The Effects of Latency in Commercial Cloud Video Gaming Services

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Abstract

Video games are typically played on a device such as a computer, console, or phone, with most of the computation on the local hardware. Cloud gaming services which take over most computation have been rising in popularity as a potentially viable alternative to traditional gaming. However, cloud gaming services are more susceptible to latency, since player inputs are sent to cloud servers, and video is then streamed back to the player's client. Our project evaluated two recently released cloud gaming services (Blade Shadow and Google Stadia) to determine how they were affected by increased latency and packet loss. We performed a user study with different added latency values to test player performance and quality of experience for each service. We then performed network experiments analyzing the effects of added latency and packet loss on bitrates. Analysis of 37 users shows that user performance and quality of experience decreased with higher added latency for both services. Shadow used significantly more bandwidth than Stadia but had better graphics quality.

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1. Introduction

Video games are typically played on a device such as a computer, console, or phone, running the applications and performing most of the computation on the local hardware. The player's inputs from a mouse, keyboard, or controller are processed by the system and the results are rendered on a screen. However, there is an inherent delay due to both hardware and software limitations. The average click to photon lag for a local game, which includes the time between the player entering an input and the result appearing on their screen, can be between 45-50 milliseconds [26]. Higher delay between player actions and results on the screen decreases interactivity for the player. This latency has always been an important issue in gaming, and extensive work has been done to minimize delay in games, resulting in improved player enjoyment and performance.

In recent years, cloud gaming services have emerged as a new way to play video games. In the common thin client cloud gaming model, player inputs are sent through the client to a server running the game, and the results of their actions are sent back as a video stream through the client to the player's screen. This means that the majority of the computation is done in the cloud rather than on the player's machine, with the client receiving the resulting video stream.

Cloud gaming has various advantages over traditional game systems. One advantage is that it allows people to play higher quality games without spending hundreds or thousands of dollars on an expensive gaming PC that may be obsolete in a few years. This also means games can be played on any platform that can run the thin client. For example, a thin client on a Mac would allow Mac users to play games that are only available on PC, giving the users a wider variety of games to play. Various PC or console games can also be played on a smartphone or tablet. Some cloud gaming services offer games to play through their services, so users do not have to waste time or disk space downloading games, while other services require users to sign in and verify they own the game before accessing it through their service. This additional verification is good for developers, since it is much more difficult to pirate games when using a cloud gaming service. Additionally, the video stream being sent to the thin client makes it easy for players to livestream gameplay to streaming services like Twitch for others to watch.

While cloud gaming has many advantages over network gaming, one major downside of cloud gaming services is increased latency compared to local gaming systems. With cloud gaming systems, player inputs must be sent to the cloud server, and then the video stream must be sent back to the player's computer. The time required to send this data back and forth inevitably causes increased delay over traditional game systems, where all the computing is done on the local machine.

Another important issue relating to cloud game performance is the potentially limited Internet capacity available to the cloud gaming user. Constant high-quality video streaming to the thin client requires high bitrates, otherwise video quality and frame rates may suffer [4]. Most commercial cloud services recommend a minimum bitrate of 5-15 Mbps for good performance [14] [15] [16] [17]. Studies have shown that some cloud services such as PlayStation Now have decreased framerates and throughput with low bandwidth [4]. This means that although minimal computer or console hardware is required to stream cloud games, users do need a high capacity Internet connection for acceptable performance with many cloud services.

Previous studies have measured the effect of latency on cloud gaming [4] [21] [22] [23] [24] [25] [27], although many of them are a few years old [21] [23] [24] [25] [27] and some of the services studied are no longer accessible or up to date [29]. Considering the short timespan that cloud gaming services have been around, a few years can result in significant changes as to what services are available and their technical capabilities. There are many more services available now, such as Blade Shadow and Google Stadia, but to the best of our knowledge, there has not yet been any published research [14] [16]. Although some past research into measuring latency exists, many of the tested systems are no longer active. Many newer services, like Shadow (launched November 2017 in France, August 2018 in the U.S.) have not been studied due to how recently they were released.

The purpose of our study is to investigate how user experience changes under suboptimal network conditions when using commercial cloud gaming services. We compare two of these newer services, Shadow and Stadia, and perform a user study to determine the impact of latency on each and look at user perspectives on changes in network conditions. For this study, we evaluate Stadia and Shadow because these are both relatively new services, without comparable research. The game we had users play is Assassin's Creed Odyssey (Ubisoft 2018). Odyssey is a third person action role playing game based in ancient Greece. This is a good game to study because it is a well-known game and can be compared to other new and popular titles on cloud platforms. Additionally, Odyssey is available through Stadia, and all owned games can be played on Shadow. This allows us to make a direct comparison between the performance of the two cloud services, with no other variables being changed.

Participants in the study played the tutorial section of the game multiple times in one-minute trials, with added latency being changed each time. This part of the game puts the player in a large battlefield, where they attempt to kill as many enemies as possible in thirty second trials. Players reported their feedback of the gameplay and overall experience after each trial, and performance was measured based on how many enemies they killed and how many times they were damaged by enemies.

Our user study had 37 participants, each of whom played through trials of the level with different latencies on both Stadia and Shadow. Five different added latencies were tested: 0ms, 50ms, 100ms, 200ms, and 500ms. Overall, player quality of experience trended downwards with increased latency for both cloud services, as did perceived responsiveness of controls. Graphics quality also declined with high latency values, although Stadia's graphics were affected significantly more than Shadow's.

We also performed network experiments to measure bandwidth consumption of both services under different network conditions. The same latency values were tested, as well as inbound and outbound packet loss values of 10%, 20%, and 40%. In general, Shadow's bandwidth consumption remained relatively constant, while Stadia varied under different latency and packet loss values. Shadow also had about 3-4 times higher bitrate than Stadia in most trials.

The remainder of this paper is set up as follows: Chapter 2 describes background information and previous research completed in this area. Chapter 3 details the methodology and processes used to complete our study. Chapter 4 displays results and analyzes data collected in both the user study and network experiments. Chapter 5 summarizes our findings, and Chapter 6 proposes ideas for future studies.

2. Background and Related Work

Prior research into cloud gaming has investigated the mechanics and performance of various services and systems. While much of the past research has involved older systems such as OnLive that are no longer available, these studies are still relevant due to the similar techniques and architecture compared to newer systems [29]. Past papers have frequently analyzed the effects of added latency on player performance and experience. Additionally, multiple studies have analyzed user Quality of Experience (QoE), and how varying latency and other performance aspects affects player enjoyment. These past projects provide extensive background information on cloud gaming, as well as demonstrating useful methodologies and techniques considered in this study. This chapter discusses previous studies done in this field and how they relate to our project. It then describes various cloud gaming systems, their histories and technical specifications.

2.1 Related Work

Previous studies into latency have been done for both traditional network gaming [30] [31] [32] and cloud gaming [1] [2] [4] [22] [23] [27]. Many of them involve user studies in which latency is varied while data on user performance and enjoyment is gathered, while others look at bitrates or the users' quality of experience.

2.1.1 Effects of Latency on Traditional Network Games

Chen, Huang, and Lei studied how sensitive players were to network latency [20]. They found a correlation between the amount of latency and how long users played the MMORPG

"ShenZhou Online". Users that experienced around 200 ms of network latency tended to play for 2 hours while users that experienced less than 150 ms played for 4 hours. While we did not have users play for this amount of time during our studies, this information helped us in coming up with questions for the survey we gave to the users after the test.

Claypool and Claypool examined the traditional game model and determined that the gameplay phase is more vulnerable to network latency compared to loading or setup phases [30]. Additionally, they found that the effects of latency can differ depending on the type of game. This is important to consider when determining the genre and the specific game to use in user study testing.

2.1.2 Effects of Latency on Cloud Games

Many studies have been done examining the effects of latency on various cloud gaming services. Many involve conducting user studies and varying the amount of latency the user experiences, and how that affects their performance and enjoyment of the game.

Anouna, Estep and French examined the effects of latency using GamingAnywhere in 2014 [1]. They had users play Neverball, an open source marble rolling game, completing the same level at different amounts of latency between 33 and 200ms. They also recorded the amount of time it took players to complete the level at each latency. It was concluded that there was a statistically significant decrease in player performance between 66 and 100ms. Latencies of under 66ms had little effect on performance. Dabrowski, Manuel, and Smieja also performed a similar study using OnLive, and found that player performance decreases with added latency [2].

