6 with a constant number of counters (0, 13, 14, 15, 17, or 20) and 3 "chaos" conditions. For each round, the number of frames displayed each second is computed then averaged over the round to get the frame rate average.

Figure 7 depicts frame rate average versus QoE for the 60 Hz target frame rate. The x-axis is the frame rate average in frames per second and the y-axis is the QoE. The circles are the QoE means for each frame rate variation condition bounded by 95% confidence intervals. The orange line is a linear regression through the mean values. Figure 8 depicts the same data, but for the 120 Hz target frame rate. From the graphs, player QoE increases with frame rate average. However, many of the points are not near the linear regression lines – the $R^2$ for 60 Hz is 0.74 and the $R^2$ for 120 Hz is 0.16.

This analysis illustrates why frame rate average is not an effective predictor of average QoE when there is variation in the frame delivery times. In effect, the average is hiding the underlying frame time variation that impacts QoE.

## 4.4 Frame Time Standard Deviation

Since a common measure of variation is the standard deviation, we analyze the relationship between the standard deviation of the frame times and QoE. In this analysis, the 60 Hz and 120 Hz conditions can be combined since the standard deviation increases from 0 (no variation) independently of the target frame rate.

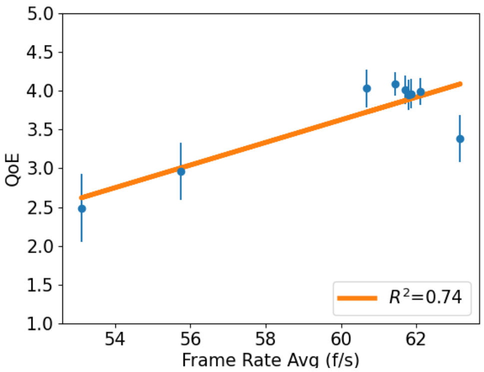


Figure 7: Frame rate average - 60 Hz

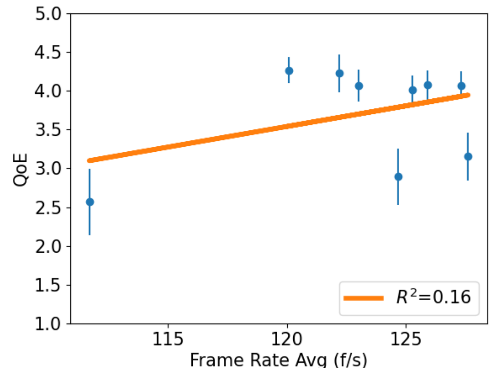


Figure 8: Frame rate average - 120 Hz

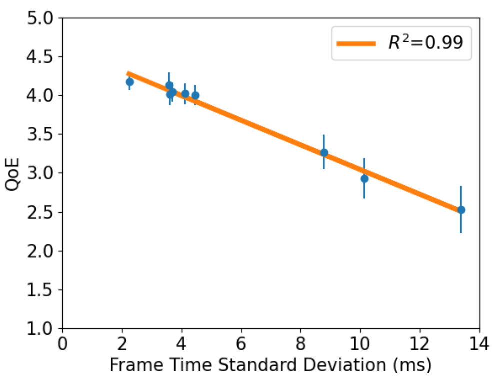


Figure 9: Frame time standard deviation

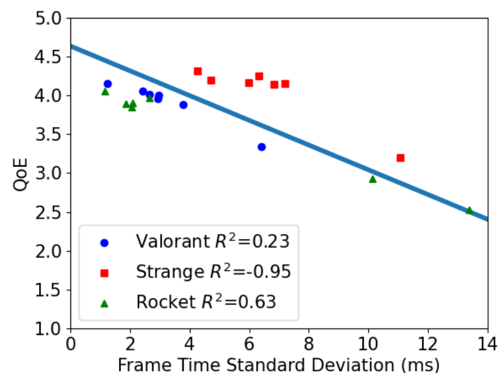


Figure 10: Frame time standard deviation - per game

Figure 9 depicts frame time standard deviation versus QoE. The x-axis is frame time standard deviation in milliseconds and the y-axis is QoE. The circles are the QoE means at each frame variation condition combining both the 60 Hz and 120 Hz data. The orange line is the linear regression for the mean values. From the graph, player QoE degrades with an increase in frame time standard deviation. The linear regression fits the means well with an $R^2$ of 0.99. This suggests frame time standard deviation can be an effective predictor for average QoE.

