LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Engineering Science
Software Engineering

PERCEIVED IMAGE QUALITY OF REAL TIME RAY TRACING IN VIDEO GAMES SURVEY

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Examiner: University Lecturer Erno Vanhala

ABSTRACT

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Perceived image quality of real time ray tracing in video games survey
Bachelor's Thesis 2021

42 pages, 0 figures, 9 tables, 3 appendices
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Keywords: Ray tracing, RTX, video games, comparison, survey, lighting, reflections, shadows, global illumination, graphics card, GPU, graphics

This thesis investigates the perceived image quality of real time ray tracing in video games. This thesis will not examine the performance impact of the technology. Ray tracing means the modeling of singular light rays. Real time ray tracing is a new technology in video games with the aim to improve the photorealism of lighting. Perceived image quality was measured with a survey, where participants chose the better-looking image from two images. The results for the survey were, ray tracing was generally perceivable from the images, and it was perceived to be better depending on the implementation the technology. Images with reflections done with the technology were perceived to be better and images with only ray traced shadows or global illumination were perceived to be not as good as images without real time ray tracing. Furthermore, it was discovered that previous experience with ray tracing had a minor effect on perceived image quality.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
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Tässä kandidaatintyössä tutkitaan reaaliaikaisen säteenseurannan vaikutusta videopelien havaittuun kuvanlaatuun. Suorituskykyyn ei oteta työssä kantaa. Säteenseurannalla tarkoitetaan yksittäisten valonsäteiden mallintamista. Reaaliaikainen säteenseuranta on uusi teknologia videopeleissä, jolla tavoitellaan parempaa valaistuksen todenmukaisuutta. Havaittua kuvanlaatua mitattiin kyselytutkimuksella, jossa kyselyn vastaajat valitsivat kahdesta kuvasta paremman. Kyselyn tulokseksi saatiin, että reaaliaikainen säteenseuranta oli tavallisesti havaittavissa kuvista ja reaaliaikaisen säteenseurannan kokeminen paremmaksi riippui teknologian toteutuksesta. Kuvat, jotka sisälsivät teknologialla toteutettuja heijastuksia, koettiin yleisesti paremmaksi ja kuvat, jotka sisälsivät vain teknologialla toteutettuja varjoja tai epäsuoran valaistuksen koettiin huonommaksi kuin kuvat ilman reaaliaikaista säteenseurantaa. Tuloksista huomattiin myös, että vastaajan aikaisemmalla säteenseuranta tuntemuksella oli vähäpätöistä vaikutusta teknologian paremmaksi kokemiseen.

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TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AMD	Advanced Micro Devices
API	Application Programming Interface
BVH	Bounding Volume Hierarchy
CGI	Computer-generated Imagery
CUDA	Compute Unified Device Architecture
DSP	Digital Signal Processor
DXR	DirectX Raytracing
GPU	Graphics Processing Unit
GPUGPU	General-purpose Computing on Graphics Processing Units
MAGI	Mathematical Applications Group, Inc.
MSRP	Manufacturer's Suggested Retail Price
NVIRT	NVIDIA Interactive Ray Tracing API
OpenGL	Open Graphics Library
PCI	Peripheral Component Interconnect
RT	Ray Tracing
VR	Virtual Reality

1 INTRODUCTION

1.1 Background

The global revenue of the game industry is expected to be 159.3 billion U.S. Dollars in 2020 and continue to grow to over 200 billion U.S. Dollar by 2023 (Wijman, 2020). The new video game consoles released in 2020 reflect this as some persons and businesses went as far as buying the limitedly available consoles to resell them for much higher price than the MSRP (Manufacturer's Suggested Retail Price) (Macák, 2020). Also, computer components such as gaming graphics cards were in high demand and their availability was especially poor (Jimenez, 2020).

Gaming's popularity (Clement, 2021) has been one of the driving factors for advancing (computer) graphics technology. For example, a significant part of technology company NVIDIA's revenue was made from graphics cards meant for gaming (NVIDIA, 2020). Semiconductor company, Advanced Micro Devices (AMD), also made a significant amount of revenue from components meant for gaming (AMD, 2021). One of the most notable new technologies in the industry is real time ray tracing. NVIDIA was first to the market with the release of RTX-series of graphics cards supporting real time ray tracing in 2018 (Smith, 2018). AMD also released graphics cards which support real time ray tracing two years later. In addition, new consoles like the PlayStation 5 ja Xbox Series-consoles are based on AMD technology and support real time ray tracing (Microsoft, 2020; Nishino, 2020).