Day, Mailloux and McManus used PlayStation Now and Vortex to study the effects of latency, bandwidth, and packet loss on the video stream [4] [15] [17]. Users played PayDay 2

(505 Games 2013), a first-person shooter game. They found that for both services, increased latency had no statistically significant effect on either framerate or throughput. Vortex performed better with packet loss and reduced bandwidth. Players had better performance in the game when latency levels were lower. Additionally, users experienced a higher quality of experience at lower latency levels, which is consistent with previous studies.

Choy, Wong, Simon, and Rosenberg performed a measurement study and analyzed possible causes of increased latency in cloud gaming systems [23]. Their simulations determined that users geographically distant from cloud gaming data centers experience high latency. Additionally, they mention that the mechanisms for distributing video are not necessarily applicable to gaming due to its high susceptibility to latency. This is important background information about latency and cloud gaming, even though it is not directly applicable to our user study.

Overall, studies have shown that users consistently have worse performance and a worse overall experience in cloud gaming systems when higher latency is introduced. This is one of the main objectives of our study, to test newer cloud gaming services and determine if this trend continues.

2.1.3 Effects of Bandwidth Constraints on Cloud Games

Frames per second can also be affected by latency, although bandwidth is another aspect to consider since bandwidth and latency are two frequent issues with cloud gaming services. Some studies have restricted network bandwidth and observed the effect on framerates, measured in frames per second (fps), in cloud gaming [4] [22].

As mentioned in Section 2.2.2, Day, Mailloux, and McManus observed the effects on bandwidth on PlayStation Now and Vortex [4] [15] [17]. Their study found that Vortex was not affected by bandwidth restriction, most likely because they have a lower bandwidth consumption normally. PlayStation Now, on the other hand, did suffer drops in framerate due to bandwidth restrictions, dropping to 35 fps from 60 fps at 5 Mb/s bandwidth. This study provides important information on bandwidth restrictions and how they may affect cloud gaming services.

Mentioned in Section 2.2.3 above, Zadtootaghaj, Schmidt, and Möller's study varied bandwidth restrictions, testing from 1.5 to 30 Mb/s [22]. They concluded that there was no significant difference between 25 fps and 60 fps in terms of how playable the circumstances were for higher bandwidths, although once bandwidth dropped below 5 Mb/s, the playable range of fps dropped. This study provides more information on bandwidth restrictions and framerates, though we could not focus on either aspect in our study.

2.1.4 Quality of Experience in Cloud Games

Previous research has studied the effects that latency in cloud gaming has on player performance. This includes measuring the quality of experience (QoE) the users have while playing. There are many ways that QoE has been defined or modeled to be studied, including effects on video quality, positive affect, and the likelihood for users to play under specific circumstances again [22] [27]. We surveyed participants to determine their QoE in our project.

Zadtootaghaj, Schmidt, and Möller focused on QoE in a study of the impact of frame rate and bit rate on cloud gaming, where they also proposed a model to predict QoE for a service [22]. The model included video quality, reactiveness, and positive affect. They also performed a user study where participants each played the games Grand Theft Auto V (Rockstar Games 2013) and Project Cars (Bandai Namco Entertainment 2015). They concluded that no significant difference in QoE was observed between 25 frames per second (fps) and 60 fps and recommended selecting 25 fps for low bandwidth connections. They also detail what questions they asked in their questionnaire, which we use to help formulate survey questions in our user study.

Clincy and Wilgor evaluated OnLive with users playing Borderlands (2K Games 2009), a first-person shooter, and they found that QoE was significantly affected by dropped packets in their study [27]. They also had a survey where they collected opinions from the users in their study and found that the lowest rated categories were “Image Quality” and “Choppiness/Stuttering,” although users rated their “Overall Experience” and “Likelihood to Play Again” fairly high. The participants were also given an exit survey where they were asked about their opinions on cloud gaming. All seven participants were “impressed” or “very impressed” with their experience. Four out of the seven said they would consider paying for a cloud gaming service, while only two of the seven considered cloud gaming a viable alternative to traditional gaming. This study demonstrates a useful method for gathering subjective data from study participants about their experience.

2.2 Cloud Services: Then and Now

Cloud gaming has been around since 2010 [29], although for much of that time there were only a few services available. In recent years, more companies have started to release cloud gaming services, and some of the options from years past are no longer available.

2.2.1 Cloud Gaming Architecture

The standard architecture for a commercial cloud gaming system involves a thin client on the user's end that sends the user inputs to the cloud servers, where the inputs are processed and the game state updates [10]. Next, the graphics processor in the cloud server renders an updated video feed of the game as a result of the inputs. The video feed is then compressed, encoded and sent back to the user's client where they can see the results of their actions with minimal delay. All the following commercial cloud services use this basic architecture.

2.2.2 OnLive

OnLive, released in 2010, was one of the most popular commercial cloud gaming systems until it was bought by Sony and closed down in 2015 [29]. Users paid a monthly fee for unlimited access to a library of various games. Due to its popularity, multiple studies have examined OnLive, some of which are described in detail in the related work section. These studies provide a useful comparison between old and newer cloud gaming services.

2.2.3 GamingAnywhere

GamingAnywhere was the first open source cloud gaming service, released in 2013 [24]. The developers believed that it would stimulate more research innovations in cloud gaming systems, since GamingAnywhere could be used to set up testbeds. The currently supported platforms for the service include Windows XP (client) and 7 (server), Linux, Mac OS, and Android [28]. The process for using GamingAnywhere started with the user logging onto a portal server to choose their game from a provided list of available games. They would then be connected to an available game server which launched the game on the server and sent the URL back to the user. From there, the user connected to the game server and played. GamingAnywhere was last updated January 29, 2015, and while the service is still available for download, its compatibility with newer operating systems such as Windows 10 is unknown.

2.2.4 Blade Shadow

Shadow is a relatively new cloud gaming service released in Europe in 2016 and in the US in 2018 [14]. As of October 2019, Shadow had roughly 70,000 monthly subscribers [33]. For a monthly fee, Shadow allows users to access a full gaming PC instead of just providing a game library. Users can then use this virtual PC for any computer task, even though the main purpose is high-end gaming. However, users must own and download the games they wish to play. To the best of our knowledge, there have been no previous published studies on Shadow.

2.2.5 Vortex

Vortex is another cloud gaming service, released in 2017. We could not find any data on how many users actively use Vortex. It is a subscription service that allows the user to play games available in their library through cloud servers and have the game streamed to the user's device [15]. Vortex is a relatively new service, and as such, there is only one study that we have found that evaluates performance for this service [4].

2.2.6 Google Stadia

Stadia is a brand-new cloud gaming service from Google, with its Founders Edition released in November 2019 [16]. Stadia allows users to select from a library of games to play, most of which the user must own through Google, but downloading is not necessary. Google will be releasing a subscription-free version of Stadia, Stadia Base, in 2020, but users can pay for an additional Stadia Pro service, which provides free games every month and increased streaming quality. We tested Stadia with the Founders Edition, and to the best of our knowledge, Stadia is too recent to have previously published studies.

2.2.7 Summary

There are many different cloud services available now, and Figure 1 below shows the similarities and differences between past and current services. Upcoming services include Nvidia GeForce Now [18], Microsoft XCloud [34], and EA’s Project Atlas [35]. XCloud has revealed some information, and Project Atlas has little to no information besides its announcement.

Service	**Years active**	**Platform**	**Bandwidth (Mb/s)**	**Resolution**	**Price**	**Game Access**
GamingAnywhere [24]	2013 - 2015 (last updated)	PC, Mac, Android, Linux	Video quality drops if below 3	Unknown	Free	Can play owned games
OnLive [29]	2010-2015	PC, Mac, Android	5 recommended	720p max	$15/month	Could only play games in OnLive's library
Playstation Now [17]	2014-Present	PS4, PC	5 recommended	720p max	$20/month	Can play games in their library as well as games owned
Vortex [15]	2017-Present	PC, Mac, Chrome, Android	10 recommended	1080p max	$10/month	Can only play games in Vortex's library, must own Steam license for most.
Blade Shadow [14]	2016-Present (Europe) 2018-Present (Most of the US)	PC, Mac, Ubuntu, Android, iOS	15 recommended	4k max	$35/month	Must already own games but no limitations due to library, must download games
Google Stadia [16]	2019 - Founder's Edition 2020 - Base and Pro	Chromecast, Google Chrome browser	10 minimum, 35 best	720p-4k depending on bandwidth	Base - Free, Pro - $10/month	Certain games available through Pro, can buy games through Google cannot play games already owned elsewhere
NVIDIA GeForce Now [18]	2020-Present	PC, Mac, NVIDIA Shield TV, Android	15 for 720p, 25 for 1080p	1080p max	Base - free, Founders - $4.99/month	Can only play games in GeForce library, some free to play games, must own most paid games

Figure 1: Comparisons of Cloud Gaming Services

2.3 Summary

Based on these background studies, increased latency generally has a negative impact on both player performance and QoE. We perform a similar experiment, using many of the same measurements and procedures. Many new cloud gaming services have been released in the past few years, with more coming out in the near future. Therefore, additional research must be performed to compare new and old systems and determine if conditions for the end users are improving over time regarding latency, frame rate, and graphics quality.