The quality of experience (Q) model from 1-low to 5-high with frame time standard deviation can be described by:

$$Q = -0.16 \cdot s + 4.63 \tag{1}$$

where $s$ is the standard deviation of the frame time in milliseconds.

Figure 10 depicts the same data, but separates the data by game. The axes are as in Figure 9, but the red squares are Strange Brigade, the blue circles are Valorant and the green triangles are Rocket League. The blue line is the linear regression model from Figure 9, but in Figure 10 this line fits the individual games rather poorly with an $R^2$ of -0.95, 0.23 and 0.63 for Strange Brigade, Valorant and Rocket League, respectively. This suggests that the relationship between average QoE and frame time standard deviation is different for each game – i.e., there may need to be a per-game model. This is unfortunate if the goal is to predict QoE for an as yet untested game.

## 4.5 Frame Rate Floor

Another previously used measure of visual performance is the lowest frame rate displayed, also called the frame rate floor. For example, a 95% frame rate floor means 95% of the frame rates are equal to or higher than this value. The 95% frame rate floor is computed by taking the distribution of frame times, selecting the top 5th-percentile value and converting that to a frame rate.

Figure 11 depicts 95% frame rate floor versus QoE for 60 Hz and Figure 12 for 120 Hz. The graphs and data are as in Figure 7 but the x-axes are 95% frame rate floor in frames per second. From the graphs, player QoE increases with an increase in 95% frame rate floor. When the lowest frame rates the player experiences rise from 25 f/s to 55 f/s in Figure 11 and from 35 f/s to 85 f/s in Figure 12, the QoE increases from about 2.5 to about 4.0.

The linear regressions fit the mean values well with an $R^2$ of 0.96 at 60 Hz and an $R^2$ of 0.97 at 120 Hz. This suggests frame rate floor can be an effective predictor for average QoE. However, as-is, frame rate floor is dependent upon the target frame rate which can vary

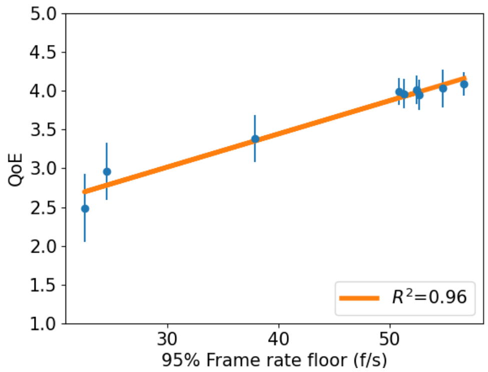


**Figure 11: 95% frame rate floor (f/s) - 60 Hz**

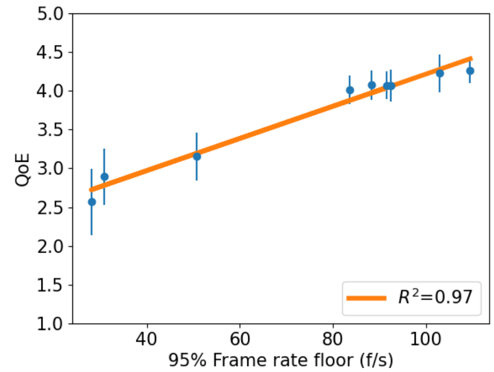


**Figure 12: 95% frame rate floor (f/s) - 120 Hz**

across game and across gaming systems. To make frame rate floor independent of the frame rate, the frame rate floor is normalized to a range of 0 to 100% using the target frame rate.