Ray tracing can be defined as simulating the behavior of a ray of light in a three-dimensional environment. The technique is usually done with reverse ray tracing, meaning that the light ray is traced from the camera to the scene and then to the light source. If ray tracing were to be performed from the light source to the camera, light rays which would not hit the camera and thus help in the image rendering, would also be simulated. Ray tracing can be used to produce photorealistic results since it is based on simulating the individual rays of light. (Glassner, 1989; NVIDIA, 2018) Present day rasterization-based algorithms use many simplification to render three-dimensional graphics in real time and image quality remains a good-quality approximation because of that. (Oh, 2018)

1.2 Goals and limitations

As real time ray tracing becomes more widely used in video games, it is a valid research topic to determine if ray tracing improves the perceived image quality. The goal of the work is to use survey material from four different games to identify if ray tracing improved the perceived image quality. The thesis did not consider the performance impact of the technology and survey material, consisting of screenshots, were taken at the highest graphical quality settings at the native resolution of 2560 x 1440. No performance enhancing technologies at the cost of image quality were used. The survey was done with still images to make image quality comparisons more effortless meaning the survey participants could observe the details in the images in more detail at their own pace.

To sum things up, the goal of the work is to answer to the following two research questions:

1. Is real time ray tracing in video games perceivable?
2. Did real time ray traced effects in video games improve the perceived image quality?

Games chosen for the image quality comparisons were Shadow of the Tomb Raider (2018), Control (2019), Cyberpunk 2077 (2020), Metro Exodus (2019) and its enhanced version Metro Exodus Enhanced Edition (2021). These games were chosen based on supported ray tracing features and release date. Shadow of the Tomb supports ray traced shadows (Burnes, 2019a). Metro Exodus Enhanced Edition supports full ray traced lightning including global illumination and reflections (Burnes, 2021). Control and Cyberpunk 2077 support ray traced shadows, reflections ja indirect lightning (Burnes, 2020, 2019b).

In theory, the thesis may contain an NVIDIA bias, because NVIDIA has funded and done a great deal of ray tracing research. NVIDIA was also first to publish graphics cards supporting real time ray tracing (Smith, 2018). All of the games chosen for the perceived image quality survey also use the NVIDIA RTX-platform (Martindale and Roach, 2021), which runs on top of Microsoft's DirectX Raytracing (DXR)- application programming interface (API). Since the games still use DXR-API on the base level, all of the four chosen games also support ray tracing on AMD graphics cards (Wikipedia, 2021a).

1.3 Thesis structure

Chapter two consists of the history of ray tracing, high level overview of DXR-API and benefits for game development. Last subchapter is related research. The history of ray tracing is also a high-level overview; first of the most notable early research and technologies and then veers into examples of what ray tracing has been used for before and to the history of hardware accelerated ray tracing.

Chapter three contains the theory for organizing a survey and the detailed description of the survey which was done to collect research material for this work. The description also contains criteria used for choosing the image comparison screenshots and other little details.

In chapter four results for the survey are presented. First background survey results then main results for all participants and then results based on background question answers. Last there is a summary and short analysis of all the open feedback collected during the survey.

Chapter five contains a deeper analysis of the results and associates the results to theory. Chapter five also describes the limitations of this thesis and provides propositions for future works. After chapter five, there is chapter six, which condenses the whole thesis into conclusions.

2 THEORY

2.1 History of ray tracing

Hoffman (1990) made the observation that after perspective projection was discovered, it can be argued that Albrecht Dürer discovered the principles of ray tracing in the early 1500s. Albrecht Dürer describes a method for painting where the painter has fixed their eye on a specific point by using a stick on a table and then the painter watches the object to be painted through a picture plane, which is a transparent surface with a grid. Then the painter paints the object to the canvas, which also has the same grid. The painter's eye can be thought to be a camera which traces rays through the picture plane into the scene. (Hofmann, 1990)

In the late 1960s and early 1970s when the computers became more common, the research towards digital raytracing began. In 1968, Arthur Appel released research about different rendering methods on shading computer models to form an image. These images were only in greyscale and the focus was to shade the images and test which objects in the scene are visible. One of his methods is an early version of ray tracing. He proposed a point by point shading method, which used rays shot from a light source to shade the scene. (Appel, 1968)

While working at the Mathematical Applications Group, Inc. (MAGI) Goldstein and Nagel (1971) proposed a system for rendering 3-d visuals using ray tracing. Their system supported building larger objects from simple shapes by combining them. The system also supported only greyscale output, but they state that color rendering would be one of the first improvement research topics. They also proposed that computer animation could be possible with their system. The system had a custom language made to configure scenes to be rendered. (Goldstein and Nagel, 1971) The improved system for rendering 3-d visuals was used to produce the Syntha Vision Sampler demo in 1974 (Computer Visuals, 1974).