3. Methodology

To determine the impact of bandwidth and latency on commercial cloud gaming services, we performed a network analysis experiment as well as a user study on two different services. This chapter describes how we chose each of the cloud services used in our study, and the specific game we used. It also specifies the hardware and software used during our experiments and user study, and the process of the user study and network experiments.

For our study, we:

- Chose cloud services to test
- Determined the game for user study
- Researched applications to assist in experimentation
- Created a user study process
- Applied for and obtained IRB approval
- Performed network experiments with Wireshark
- Recruited participants for the user study
- Completed the user study
- Analyzed the results of the experiments and the user study

3.1 Cloud Services

To choose the specific cloud gaming services to test, we applied a few criteria. Originally, we selected Vortex and Blade Shadow, because both services are relatively new and had different means of accessing games [14] [15]. Additionally, as far as we could find, there has not been much scholarly research done on either of these services. Vortex has a library of games that users can play, with paid games requiring users to link external accounts where they have purchased the games. Shadow provides a virtual PC, allowing subscribers to use any functions they would be able to access on a normal computer, including playing video games. We also planned to test with Google Stadia, which proves a similar method of game library access to Vortex [16].

About a week before we had planned to begin our user study, Vortex removed our game of choice, Assassin's Creed Odyssey (see Section 3.2), from their library. This meant that we could no longer access the game through this service, so we continued the study with just Shadow and Stadia. These choices still fulfilled our initial goals of comparing two relatively new cloud gaming services with different methods of game access. Furthermore, since Stadia was just released, minimal published research had been done in this area.

3.2 Game Choice

Figure 2: Assassin's Creed Odyssey Gameplay

There were a few criteria we applied in choosing the game to test in our study. The most important of these was that the game was available in both Stadia and Vortex's libraries, so that direct comparisons can be made between each cloud service. This narrowed the list down to about 10 different games, since Stadia is a new service and does not have a very large selection of games. We decided on Assassin's Creed Odyssey (Ubisoft, 2018) for a few reasons. Odyssey is the newest installment in the popular Assassin's Creed series, with high end graphics comparable to many newer games. It is a third person action role playing game with real-time combat, which we hypothesize will be affected by changes in latency or packet loss. Finally, skippable cutscenes and large battle sections make the game easy to incorporate into a user study.

3.3 Platform

We used Clumsy to add artificial network latency during our project [36]. This software can have many different effects on incoming or outgoing packets, including lag, drop, throttle, duplication, changing order, and tampering. In this project we utilized the latency and packet loss options.

We used Bandicam to record gameplay for the user study [38]. This allowed us to determine the number of enemies killed by each participant in each trial, as well as how many times they were damaged by the enemies, which constitutes objective performance data.

Finally, we used Wireshark to analyze bandwidth with both Stadia and Shadow [39]. Wireshark provides detailed data about all packets sent and received on the network.

3.4 Experiments

The experiments we performed all involved analyzing packets with Wireshark. For all tests, we enabled the Clumsy program before connecting to Stadia and Shadow. The environment was a computer lab at WPI, using the WPI network with an Ethernet connection.

We tested both systems with different amounts of latency and different levels of packet loss. For latency, we recorded data for one-minute trials of battlefield gameplay with added latencies of 0ms, 50ms, 100ms, 200ms, and 500ms. These are the same values tested in our user study. For packet loss, we tested values of 10%, 20%, and 40% within the same game area. These values are displayed in Figure 3. We also recorded a nine-minute trial that included cutscenes as well as fighting on the battlefield. After opening the game, we resumed gameplay at the tutorial battlefield section of the game. Once the allotted time was over, we paused the game and stopped Wireshark packet detection and saved the file for subsequent data analysis.

Network Parameter	**Values Tested**
Added latency	0ms, 50ms, 100ms, 200ms, 500ms
Packet loss	0, 10%, 20%, 40%

Figure 3: Values and Network Parameters Tested in Wireshark Experimentation

3.5 User Study

In our user study, we concentrated on collecting both objective and subjective data about the effects of latency on both cloud gaming services. The same computer lab on the WPI campus was used for all participants.

Before testing, we submitted our study protocol to WPI Institutional Review Board for approval. This involved filling out the application as well as both members of our team completing an online course in research methods and guidelines. Since Assassin's Creed Odyssey is rated M by the ESRB for blood and gore, intense violence, sexual themes, and strong language, the IRB conditioned our approval on participants stating their ages were 18 or older.

3.5.1 Recruiting Participants

In order to find subjects for our user study, we accessed two different pools of students. First, we worked with the Psychology department to enter our study onto their Sona Systems site [40], since students in Psychology classes at WPI are required to participate in multiple research studies for credit in each class they are taking. Second, we sent an email advertising to the students in Interactive Media and Game Development (IMGD) classes, since the IMGD department also requires students in classes to participate in game playtesting sessions for class credit. We also provided three $25 Amazon gift cards, raffled off to people who completed the study.

3.5.2 Study Logistics

For both the user study and network experiments, we connected to the WPI network with an Ethernet connection. For our computers, we used Dell laptops with the following specifications:

- Intel(R) Core(TM) i5-7440HQ CPU @ 2.80GHz
- 16GB RAM
- 500GB hard drive
- 1920x1080p, 60Hz screen
- Windows 10 Operating System

For gameplay, we chose the tutorial battlefield area because it was easy for a player to access and had many enemies for players to fight, and the game would not need to be reset between trials. Based on pilot studies where volunteers went through our protocol, we further refined our study methods, including lowering trial duration to 30 seconds to prevent cutscenes from triggering when too many enemies were killed.

For the user study, we arrived at the computer lab before each session was scheduled and set up the laptops and the cloud services. We opened the game up on each laptop, one with Stadia and one with Shadow, and paused the game at the start of the tutorial battle sequence. We also opened all the required forms and surveys, to ensure we could run through each user quickly and easily. We had two slots available for each half hour block when both of us were able to be there, and one of us would run through a user on each system, and then swap and repeat the process with the other system.

When students first arrived at the computer lab, we had them read through a consent form about the study. We assigned a unique user number to each participant. They then filled out a short survey on Google Forms with demographics questions as well as some questions about their video game and cloud gaming experience.

The demographics and background questions are as follows:

- Age
    - 18-24 years
    - 24-30 years
    - 30+ years
- Major
- Rate your ability as a gamer
    - Low 1-5 High
- What game genres do you typically play (if any)?
    - Action
    - Adventure
    - First-person shooters
    - RPG
    - Simulation
    - Sports
    - Strategy
    - None
    - Other
- How much time do you typically spend each week playing video games?
    - Less than 1 hour
    - 1-5 hours
    - 6-10 hours

    - 11-15 hours
    - 15-20 hours
    - More than 20 hours
- Have you played Assassin's Creed Odyssey before?
    - Yes
    - No
- If so, how much have you played Assassin's Creed Odyssey?
    - 1-5 scale with 1 - Never played before and 5 - Finished the game
- Have you used cloud gaming services (Ex: PlayStation Now, Vortex, Steam Link) before?
    - Yes
    - No
- Which cloud gaming service have you used?
    - Blade Shadow
    - Vortex
    - Google Stadia
    - PlayStation Now
    - Steam Link
    - OnLive
    - Nvidia GeForce Now

If participants did not bring their own earbuds or headphones, we had extras to provide them that were cleaned between uses. Players used a standard Xbox 360 controller to play through each trial. Before the trials began, we had the players practice in-game combat to get used to the game controls and provided them with a list of controls on a separate laptop. When they were ready, we started our command line script that starts Bandicam and Clumsy, changing latency values when any key is pressed in the Command Prompt window. We told users to kill as many enemies as possible in each thirty second trial. After each trial, users would fill out another short survey about their game experience in that specific trial. The after-trial survey questions are as follows:

- How would you rate the graphics quality of the game?
    - 1-5 scale with 1 - Bad and 5 - Good
- How would you rate the responsiveness of controls?
    - 1-5 scale with 1 - Bad and 5 - Good
- How likely would you be to continue playing the game under these conditions?
    - 1-5 scale with 1 - Not likely and 5 - Very likely
- Do you have any other comments?