Figure 13 depicts QoE versus 95% frame rate floor as a percentage of the target frame rate with data from both 60 Hz and 120 Hz combined. The graph is as for Figure 9 but the x axis is the 95% frame rate floor as a percentage of the target frame rate. The linear regression fits the combined data well with $R^2$ 0.97.

Figure 14 depicts the linear regression in Figure 13 for the individual games. The figure is the same as Figure 10 but the x-axis is 95% frame rate floor percentage. The linear model fits all the games well with $R^2$ of 0.82, 0.85 and 0.93 for Strange Brigade, Valorant and Rocket League, respectively. Unlike the frame time standard deviation, here, the overall frame rate floor predictor is also an effective predictor of the QoE for the individual games.

Besides 95%, other frame rate floors that have been considered are the 99% and the 90%. Figure 15 depicts a comparison of the different frame rate floors versus QoE. The axes are as in Figure 13, with the blue line and points for 99% floor, green for 95% floor and red for 90% floor. In general, all three are effective predictors of QoE, but 95% floor has a slightly higher $R^2$ of 0.97 compared to an $R^2$ of 0.94 for 90% and an $R^2$ of 0.87 for 99%.

The linear models for predicting QoE (1-5) based on frame rate floor percentage are in Table 4.

**Table 4: Frame rate floor linear models**

| Frame rate floor | $R^2$ | Slope | Intercept |
|---|---|---|---|
| 95% | 0.97 | 0.025 | 1.95 |
| 90% | 0.94 | 0.026 | 1.74 |
| 99% | 0.87 | 0.024 | 2.29 |

## 4.6 Acceptable Experience

This section analyzes the data from the second question asked of users each round – whether or not the experience was acceptable.

Figure 16 depicts acceptability versus QoE. The x-axis is QoE from 1 to 5 and the y-axis is the fraction of rounds that were rated acceptable. An acceptable fraction of 1 means the experience was acceptable to all users and a 0 means it was acceptable to no users. The rectangles are the mean values with 95% confidence interval bars. On the top of the graph, the "n=" shows the number of users that provided that QoE value as a rating. From the graph, QoE scores rated 4 or 5 were always acceptable, and those rated 3 were almost always acceptable.

These thresholds can be used in conjunction with the model for frame rate floor to ascertain what frame variation is needed by a game system in order to achieve acceptable QoE. Figure 17 depicts almost always acceptable QoE and always acceptable QoE with the 95% floor percentage model from Figure 13. The red dashed line denotes an almost always acceptable QoE and the green dashed line is an always acceptable QoE. From this graph, with a 95% floor of 42%, the QoE is almost always acceptable and with a 95% floor of 83%, the QoE is always acceptable.

# 5 DISCUSSION

Average frame rate has been widely used as a measure of video smoothness and is often applied to games for the same reason. Higher average frame rates are generally preferred by viewers and game players over lower average frame rates. However, the average frame rate alone does not always effectively predict QoE because it can hide meaningful frame rate variation. And, unfortunately, frame rate variation can be common in PC games since they can be played on a variety of systems, some of which are underpowered so cannot provide for consistent frame rates for all types of gameplay. This is especially true of newer games that tend to push the limits for older game systems.

A direct measure of frame rate variation is the standard deviation in the frame time. Frame time standard deviation has the advantage of being easily understood – frame time is the time between frames being displayed and standard deviation is akin to the "average" distance from the mean frame time – with units (milliseconds) that do not need to be adjusted for different target frame rates (e.g., playing a game at 60 Hz versus 120 Hz). The results from our user study show that frame time standard deviation can be used in a linear model to predict the overall average QoE very well ($R^2$ 0.99). Unfortunately, when this model is applied to individual games it