In the late 1970s and early 1980s both Turner Whitted and Scott D. Roth released their research on more advanced methods for raytracing. The improved method supported global illumination information to support more accurate rendering of reflection, shadows, and refraction. (Roth, 1982; Whitted, 1980) Roth called his method "Ray Casting", but it

described a very similar process to Whitted's publication and Roth cites Whitted in his article and states that he had arrived at similar conclusions coincidentally. (Roth, 1982)

Research on ray tracing continued to gain traction throughout the 1980s and there were multiple improvements still to be made. For instance Cook, Porter, and Carpenter (1984) presented a method for rendering motion blur, depth of field, penumbras, translucency, and fuzzy reflections by using distributed ray tracing for the secondary rays after the first intersection in the scene. Kajiya and Von Herzen (1984) presented improved method for rendering volume densities (clouds, fog, flames, dust, particle systems) with ray tracing.

Similarly, there were also research on ray tracing performance improvements. Weghorst, Hooper, and Greenberg (1984) made improvements on bounding volume formation by optimizing the bounding volume formation by utilizing topological information of a hierarchically defined environment. Furthermore, they presented a preprocessor utilizing Z-buffer information for speeding up ray-intersection tree generation time. Kay and Kajiya (1986) presented better algorithm for bounding volume formation supporting arbitrarily tight bounding volume formation with efficient algorithm for bounding volume hierarchy traversal. Furthermore, Andrew S. Glassner released his widely cited book "An Introduction to Ray Tracing" in 1989 (Glassner, 1989).

Today the more advanced form of ray tracing, path tracing has replaced the older methods, since it has become feasible due to the advancement in computing power and noise reduction algorithms (Christensen and Jarosz, 2016). Path tracing was first introduced by James T. Kajiya in his paper "The Rendering Equation". He presented a Monte Carlo based solution for his rendering equation describing path tracing. In path tracing a single light ray is bounced multiple times in the scene until it hits a light source, meaning as the name implies the path of the ray is traced. Multiple rays can be path traced for a single pixel depending on the required sample count. Path tracing provides more realistic global illumination rendering and also supports other optical effects. (Kajiya, 1986)

Bi-directional path tracing was introduced by Eric P. Lafortune and Yves D. Willems in 1993. In Bi-directional path tracing rays are traced at the same time from the light source

and the eye or the camera. “All hit points on the respective particle paths are then connected using shadow rays and the appropriate contributions are added to the flux of the pixel in question” (Lafortune and Willems, 1993). The method was explored further in Eric Lafortune’s PhD thesis (Lafortune, 1995).

Noise in the path traced images remained a problem. Noise could be eliminated by using hundreds or sometimes even thousands of samples per pixel in an image, but this would be extremely expensive to compute leading to research towards noise reduction in path tracing. For example, Jensen and Christensen propose a method for reducing noise only in diffuse illumination light to prevent excessive image blurring when using noise reduction since path tracing noise is mainly generated by light, specifically indirect illumination, being reflected diffusedly. (Jensen and Christensen, 1995)

In the case of computer-generated imagery in particular animation and specifically Pixar, ray tracing was deemed too expensive to use and texture mapping was chosen to approximate more complex lightning effects. On the other hand, Reyes-architecture was designed with a “back door”, which would allow support for other rendering techniques, for example ray tracing, in the future. (Cook et al., 1987) Ray tracing usage remained very limited for the following decade and as an example it was only used for rendering reflections on a glass bottle in the form of hybrid rendering in the 1998 movie A Bug’s Life (Apodaca et al., 2000).

Realtime ray tracing research started to appear only in the late 1990s (Humphreys and Ananian, 1996) since ray tracing remained a very costly operation. For example, the research papers “An Improved Illumination Model for Shaded Display” and “Ray tracing Volume Densities” had a few ray traced examples which by modern standards are low resolution and simple scene complexity, took from little less than hour to multiple hours to render (Kajiya and Von Herzen, 1984; Whitted, 1980).