The users repeated this process four more times, and then swapped and did the same thing with the other system, either Stadia or Shadow depending on what they started with.

After the user completed the trials on both systems, we then opened the debriefing form, which provided details on the purpose of the study. We had the participants fill out a final survey with their name and email if they needed either Psychology or IMGD credit, or if they wanted to enter the gift card raffle.

4. Results and Analysis

This chapter displays the results and analyzes the data collected from both our user study and network experiments.

4.1 Experiment Results

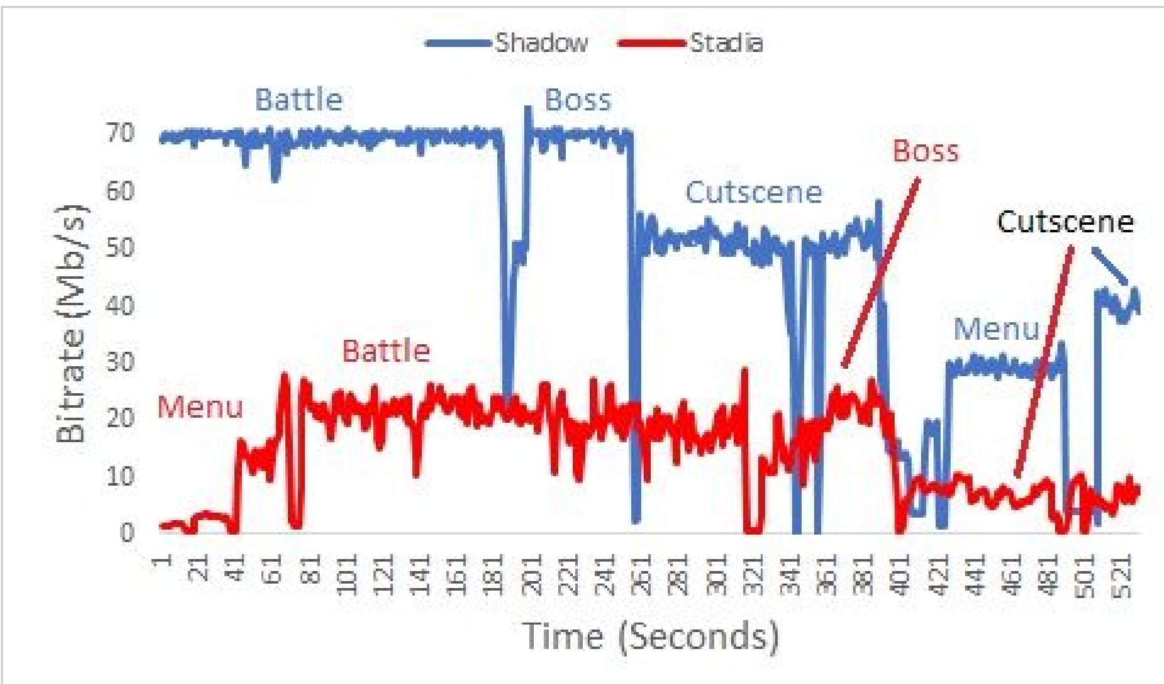

Figure 4: Bitrate over Time for an Extended Trial
Bitrate varies for both Shadow and Stadia when going between gameplay, cutscenes, loading screens, and menus.

Figure 4 shows a roughly 9-minute trial with both Shadow and Stadia where we played through the battle area, as well as a boss fight and some cutscenes and menu scenes. The x-axis is time in seconds, and the y-axis is the bitrate in Mb/s. For both Shadow and Stadia, the bitrate went down to almost zero during loading screens between parts of the game. Additionally, for Shadow, cutscenes used significantly less bandwidth, while Stadia used similar bandwidth to normal gameplay. However, both services' bitrates went down when in a static menu, Shadow even lower than during cutscenes. This shows that both services lower the bandwidth used when streaming less graphically intense portions of the game.

For the subsequent network experiments, we looked at the effects of both packet loss and added latency on Shadow and Stadia. We took measurements for latency values of 0ms, 50ms, 100ms, 200ms, and 500ms and inbound and outbound packet loss values of 10%, 20% and 40%. For all these values, we observed bandwidth over time for one minute, measured in Mb/s. Additionally, for all network changes, we started Clumsy before connecting to Shadow or Stadia [36]. Notable graph results are shown in Figures 6-8, while all results are summarized in Figure 5. For some conditions, the programs would not start and are shown in Figure 5 as N/A.

In all trials, Shadow remained stable in bitrate, with low standard deviations as shown in Figure 5. Stadia, however, uses much lower bandwidth when it is paused, if users are not actively using the service. Therefore, in all trials Stadia uses much less bandwidth for the first few seconds, since we started Wireshark before resuming gameplay in our tests. Shadow uses consistent amounts of bandwidth whether or not the Shadow window is actively being used.

Figure 6 displays the cumulative distribution of downstream bitrate in Mb/s with no latency or packet loss. The x-axis is the bitrate, and the y-axis is the cumulative distribution. For all values, Shadow used significantly more bandwidth than Stadia. This is probably because Stadia has no way to set bandwidth, whereas Shadow automatically detects the conditions of the network and sets an appropriate bitrate, with a maximum of 70. Since we used an ethernet connection to the WPI network, Shadow used 70 Mb/s. However, with lower speed networks, Shadow would use less bandwidth depending on the amount available.

Figure 7 shows the cumulative distribution of bitrate in Mb/s with 20% outbound packet loss. This graph uses the same axes as Figure 6. This was the only network condition for which Shadow's bitrate significantly changed, going up to an average of 137.21 Mb/s, which is almost double the normal bitrate. Stadia, however, remained roughly the same. Note, neither Shadow nor Stadia changed with 10% outbound packet loss. At 40% outbound packet loss, Shadow would not connect at all, but Stadia's average bitrate decreased slightly.

Figure 8 displays the cumulative distribution of upstream bitrate in Mb/s with no network changes. In terms of upstream bitrate, Stadia is higher with an average of 0.53 Mb/s, while Shadow averaged 0.18 Mb/s. With increased latency, at 100ms, Stadia decreased slightly to 0.35 Mb/s, but was still greater than Shadow at 0.21 Mb/s.

Test	Shadow Mean Bandwidth (Mb/s)	Stadia Mean Bandwidth (Mb/s)	Shadow Standard Deviation	Stadia Standard Deviation
Base downstream	69.43	18.70	1.33	7.18
50ms downstream	67.66	11.60	2.19	6.24
100ms downstream	68.28	7.17	1.73	2.04
200ms downstream	68.83	N/A	1.43	N/A
500ms downstream	68.53	N/A	1.32	N/A
Base upstream	0.18	0.53	0.04	0.14
100ms upstream	0.21	0.35	0.03	0.06
10% outbound loss	69.57	20.05	.94	6.47
20% outbound loss	137.21	21.20	3.22	7.09
40% outbound loss	N/A	17.69	N/A	8.00
10% inbound loss	76.88	22.71	2.15	5.53
20% inbound loss	81.87	11.34	3.18	3.90
40% inbound loss	N/A	8.35	N/A	3.20