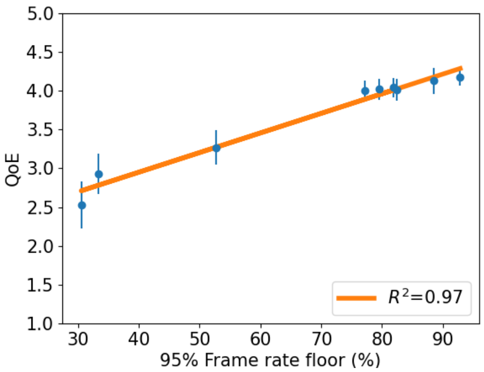


Figure 13: 95% frame rate floor (percent)

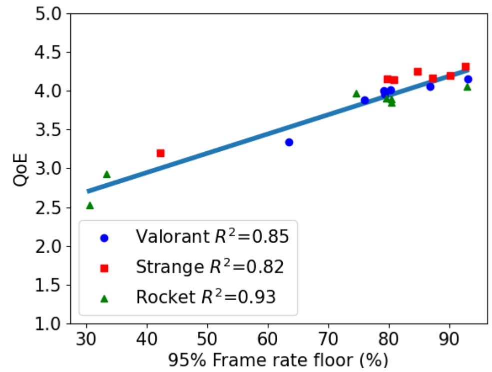


Figure 14: 95% frame rate floor (percent) - per game

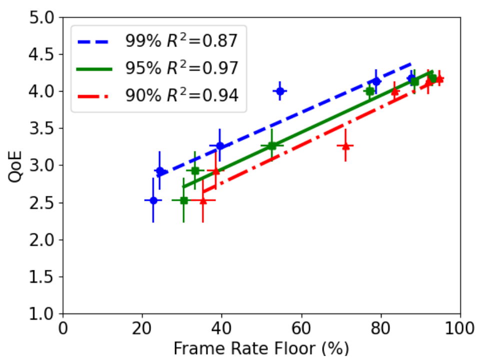


Figure 15: Other frame rate floors (percent)

may not be so accurate – in our case, particularly so for the game Strange Brigade. This inaccuracy may be because our user study participants were not familiar with Strange Brigade so perhaps tended to tolerate more frame rate variation since they were not used to the game itself. In any case, the lack of per-game accuracy makes it difficult to predict the QoE based on frame time standard deviation for an untested game.

Another measure of frame rate variation that has been used by practitioners is the frame rate floor – the lowest frame rate a player experiences. Frame rate floor is also relatively easy to understand, but has the disadvantage of begin tied to a specified target frame rate – i.e., a frame rate floor of 58 f/s is much worse if the target is 120 Hz than it is if the target is 60 Hz. However, frame rate floor can be converted to a percentage – e.g., 58 f/s has a frame rate floor of 97% at 60 Hz and 48% at 120 Hz – to enable a single, predictive model. The results from our user study show frame rate floor can be used in a linear model to predict QoE very well, too ($R^2$ 0.97). This accuracy drops a bit when the general model is applied to individual games, but is still fairly accurate ($R^2$ 0.82, $R^2$ 0.95 and $R^2$ 0.93 for our three games). Different floor percentages have been used in practice – 90%, 95% and 99% – and these are all decent predictors for QoE, but the 95% frame rate floor appears to be a slightly more accurate a predictor than the others.

Not surprisingly, the acceptability of a the experience correlates with the QoE ratings, with QoE ratings of 4 or higher (on a 1-5 scale) always acceptable and ratings of 3 or higher almost always acceptable. These results can be used in conjunction with the QoE models for frame rate variation to provide targets for frame rate consistency that provide good QoE. Specifically, based on our results and model, having a 95% frame rate floor percentage that is within about 40% of the target frame rate will almost always be acceptable and within about 80% will always be acceptable. Note, the model is applicable to the range of frame rates we tested, so 60 Hz to 120 Hz. Extrapolating the results outside of this range should be done cautiously. In particular, the model may not hold for frame rates well under 60 Hz (e.g., 30 f/s) since prior work has shown that player performance and QoE drops of precipitously at frame rates below 30 f/s [9].