In 1996 there was a proposal for accelerating ray tracing using off the shelf Digital Signal Processor (DSP) hardware which could even work in real time depending on scene complexity (Humphreys and Ananian, 1996). In 2002 there was a proposal for custom hardware architecture for ray tracing, featuring integrated circuit with ray tracing cores on a

Peripheral Component Interconnect (PCI) extension card. In simulation it was found to be able to render Open Graphics Library (OpenGL) like scenes through ray tracing in real time. (Schmittler et al., 2002)

Timothy J. Purcell demonstrated the feasibility of running ray tracing on programmable Graphics Processing Unit (GPU) shaders in 2002. However, the limitations of the first-generation programmable shader technology meant that the demonstration had to be made by utilizing a simulation of the next generation programmable hardware. The demonstration included a shadow caster, a ray caster, Whitted style ray tracing and path tracing ray tracers. It was also mentioned that ray tracing could be used with rasterization in the form of hybrid rendering. In the paper it was also predicted that the GPU hardware would advance into a more general programming model. (Purcell et al., 2002) This prediction proved to be correct as demonstrated by unified shader model and General-purpose computing on graphics processing units (GPGPU) (Wikipedia, 2021b, 2021c).

Once GPGPU programming APIs were developed, GPU based ray tracers started to appear in research and commercial applications (Budge et al., 2008; Kirn, 2010; Trinity3DTV, 2009). NVIDIA also released a proprietary ray tracing API running on top of Compute Unified Device Architecture (CUDA) named NVIDIA Interactive Ray Tracing API (NVIRT) (Robison, 2009). NVIRT was later renamed to Optix (Bayer, 2009). In 2018 Microsoft introduced DirectX Raytracing extension to DirectX 12 API (Microsoft, 2018). Shortly after the announcement, “Reflections” demo was released demonstrating the effects of real time ray tracing using a Star Wars scene (ILMxLAB, 2018).

2.2 Overview of different types of ray tracing and DirectX Raytracing

The most basic form of ray tracing simply shoots a ray into the scene and after the first intersection goes directly to a light source (Appel, 1968). Whitted style ray tracing generates secondary rays after the ray intersection to collect global illumination information. This can be described as recursive ray tracing. (Whitted, 1980) By distributing these secondary rays according to the properties of the intersection surface more advanced graphical effects can

be rendered (Cook et al., 1984). Then there is path tracing where multiple light rays per pixel are bounced randomly in the scene to render most realistic images (Kajiya, 1986).

Microsoft DirectX Raytracing is one ray tracing API, and it is an extension to the DirectX 12 API. DXR runs only on Windows since it is part of proprietary DirectX 12 API (Microsoft, 2018). Today, cross platform Vulkan API also has very similar ray tracing extensions (Koch et al., 2020). Currently, real time ray tracing is primarily used to complement the existing rasterization-based rendering to render more accurate effects like global illumination and reflections. However, there has also been fully path traced renderers like Minecraft With RTX on DXR (Boksansky et al., 2020) and Quake II RTX on Vulkan (Panteleev and Schied, 2019).

Real time ray tracing API like DXR has the following basic working principle. First an acceleration structure(s) is/are made from the scene to make the geometry traversal more efficient. The most common acceleration structure is Bounding Volume Hierarchy (BVH) (Wyman et al., 2018). The rays are then traced by using special ray tracing shaders, which are compute like workloads. Different ray tracing shaders can be used for different objects on the scene to render different materials. After ray intersection, new rays can be generated from the intersection to render recursive ray tracing or bounce lightning (like in path tracing) effects. (Microsoft, 2018; Microsoft, GitHub, 2021) The ray tracing output will also need to be denoised since pixels cannot have too many samples to keep the process in real time (Wyman et al., 2018).

The main benefits of ray tracing are visual and in game development. Ray tracing is naturally closer to real life behavior of light and since it is done real time it can also support dynamic light sources. In addition, rays are also traced in the whole 3D scene, which means that whole scene can contribute to the final image and instead of only the viewport. These are the main factors for enhanced visuals. (Microsoft, 2018)

In game development, ray tracing can speed up and simplify the game development workflow. For example, modern rasterization rendering engines use precalculated lightning to render more realistic images. Precalculated or “baked” lightning has multiple

disadvantages: it makes the game installation bigger, it is static, which makes it harder to render dynamic effects and it needs to be "baked" each time changes are made to the scene in development, which slows down the development. Real time ray tracing can also be used for reflections rendering, meaning that both cube maps and screen spaced reflections can be removed. (Makarov and Knapik, 2021; The 4A Games Team, 2021)

2.3 Related previous research

Direct research on the perceived image quality of real-time raytracing could not be found, but there were other related research. Zibrek et al., (2019) researched "Is Photorealism Important for Perception of Expressive Virtual Humans in Virtual Reality". They had over 900 responses and also tested stylized graphics. The research did not use ray tracing since it was too expensive for real time application of Virtual Reality (VR). They found that photorealism does increase the perception of being present in an actual space and "is an important factor in interactive emotional scenarios".