Figure 5: Summary of Network Experiments

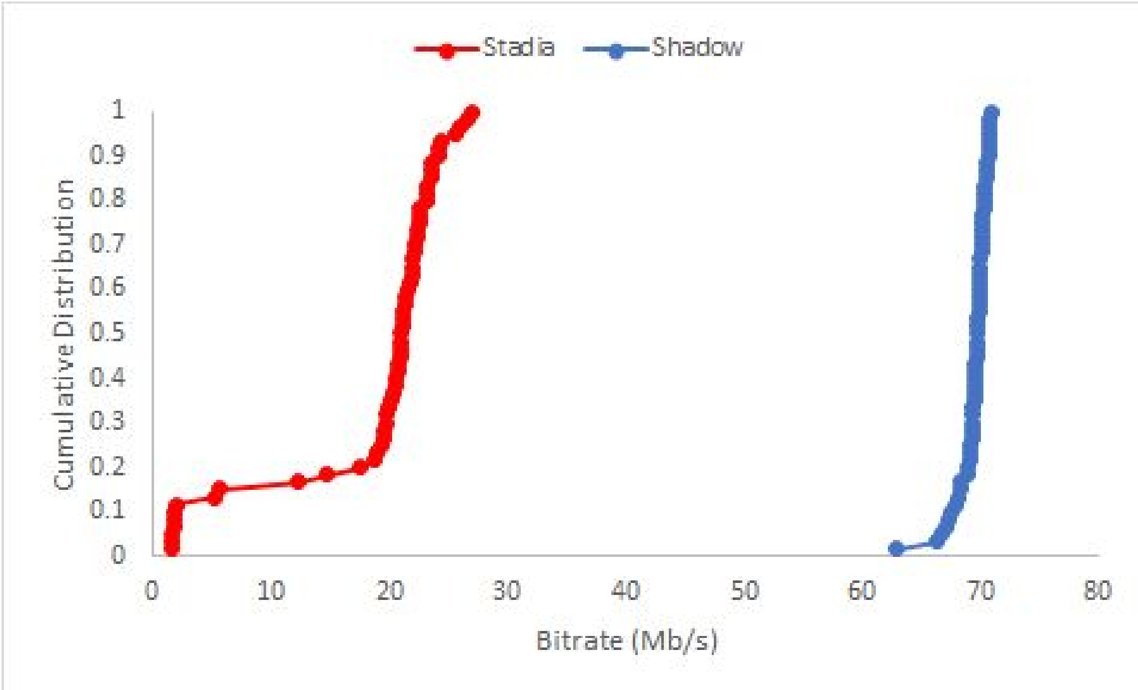

Figure 6: Cumulative Distribution of Downstream Bitrate
Shadow consistently maintains around 70 Mb/s, while Stadia is around 20-30 Mb/s

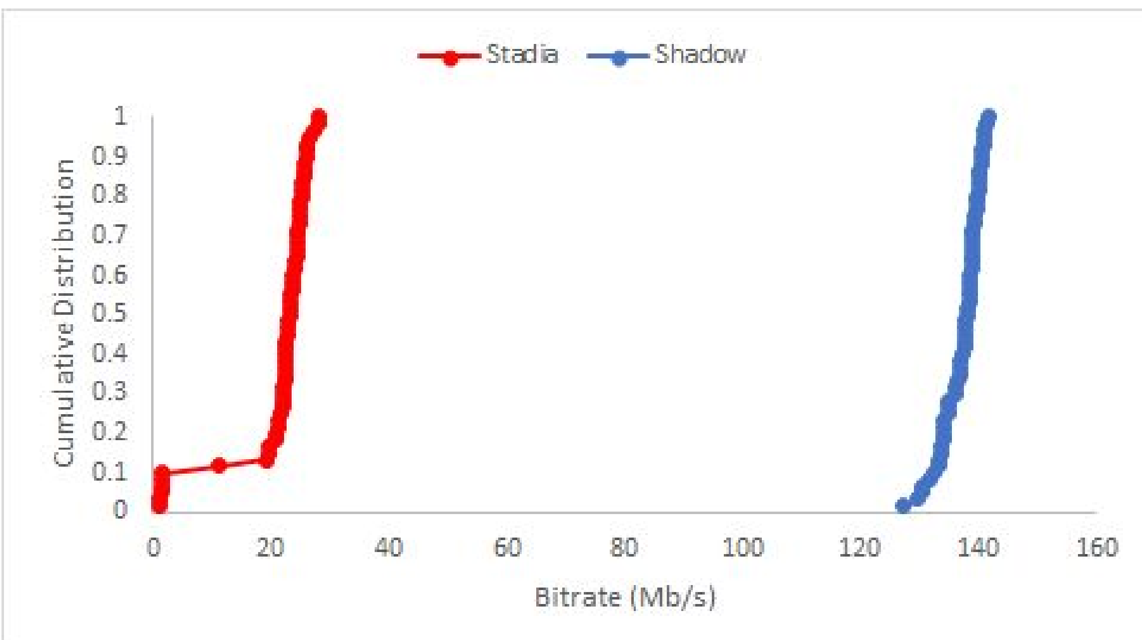

Figure 7: Cumulative Distribution of Bitrate with 20% Outbound Packet Loss
Stadia maintains similar 20-30 Mb/s, while Shadow roughly doubles to 130-140 Mb/s

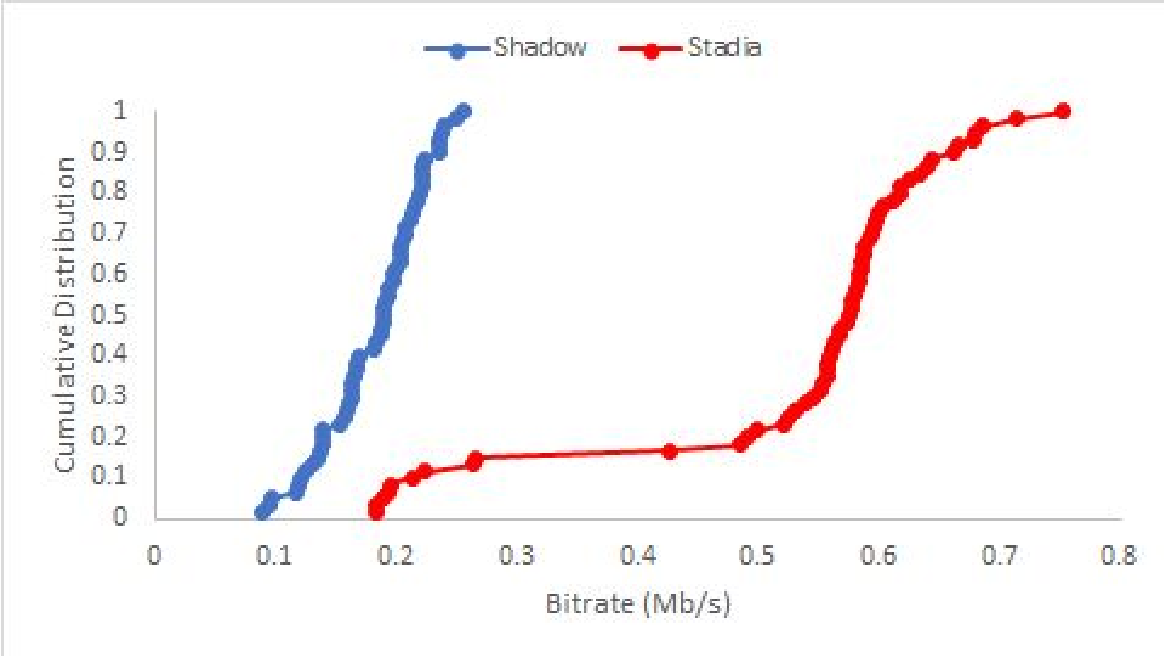

Figure 8: Cumulative Distribution of Upstream Bitrate
Stadia's upstream is slightly larger than Shadow, though both are less than 1 Mb/s

In terms of added latency, Shadow's downstream bitrate never varied much. Although Stadia would not connect at 200 or 500ms, it seemed to trend towards a lower bitrate as latency increased. Furthermore, Stadia's graphics quality decreased drastically as latency increased while Shadow's remained relatively consistent. Shadow's downstream bitrate was always much higher than Stadia's for all latency values.

With packet loss, Shadow's bitrate increased slightly with higher levels of inbound packet loss, and almost doubled with 20% outbound packet loss. Shadow would not connect at 40% packet loss, so this value could not be tested. The bitrate for Stadia decreased significantly with inbound packet loss, going down to an average of 8.35 Mb/s for 40% loss, but only slightly decreased with outbound packet loss. Regarding subjective experience, graphics quality on Stadia decreased with inbound packet loss similar to added latency, while Shadow remained fairly consistent. However, outbound packet loss on Shadow was noticeable due to inputs frequently being lost, while Stadia did not have this problem even at a rate of 40% packet loss. This indicates that Stadia has measures in place to negate the effects of packet loss, while Shadow does not, and user experience suffers more under these conditions in Shadow.

4.2 User Study Results

For our user study, first participants filled out a demographics survey. Then they played a portion of Assassin's Creed Odyssey for a minute at a time for five trials. We varied the latency values in a set order each time, starting with 200 ms added latency, then 50 ms, 100 ms, 0 ms, and lastly 500 ms added latency. After each trial, subjects filled out a post-trial survey where they rated the graphics quality, responsiveness of the controls, and their willingness to play under the trial's circumstances. This section details and analyzes the results from our user study.