Also of note, a 60 f/s experience for a user playing a game on a 120 Hz system is likely not the same as a 60 f/s experience for a user playing a game on a 60 Hz system. The 60 f/s average on a 60 Hz system has no frame variation, whereas the 60 f/s average on a 120 f/s system (probably) has considerable frame variation. It is this variation that is missing from any prediction of quality using only the frame rate average. i.e., as shown in Section 4.3, the average frame rate alone does not provide an accurate assessment of performance – specifically, it is missing any measure of frame time variation.

Our frame variation model and QoE targets can provide guidance for players, game developers, and computer system developers: (1) Players could use the model for their own game systems to pick graphics settings (e.g., reduce graphics quality) that reduce variation, or even decide whether or not to do a computer upgrade; (2) Game developers could use the model for their target systems to decide if additional optimizations are needed to smooth out the frame rates; (3) Computer systems developers could use the models with reference games to decide if and how much the hardware and software improvements they are developing improve QoE. To be used in practice, a sample of the gameplay is recorded and the frame times measured (we use Presentmon [10]). These frame times are sorted and the highest 5% taken and converted to a frame rate. This frame rate is then normalized as a percentage of the target frame

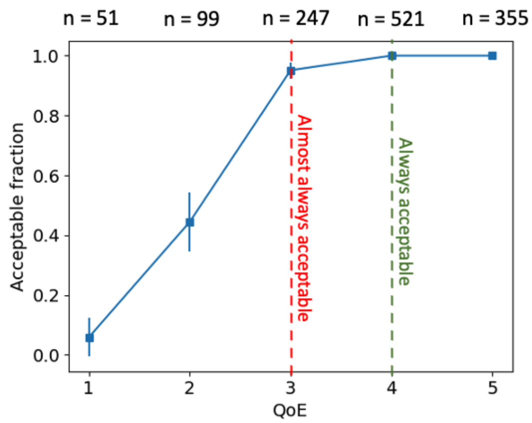


**Figure 16: Acceptable QoE**

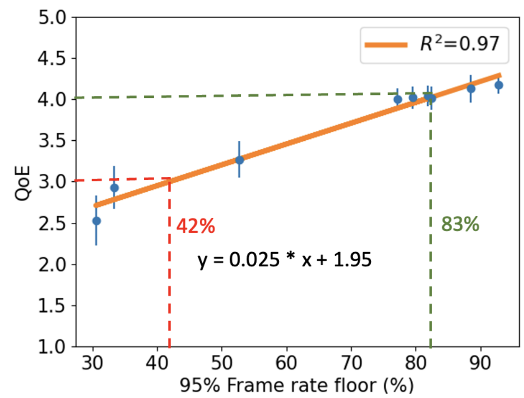


**Figure 17: Acceptable thresholds with 95% frame rate floor (percent)**

rate (the maximum frame rate as capped by the monitor refresh rate or the game engine update rate). The final value can be used with the model from Table 4 (i.e., $Q = 0.025 \cdot s + 1.95$) to predict QoE, aiming for a QoE of 3 or 4 for acceptability.

By studying user perception for games, researchers can gain insights into QoE for a broader range of human-computer interaction [5]. While our models are specific to computer games, the relationships noted between QoE and frame rate variation likely pertain to other human-computer interactions. For HCI researchers, this suggests ascertaining frame rate variation when assessing QoE in addition to just frame rate average. Moreover, since our results suggest that the "worst" frame rates a user experiences (the 95% frame rate floor) dominates a user's experience, particular attention should be paid to the lowest frame rates experienced.

## 6 LIMITATIONS

Our methodology intentionally loads the CPU with additional computations in order to add variation to the frame times. From Figures 3-5 and the standard deviations observed (Figure 9), this appears to be effective. However, systems that have insufficient capacity in some other sub-system (e.g., GPU) may have different variation patterns.