Lehmuskallio et al., (2019) researched a case study with 20 professional photographers and editors as study participants, whether participants could distinguish between computer-generated imagery (CGI) renders and photographs. The study found that it was difficult for participants to distinguish between CGI renders and photographs and participants could not do it accurately. The study used landscape photographs and renders. CGI images were sourced from the internet, and it can be speculated with high confidence that the CGI images were rendered with offline (not real-time) ray tracing techniques, probably path tracing.

Huo and Yoon, (2021) researched deep learning based denoising filters for Monte Carlo path tracing. Monte Carlo path tracing produces photorealistic results but requires extensive sampling for each pixel, which is why for faster rendering low sample counts are used and image is denoised to get the final image. Huo and Yoon, (2021) compared many different deep learning based denoising filters and found it to be promising candidate for future research and usage in production renders.

3 RESEARCH METHOD

3.1 Choosing a research method

Because the objective of this work was trying to measure subjective quality, multiple opinions on the subjective image quality were needed to make any conclusions. This led to the research towards survey methods. “A survey is a system for collecting information from or about people to describe, compare, or explain their knowledge, attitudes, and behavior.” The main method is asking questions from people in the sample size and analyzing the answers. The questions can be asked by written or digital form or by for example interviewing. The questions itself should be explicit and easy to understand. The methods for asking the questions in a survey can be self-administered questionnaires, interviews, structured record reviews or structured observations. (Fink, 2003)

The questions can be open or closed. Closed questions are generally easier to analyze but open questions can provide additional insights. Responses can be divided to three groups nominal, ordinal or numerical responses depending how numerical the response values are. Survey design is divided to two main categories, experimental and descriptive or observational. Experimental has at least two groups, experimental and control. Descriptive design has no new groups and produces information on phenomena which already exists. (Fink, 2003)

People for the survey are chosen with a sampling method from the population. This subset of the population is called the sample. Sample should be chosen carefully and should contain different types of people to produce accurate data. Survey can have eligibility criteria and some people can be excluded or included from the survey. Sampling has two main categories, probability sampling and non-probability sampling. Probability sampling aims to have each eligible unit to have an equal chance to be selected to the sample while nonprobability sampling does not guarantee it. Because of this difference, non-probability sampling is usually more economical and convenient, but it is susceptible to selection bias. (Fink, 2003)

Once survey has been held and responses collected, they need to be analyzed. There are two main methods for analyzing surveys depending on the survey question types. Statistical methods and qualitive data analysis. Statistical methods can for example measure a frequency of different answers to questions and statistical methods work best on closed questions. Qualitive data analysis is used to analyze open ended questions and collect usable meaning and information from the responses. (Fink, 2003)

3.2 Survey Description.

Punter et al. (2003) gave recommendations and guidelines for conducting online surveys in their conference paper "Conducting On-line Surveys in Software Engineering". The survey should be anonymous, easy to use, which can be accomplished with click buttons and pull-down menus for example and the survey should not be too long or the respondent might not finish or even start it because of low motivation. They also recommend that all question should fit on one screen and all the questions which do not fit should be moved to their own page/section. respondents should also be motivated with something if possible. (Punter et al., 2003)

In addition to the recommendations, Punter et al. (2003) listed disadvantages of online surveys. For example, people uncomfortable with technology might not answer, online survey tools can be expensive and complex and systematic sampling method can't be used, because usually the list of whole population is not available to systematically sample from. (Punter et al., 2003). When contemplating these disadvantages, it should be noted that they were given almost 20 years ago. For example today 60% of the population use internet (DataReportal, 2021) and one does not have to make complex survey tools themselves or use expensive tools. There are free survey tools like Google Forms (Google, 2021), Microsoft Forms (Microsoft, 2021) and LUT-university offers students paid tool Webropol (Lappeenranta University of Technology, 2015; Webropol Oy, 2021). Lack of systematic sampling is also not too big of a disadvantage in this survey, since the main question is can people detect the difference in the images and did ray tracing improve the perceived image quality i.e., was it the better-looking image.

The survey consisted of a short background section and image comparisons, where the survey participants were asked to choose the better-looking image for them. Background survey asked questions about age, videogaming background and questions about ray tracing; do you know what ray tracing is/means and have you played videogames with ray traced effects. After that, there were 20 image comparisons divided into 4 sections. Each comparison had the two images on top of each other with a slider tool which could reveal the other image according to the survey participants needs. After participant had reached conclusion, which image was better, participant chose the option depicting the better-looking image. Last question was an optional open text box where respondents could provide feedback or write anything that came to their mind.