4.2.1 Demographics

Thirty-seven people signed up for and participated in our user study. We had technical difficulties with our first participant, however, and latency values were not actually changing during this trial, so we did not include this person's survey results or demographics information.

Out of the remaining 36 subjects, 35 of them were between the ages of 18-24, with 1 subject being between 24-30. Figure 9 below shows the different majors of the subjects. Due to us mainly pulling our subjects from the IMGD playtesting pool, most of the people were majoring in computer science, IMGD, or double majoring in both. We recruited a total of 4 subjects from the WPI psychology pool.

Major	Number of people
Architectural Engineering	1
Computer Science (CS)	8
CS/IMGD Double Major	5
CS/other Double Major	2
Environmental Engineering (IMGD minor)	1
Interactive Media and Game Development (IMGD)	13
Management Engineering/other Double Major	2
Mechanical Engineering	1
Psychological Sciences	1
Robotics	2
Undeclared	1

Figure 9: Summary of Majors

Question	Yes	No
Have you played Assassin's Creed Odyssey before?	8	28
Have you used cloud gaming services before?	12	24

Figure 10: Summary of Participants' Gaming History

Figure 10 shows the responses to two other questions asked in our demographics survey. Not featured in the table, we also asked subjects to rate themselves on a scale from 1-5 (low-high) on how much of a gamer they were. On a scale from 1-5, 3 people answered with 1, 4 people rated as 2, 11 people chose 3, 14 people rated as 4, and 4 people rated themselves as a 5.

Out of the 8 people who had played Assassin’s Creed Odyssey before, when asked how much they had played the game on a scale from 1-5 (Never played - Finished the game), 3 people answered with 2, and the other 5 answered with 5.

Among the people that had used cloud services before, 9 have used PlayStation Now, 5 have used Steam Link, 1 used OnLive, 1 used Nvidia GeForce Now, and 1 used Google Stadia. As there were a total of 12 people who answered this question, 4 people answered as having used more than one of the listed cloud gaming services.

Time spent on video games weekly	**Responses**
Less than 1 hour	7
1-5 hours	9
6-10 hours	7
11-15 hours	7
15-20 hours	6
More than 20 hours	0

Figure 11: Average Time Spent Playing Video Games Weekly

Genre played	Responses
Action	22
Adventure	21
First-person shooters	12
Multiplayer Online Battle Arena (MOBA)	4
None	1
Platformers	1
Rhythm	2
Role-Playing Games (RPG)	18
Simulation	10
Sports	3
Story-based Narratives	1
Strategy	20

Figure 12: Game Genres Typically Played by Participants

Figure 11 shows the average amount of time the subjects spend playing video games weekly. There was an even spread, most people playing 1-5 hours a week, but there were also a fair number of people playing for less than 1 hour, 6-10 hours, 11-15 hours, and 15-20 hours per week. This shows that we did have a variance in gaming experience from our test subjects.

Figure 12 shows the game genres the subjects usually prefer to play. Action, Adventure, and Strategy were the top three genres played out of our participant pool, with Role-Playing Games coming in close after Strategy. A few people put down Sports and Rhythm games as their typical genres. Note that, like the question on cloud services discussed above, this question also allowed subjects to pick multiple answers, so the total number of responses from the graph is larger than the number of participants.

4.2.2 Subjective Data

For our post-trial survey, we asked participants to rate the graphics quality, responsiveness of the controls, and their willingness to continue playing under the given conditions from 1-5 each for each of the added latency values. The results gathered from these surveys have been averaged and displayed in Figures 13-15.