Similarly, we test only one specific hardware configuration (described in Section 3.2) whereas PC game players have a variety of setups. While the CPU and graphics card impact the frame variation a player experiences, the hardware itself likely does not impact the *way* the variation affects the player QoE. However, the display size and resolution likely does impact QoE, since prior work has shown it impacts performance [12].

As noted in Section 4.1, our participant sample is skewed towards males (26 out of 33 participants) and college students. While this may reflect the gender breakdown present in some first-person shooter games today (e.g., Valorant), the results reported may not be indicative of players from other demographics, such as females and older players.

We intentionally chose 3 games from different genres for our tests rather than just one to reduce the risk of results that pertain to a single game. However, there are many other games in the same genre (e.g., other first-person shooter games) and other genres (e.g., Multiplayer Online Battle Arena games) where players may have different sensitivities to frame variation. In particular, genres with different camera control (e.g., Real-Time Strategy games) and graphics fidelity (e.g., escapist games) may see players with different tolerances for variation. Moreover, none of our participants were familiar with the game Strange Brigade – this may explain why the model of QoE with frame time standard deviation did not fit this game well (see Figure 10), but it would then also suggest that players familiar with a game may have a different tolerance for frame rate variation than less experienced players. Similarly, we did not control for the frame rates players experience in their own gaming setups. It is possible that the QoEs observed in our study depend upon the participant's baseline of their own monitor display rates or display sizes.

Serious PC game players often customize the in-game graphics settings (e.g., graphics resolution) to suit their personal play preferences, trading off better and smoother frame rates for graphics quality. These custom changes may mitigate frame rate variation and presumably improve the specific player's experience. However, since customizations that deviated from our settings create a difference in test conditions between users, we did not allow any changes to the computer settings. This holds for other game configurations, too, such as other mice, keyboards or monitors.

## 7 CONCLUSION

People are increasingly turning to games for entertainment evidenced by the growth in the games industry. Frame rates can affect the smoothness of visual display and is an important factor in player quality of experience (QoE). While previous studies have assessed the impact of different steady frame rates on QoE, the degree to which variation in frame rates impact QoE is not well known. Understanding the effects of frame rate variation on player experience can help players change in-game settings to better adapt to frame rate variation, can inform game developers on game design and development techniques to mitigate the effects of frame rate variation, and can help hardware companies to better integrate technologies for more stable frame rates.

This paper presents results from a user study that assesses player QoE with different amounts of frame rate variation. We selected three games of different types – Rocket League (a third-person sports game), Strange Brigade (a third-person shooter game) and Valorant (a first-person shooter game) – and ran them on a PC setup that induced different amounts of frame rate variation. Thirty-three (33) participants played the games for 45 rounds each experiencing 7 different frame rate variation conditions at 2 different target frame rates for each game. After each round, users provided a Quality of Experience (QoE) opinion via a survey.

Analysis of the results shows average frame rates by themselves do not effectively predict QoE when there is variation in the frame times. The standard deviation of the frame times – one of the most direct measures of frame rate variation – is a good predictor of the overall average QoE, but may not be accurate for the individual games. The 95% frame rate floor is a good predictor of overall average QoE and is also a good predictor of the average QoE for individual games. QoE is always acceptable when the 95% frame rate floor is within about 80% of the target frame rate.

Our future work is to investigate frame rate variation caused by other system configurations, for example, the GPU and the storage devices. Other future work could apply the same methodology used in our paper to games from other genres, e.g., Multiplayer Online Battle Arena (MOBA) games like *DOTA 2* (Valve, 2013) and *League of Legends* (Riot Games, 2019), and Real-Time Strategy (RTS) games like *Starcraft* (Blizzard, 1998). In such a case, we can validate our results with other game genres. We may also look to apply our methodology to applications beyond games, e.g., multi-media collaboration in videoconferencing or virtual reality. Other future work could explore how the effects of frame rate variation on QoE by player skill, using either self-rated skill [13] or measures of proficiency in computer games.

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