As previously said the images were taken with a native resolution of 2560 x 1440 at the maximum graphics quality settings the games supported. Video quality settings for each game can be found at (Appendix 1), system specifications for the image capture system can be found at (Appendix 2) and images for the image comparisons at (Appendix 3). Since the survey had 20 image comparisons with 4 games, each game contributed 5 image pairs for the comparisons. Scenes for the images were chosen as equitable as possible and were chosen to include indoor, outdoor, different time of day and different weather environments. However, not every game supported all these features. The order of the images in the comparisons was also randomized and each game had its own section in the survey.

Moreover, the survey was done with a link that anyone can access to improve anonymity. The background survey did not ask all but one personal question and the only personal question that was asked was age with a ten-year accuracy. This configuration for the survey was chosen to comply with the guidelines by Punter et al. (2003). The survey is not too long, it is anonymous, and it is easy to use since user needs to only click the better-looking image option, click radio buttons, or use pulldown menus in the background section.

Since the survey was distributed with a link that anyone can open and answer the survey on their own, survey is self-administered (Fink, 2003). Furthermore, the type of data is nominal since it has no numerical value and most of the questions are closed which makes it easier to use statistical methods for analyzing the survey results (Fink, 2003). The survey will use

nonprobability sampling with a mixture of convenience sampling and snowball sampling (Fink, 2003) since no name list of the populations is available for systematic sampling methods. Background section can be used to verify that the survey has had respondents from different backgrounds.

Survey sample size can be calculated with the right formula.

$$n = \mathrm{N} * \frac{\frac{\mathrm{Z}^2 * p * (1-p)}{e^2}}{[N - 1 + \frac{\mathrm{Z}^2 * p * (1-p)}{e^2}]} \quad (1)$$

In the Eq. 1 n is the survey sample size, "N = Population size, Z = Critical value of the normal distribution at the required confidence level, p = Sample proportion, e = Margin of error". (Thakur, 2019) Population size can be 2.7 billion, which is the estimated number of video gamers in the world (Wijman, 2020). Margin of error can be 10% and Z value can be 1.96, which corresponds to 95% confidence level. These values should be enough to make conclusion that is the image quality difference perceivable. Standard deviation of 0.5 can be used for Sample proportion, since it is not known (Qualtrics, 2021; Thakur, 2019). Calculating the Eq. 1 with the values gives a sample size of 96.04 ~96.

4 RESULTS

The survey was run from 4.8.2021 to 19.8.2021. Survey was shared on multiple discord servers, subject association messaging channels, appropriate work slack channels and on reddit. 912 people completed the survey and 1998 people opened it. Minimum survey sample size as calculated in Eq. 1 was reached and exceeded by almost ten times. To make the results more readable, some results feature tables where ray tracing has been shorted to "RT".

4.1 Background survey

Table 1 – *Background question 1*

How old are you?		
	n	**Percent**
0-9	0	0%
10-19	55	6.2%
20-29	474	53.6%
30-39	276	31.2%
40-49	70	7.9%
50-59	7	.8%
60-69	0	0%
70-79	0	0%
81+	3	.3%

As seen in the background survey Table 1 – Background question 1 most of the survey participants were 20-29 years old (53.6%). Rest of the respondents were 30-39 (31.2%), 40-49 (7.9%) and 10-19 (6.2%) years old. There were also other age groups, but they had too few respondents to produce any statistically significant results.

Table 2 - *Background question 2*

Have you played PC or console video games in the last 10 years?		
	n	**Percent**
I have played.	901	99.1%
I have not played.	8	.9%

Second background question asked participants whether they had played PC or console video games in the last 10 years. As seen in Table 2, 99.1% or 901 of the participants had

played video games in the last 10 years. Only 0.9% or eight respondents had not played PC or console games in the last 10 years.

Table 3 - *Background question 3*

Do you know what is ray tracing?		
	n	**Percent**
Yes, I do.	709	77.9%
I have heard the words before, but I don't know.	107	11.8%
No, I do not.	94	10.3%

Third question asked participants whether they knew what ray tracing is. From the Table 3, it can be observed that 77.9% knew in their mind what ray tracing is, 11.8% had heard about it before but did not know and 10.3% did not know.

Table 4 - *Background question 4*

Have you seen real time ray traced graphical effects in video games?		
	n	**Percent**
Yes I have.	621	68.1%
No I have not.	115	12.6%
I do not know.	176	19.3%

Last background question asked whether participants had seen real time ray traced graphical effects in video games. As seen in Table 4 68.1% had seen, 12.6% had not seen and 19.3% did not know if they had seen ray traced graphical effects in video games.