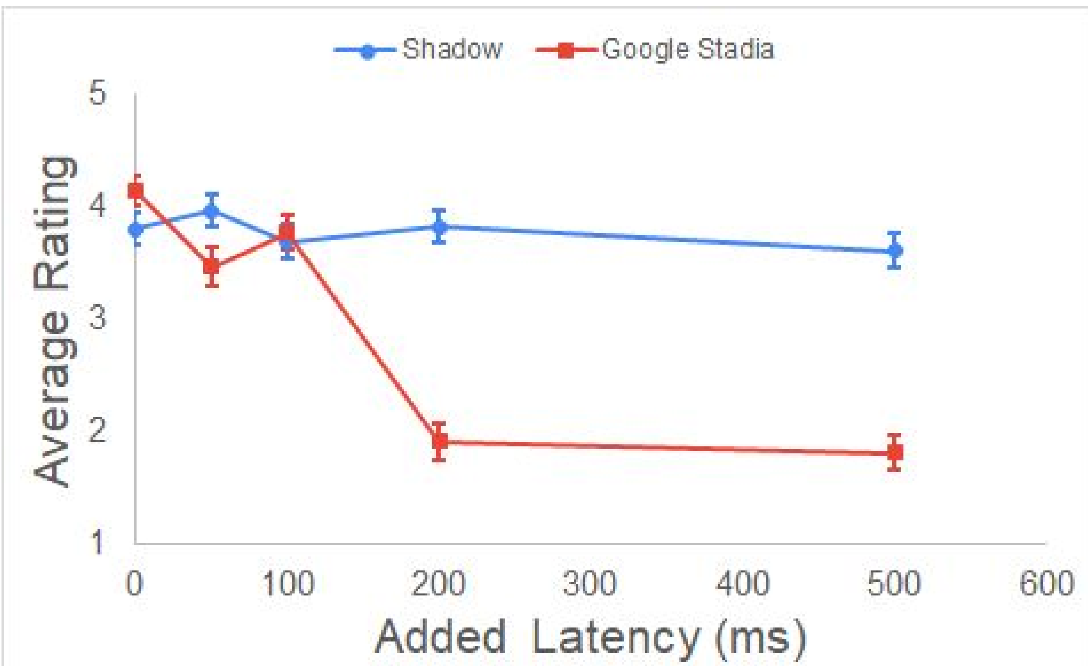

Figure 13: Average Rating vs Added Latency for Graphics Quality

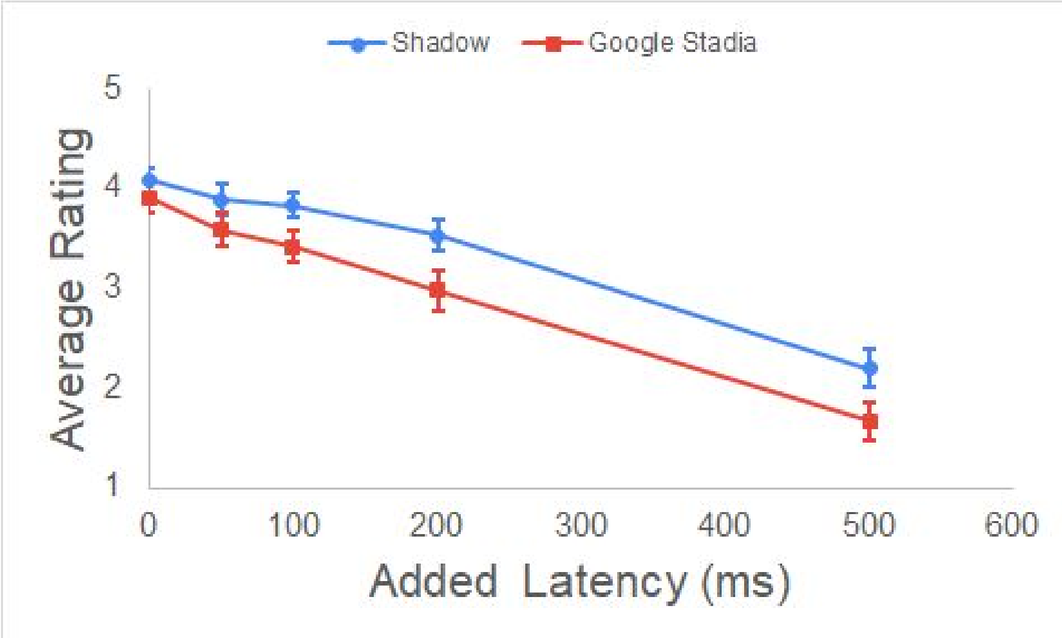

Figure 14: Average Rating vs Added Latency for Responsiveness

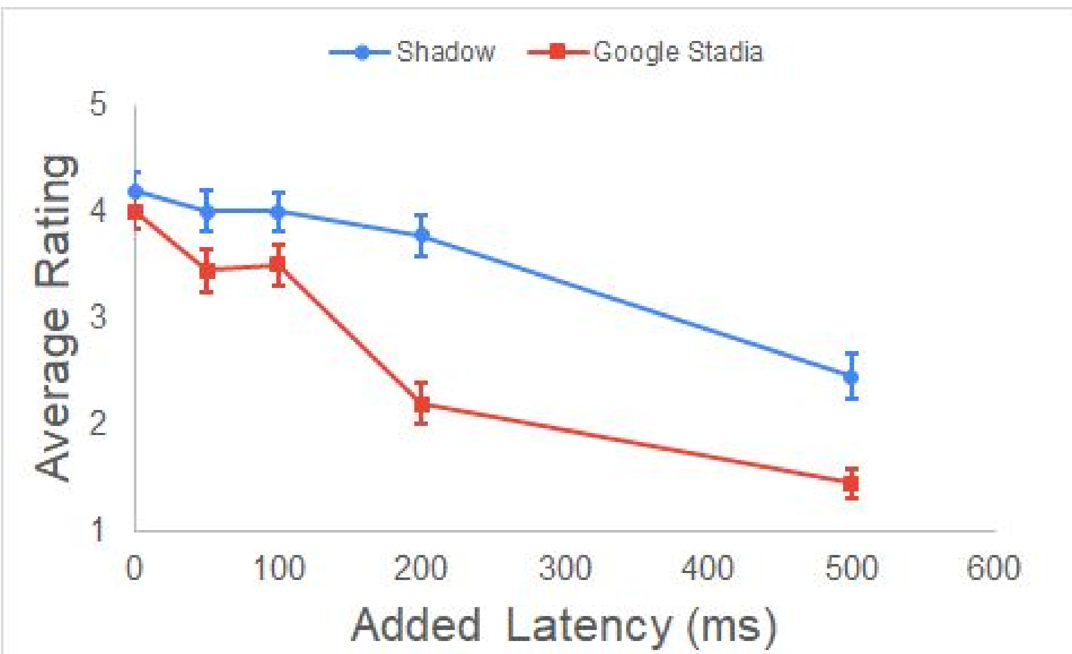

Figure 15: Average Rating vs Added Latency for Willingness to Play Again

Figure 13 depicts the average rating for graphics quality as the amount of added latency increases for both Shadow and Google Stadia. The values on the y-axis are the average rating from 1-5. The values on the x-axis are the amounts of added latency in units of milliseconds. The data for Shadow is shown in blue with the circle markers. The data for Google Stadia is shown in red with the square markers. The error bars on each of the markers display standard error. The figure shows that for added latency values between 0 ms and 100 ms, the graphics quality is largely unaffected. However, once we added 200 ms of latency, the average rating took a dive for Stadia, for an average roughly around 2 out of 5. Shadow seemed to have consistent graphics quality, even up to 500 ms of latency.

Figure 14 depicts the average rating for the responsiveness of the controls as the amount of added latency increases for both Shadow and Google Stadia. The format of the graph is similar to Figure 13. The figure shows a steady decline in the rating for responsiveness for both Shadow and Stadia, with Stadia having a slightly lower average rating than Shadow on that aspect overall.

Figure 15 depicts the average rating for willingness to play under the given conditions again as the amount of added latency increases for both Shadow and Google Stadia. The format of the graph is similar to Figures 13 and 14. The figure shows a similar shape to that of Figure 13, where from 0 ms to 100 ms, people were more likely to continue playing and accept added latency during the game. Both Shadow and Stadia's ratings decreased at 200 ms of added latency and went further down at 500 ms. Stadia would disconnect after we had changed the latency around too quickly to have a "stable" connection. At 500 ms, Stadia would frequently not let the game be rejoined. Because of this, there were some subjects whose post-trial surveys could not be entirely filled out and are missing either just the 5th trial (7 participants) or both the 4th and 5th trial (2 participants).

4.2.3 Objective Data

The objective data collected includes the number of enemies killed as well as the number of times participants were hit by enemy attacks during each trial. Figures 16 and 17 display these results. In each graph, the y-axis represents either the number of enemies killed or the number of times the player was damaged.

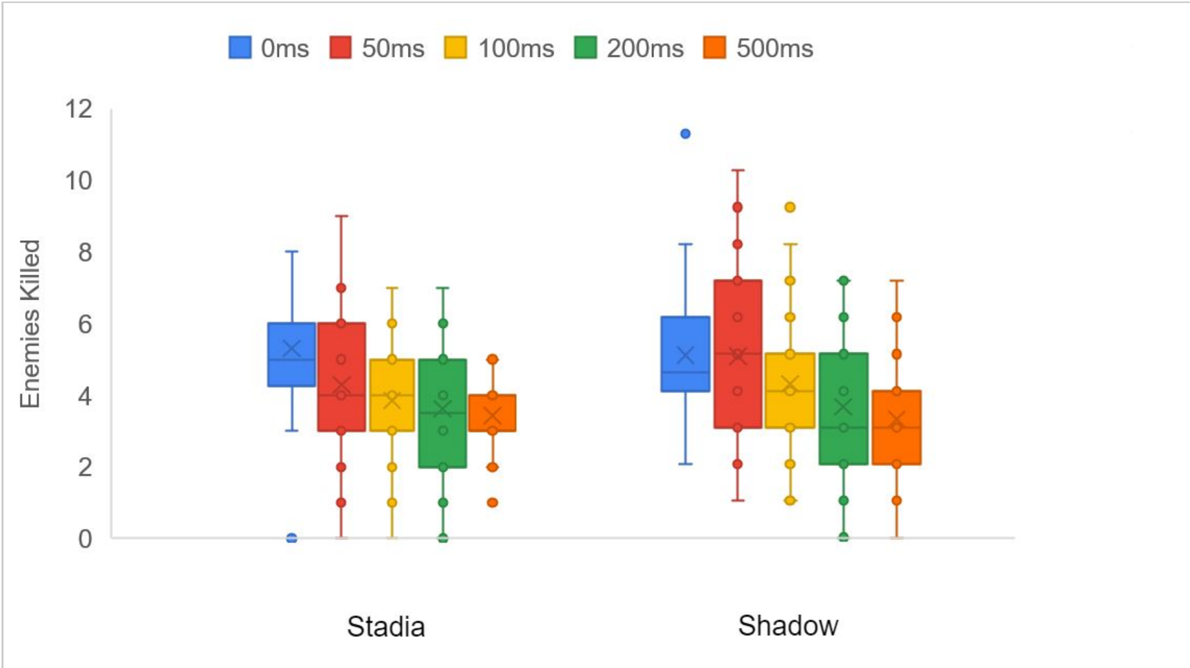

Figure 16: Average Number of Enemies Killed for Various Added Latencies
In both Stadia and Shadow trials, the number of enemies killed downward as latency increased.