Table 5 *- How does age affect other background questions*

Respondent's age:	**20-29**		**30-39**		**40-49**	
	n	**Percent**	**n**	**Percent**	**n**	**Percent**
Do you know what is ray tracing?						
Yes, I do.	367	77.4%	221	80.7%	56	80%
I have heard the words before, but I don't know.	57	12%	30	10.9%	6	8.6%
No, I do not.	50	10.6%	23	8.4%	8	11.4%
Have you seen real time ray traced graphical effects in video games?						
Yes I have.	331	69.8%	190	68.9%	38	54.3%

No I have not.	57	12%	31	11.2%	16	22.8%
I do not know.	86	18.2%	55	19.9%	16	22.9%

Table 5 - How does age affect other background questions shows how age relates to other background questions. From the table it can be observed that background question 3: “Do you know what is ray tracing?” answers differ only by a maximum 3.5% in all age groups with enough survey participants for meaningful analysis. 4th background question “Have you seen real time ray traced graphical effects in video games?” differs further. Survey participants who were 20-29- and 30–39-year-old had almost same percentages and differed by a maximum of 1%. Survey participants aged between 40–49-year-old differed more from 20-29- or 30-39-years old participants. From the 40-49 years old participants 54.3% had seen ray traced effects in games compared to 69.8% and 68.9% from 20-29- and 30–39-year-old participants, 22.8% had not seen ray traced effects in games compared to 12% and 11.2% from 20-29- and 30–39-year-old participants and 22.9% did not know whether they had seen ray traced effects in games compared to 18.2% and 19.9% from 20-29- and 30–39-year-old participants.

4.2 Main results

After the background survey, respondents were asked to choose better looking image for them from the two images. There was a total of 20 image comparisons which were divided to 5 image comparisons per game. Answers from all backgrounds are calculated for the total result and it also contains game specific averages in addition to the total average.

Based on the research questions, null hypothesis would be that there is no difference between images with ray tracing on and ray tracing off and results would be the same or close to 50% on both images. If ray tracing was perceived to be better, images with ray tracing on should have been chosen by more than 50% of the survey participants and images with ray tracing off should have been chosen by more than 50% of the survey participants if ray tracing was not deemed to increase the perceived image quality.

Table 6 – Main image comparisons results

Choose the image that looks better to you					
	RT On (n)	**RT Off (n)**	**n total**	**RT On (%)**	**RT Off (%)**
Control					
Image Comparison 1	745	159	904	82.4%	17.6%
Image Comparison 2	686	217	903	76.0%	24.0%
Image Comparison 3	465	439	904	51.4%	48.6%
Image Comparison 4	642	264	906	70.9%	29.1%
Image Comparison 5	498	404	902	55.2%	44.8%
Game averages	**607.2**	**296.6**	**903.8**	**67.2%**	**32.8%**
Shadow of the Tomb Raider					
Image Comparison 6	192	715	907	21.2%	78.8%
Image Comparison 7	287	619	906	31.7%	68.3%
Image Comparison 8	203	704	907	22.4%	77.6%
Image Comparison 9	144	758	902	16.0%	84.0%
Image Comparison 10	530	378	908	58.4%	41.6%
Game averages	**271.2**	**634.8**	**906**	**29.9%**	**70.1%**
Cyberpunk 2077					
Image Comparison 11	592	310	902	65.6%	34.4%
Image Comparison 12	405	501	906	44.7%	55.3%
Image Comparison 13	656	248	904	72.6%	27.4%
Image Comparison 14	685	223	908	75.4%	24.6%
Image Comparison 15	553	355	908	60.9%	39.1%
Game averages	**578.2**	**327.4**	**905.6**	**63.8%**	**36.2%**
Metro Exodus					
Image Comparison 16	484	423	907	53.4%	46.6%
Image Comparison 17	261	648	909	28.7%	71.3%
Image Comparison 18	346	562	908	38.1%	61.9%
Image Comparison 19	211	697	908	23.2%	76.8%
Image Comparison 20	229	676	905	25.3%	74.7%
Game averages	**306.2**	**601.2**	**907.4**	**33.7%**	**66.3%**
	RT On (n)	**RT Off (n)**	**n total**	**RT On (%)**	**RT Off (%)**
Total averages	**440.7**	**465**	**905.7**	**48.7%**	**51.3%**

In the Table 6, results for the whole survey can be found. Overall, on average from all the games, images with ray tracing off were chosen by 51.3% of the respondents and images with ray tracing on were chosen by 48.7% of the respondents. Z test can be performed for the overall results using calculator by Infrrr (Infrrr, 2021). Null hypothesis is 0,5 sample proportion is RT On result average 0.487 and sample size is the number of average responses ~905. According to the calculator, with 5% significance level there is not sufficient evidence to reject null hypothesis and" You would expect to see a sample proportion as extreme as 0.487 43.41% of the time under the null hypothesis.".