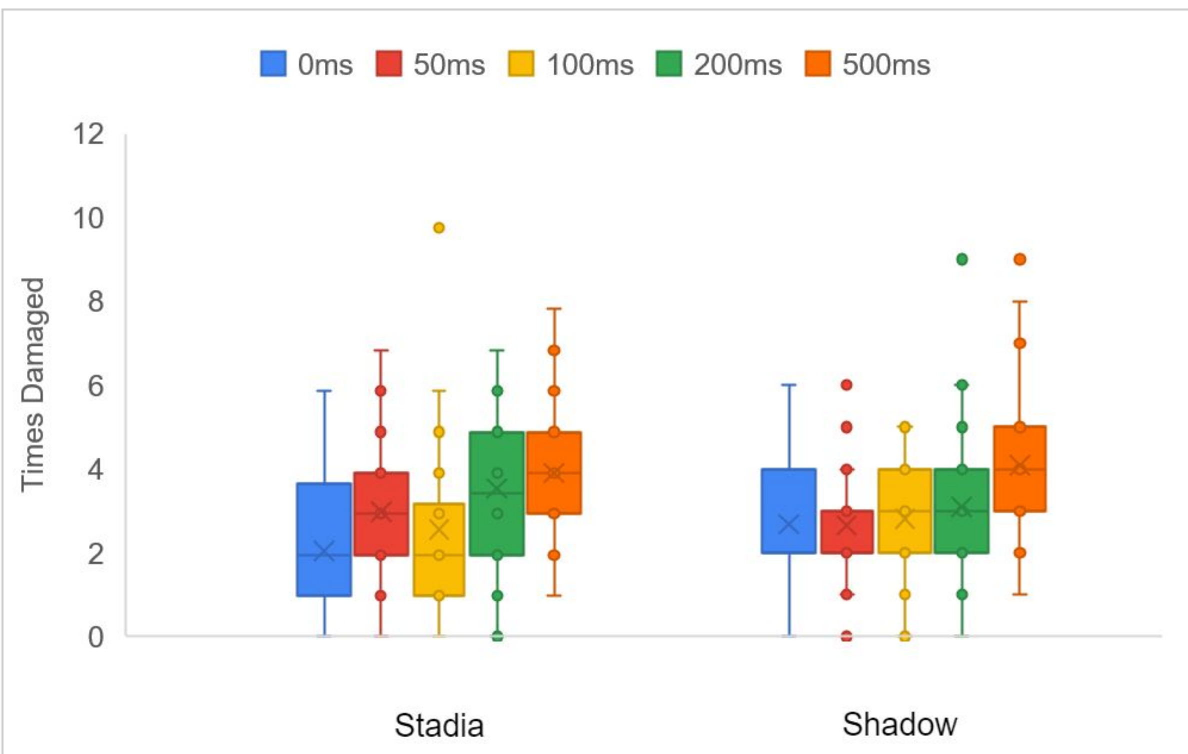

Figure 17: Average Number of Times Damaged for Various Different Added Latencies
In both Stadia and Shadow trials, the number of times the player was damaged by enemies

Figure 18: Average Enemies Killed by Self Rated Gaming Experience
The number of enemies killed trends slightly upward for participants with more gaming experience.

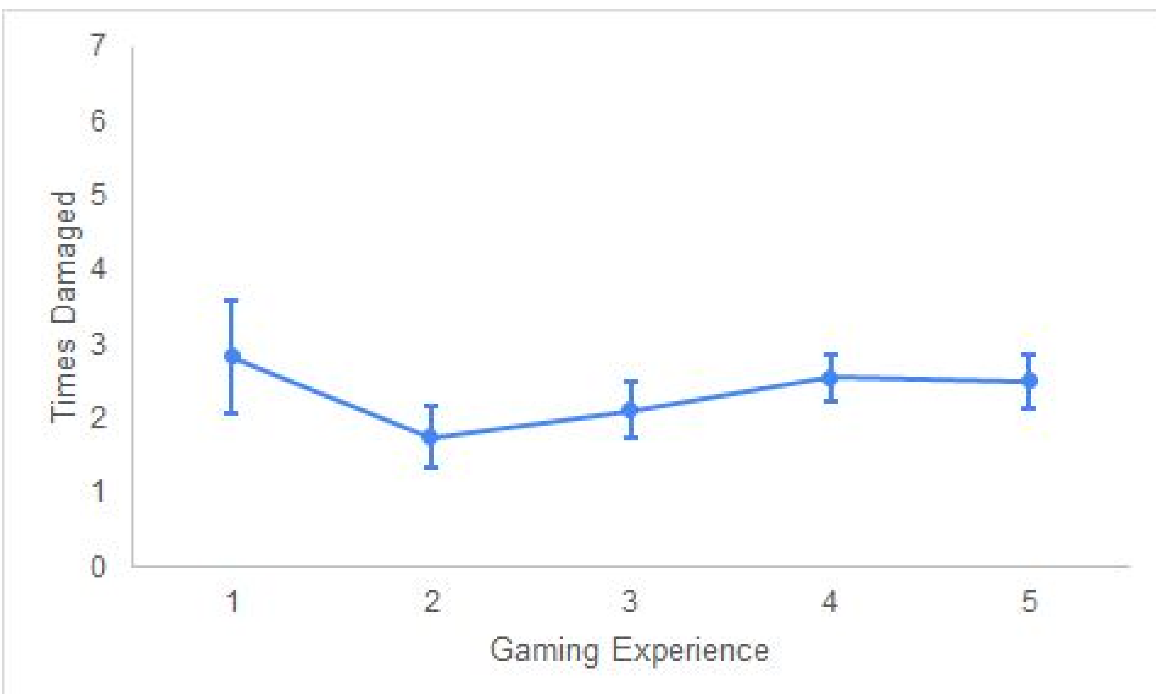

Figure 19: Average Times Damaged by Self Rated Gaming Experience
There does not appear to be any correlation between the number of times participants were damaged by enemies and their gaming experience.

Figures 18 and 19 show the average number of times players of each gaming experience rating were damaged and how many enemies they killed. For both figures the x-axis is their self-rated gaming experience from our demographics survey from 1-5, and the y-axis is either times damaged or enemies killed. The error bars on each of the markers display standard error. This data is averaged from trials in both Stadia and Shadow. From these graphs, there does appear to be a slight upwards trend in enemies killed, with higher gaming experience participants killing on average more enemies. However, for the number of times damaged, there does not appear to be any correlation.

Overall, the number of enemies killed decreased as latency increased in both Shadow and Stadia trials. Although there are outliers in both graphs, these are most likely either players who are experienced at the game, or very new to this type of game, and do well or poorly in all trials. The amount of damage taken shows a larger increase at higher latencies in Stadia than Shadow, which could be related to the graphics quality of Stadia. At higher latencies Stadia's graphics decrease drastically, whereas Shadow's remain relatively stable or suffer a slight decrease. Player performance in general seems to decrease at higher latency values in both systems.

5. Conclusion

As more commercial cloud gaming services are released and used, latency will increasingly be an important consideration to measure their performance. Cloud services are more susceptible to latency than traditional games since the player's inputs are sent to the server for processing, and then the video stream is sent back to the user's client. Increased latency, especially in cloud services, often decreases user enjoyment and performance.

For this project, we conducted a user study with 37 participants who played Assassin's Creed Odyssey on Google Stadia and Blade Shadow. They played the tutorial battle section of the game, killing as many enemies as possible in 30 second trials with added latencies of 0ms, 50ms, 100ms, 200ms, and 500ms. Analysis of the results shows that both player performance and enjoyment of the game decreased with added latency, especially at levels of 200ms and 500ms with both Stadia and Shadow. Additionally, Stadia's graphics quality decreased drastically at higher latencies, while Shadow's remained relatively stable.

We also performed network experiments with both cloud services using Wireshark to analyze the network traffic. We tested added latencies of 0ms, 50ms, 100ms, 200ms, and 500ms, as well as packet loss values of 10%, 20%, and 40%. Shadow used significantly more bandwidth than Stadia in all downstream trials, although Stadia used slightly more upstream bandwidth. However, Stadia was not visibly affected by high levels of packet loss, while Shadow frequently lost user inputs.

Overall, our results showed that both cloud services were negatively affected by high levels of latency, and that player performance and quality of experience decreased with higher amount of latency. Stadia's graphics quality was significantly worse than Shadow at high latencies but was similar with no added lag. If commercial cloud gaming services continue to minimize added latency, they should be a viable option for playing a wide variety of video games in the future.

6. Future Work

We have identified several areas of future work to gain more understanding and knowledge of cloud gaming systems. First, we only looked at Shadow and Google Stadia in this study [14] [16]. We were originally going to study Vortex as well, to compare our results with the IQP study from 2019 that also evaluated Vortex [4] [15]. However, a few days before we were going to start collecting data, Vortex removed Assassin's Creed Odyssey from their library. Future studies could look at Vortex and Nvidia GeForce Now, the latter of which was released after we finished collecting data [18]. This could be valuable to compare the similarities and differences of the systems' performances over the same time period.

Another way to extend this study would be to analyze performance with different game genres that may be affected differently by varied network conditions. For example, first person shooters rely heavily on quick and accurate movements and aiming, so increased latency or packet loss would most likely have a greater impact on these games than games like Assassin's Creed Odyssey. Rhythm games are also likely to be negatively affected by degraded network conditions. In these rhythm games, precise timing for inputs is essential, so testing how these games play on commercial cloud gaming services could provide valuable data. One other game genre to study could be multiplayer online games. Since these games send data to and from other servers as well as the client, changing latency or packet loss affect these games differently.

Restricting bandwidth is another area of future work. There are tools that enable bandwidth restrictions that could be used in experiments like those we did using Clumsy [36].

Since cloud gaming systems require significant bandwidth to stream high quality video to the end users, restricted bandwidth may reduce graphics quality or lower frames per second.

Another way to extend this study would be to have more participants. Although we ended up above our goal of 30 people, additional participants would add more statistical power to the results. Additionally, most of our study participants were from the Interactive Media and Game Development user pool, and all but one was between the ages of 18-24. Future studies could look for a wider variety of ages to relate the results to a larger population.

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