Results can also be observed in game-by-game basis. In Control images with ray tracing on were chosen by an average of 67.2% of the survey participants and images with ray tracing off were chosen by 32.8% of the participants. Z-test provided by Infrrr can be performed for this result as well with the same null hypothesis, sample proportion of 0.672 and a sample size of ~904. According to the calculator, with 5% significance level there is sufficient evidence to reject null hypothesis and "You would expect to see a sample proportion as extreme as 0.672 < 0.0001% of the time under the null hypothesis" (Infrrr, 2021). These results mean that in Control images with ray tracing on were perceived to be better.

Next game in the Table 6 – Main image comparisons results is Shadow of the Tomb Raider. Images with ray tracing on were chosen by an average of 29.9% of the survey participants and images with ray tracing off were chosen by 70.1% of the participants. Z-test provided by Infrrr can be performed for this result as well with the same null hypothesis, sample proportion of 0.299 and a sample size of 906. According to the calculator, with 5% significance level there is sufficient evidence to reject null hypothesis and "You would expect to see a sample proportion as extreme as 0.299 < 0.0001% of the time under the null hypothesis." (Infrrr, 2021). These results mean that in Shadow of the Tomb Raider images with ray tracing off were perceived to be better.

Third game in the Table 6 – Main image comparisons results is Cyberpunk 2077. Images with ray tracing on were chosen by an average of 63.8% of the survey participants and images with ray tracing off were chosen by 36.2% of the participants. Z-test provided by Infrrr can be performed for this result as well with the same null hypothesis, sample

proportion of 0.638 and a sample size of 906. According to the calculator, with 5% significance level there is sufficient evidence to reject null hypothesis and ”You would expect to see a sample proportion as extreme as 0.638 < 0.0001% of the time under the null hypothesis.” (Infrrr, 2021). These results mean that in Cyberpunk 2077 images with ray tracing on were perceived to be better.

Last game in the Table 6 – Main image comparisons results is Metro Exodus. Images with ray tracing on were chosen by an average of 33.7% of the survey participants and images with ray tracing off were chosen by 66.3% of the participants. Z-test provided by Infrrr can be performed for this result as well with the same null hypothesis, sample proportion of 0.337 and a sample size of ~907. According to the calculator, with 5% significance level there is sufficient evidence to reject null hypothesis and ”You would expect to see a sample proportion as extreme as 0.337 < 0.0001% of the time under the null hypothesis.” (Infrrr, 2021). These results mean that in Metro Exodus images with ray tracing off were perceived to be better.

4.3 Result based on background question 1

Background question 1 asked participants how old they were. Detailed results for every selectable age group can be found in the Table 1. Age groups 20-29, 30-39 and 40-49 were taken in for the analysis and others were discarded from analysis because of the low number of respondents. The results are presented in the following Table 7 - Result based on background question 1.

Table 7 *- Result based on background question 1*

Choose the image that looks better to you									
Respondent's age:	**20-29**			**30-39**			**40-49**		
	n total	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**
Control									
Img. Comp. 1	469	84.0%	16.0%	274	82.5%	17.5%	69	69.6%	30.4%
Img. Comp. 2	469	77.6%	22.4%	274	73.4%	26.6%	68	69.1%	30.9%
Img. Comp. 3	472	50.6%	49.4%	272	52.9%	47.1%	68	51.5%	48.5%
Img. Comp. 4	473	73.8%	26.2%	272	71.7%	28.3%	69	58.0%	42.0%
Img. Comp. 5	470	54.5%	45.5%	272	53.7%	46.3%	68	57.4%	42.6%
Game averages	**470.6**	**68.1%**	**31.9%**	**272.8**	**66.8%**	**33.2%**	**68.4**	**61.1%**	**38.9%**
Shadow of the Tomb Raider									
Img. Comp. 6	473	20.9%	79.1%	273	19.4%	80.6%	70	24.3%	75.7%
Img. Comp. 7	472	29.9%	70.1%	274	30.7%	69.3%	68	44.1%	55.9%
Img. Comp. 8	473	19.0%	81.0%	273	25.6%	74.4%	69	31.9%	68.1%
Img. Comp. 9	471	16.3%	83.7%	270	14.8%	85.2%	69	18.8%	81.2%
Img. Comp. 10	474	54.9%	45.1%	273	65.6%	34.4%	69	62.3%	37.7%
Game averages	**472.6**	**28.2%**	**71.8%**	**272.6**	**31.2%**	**68.8%**	**69**	**36.3%**	**63.7%**
Cyberpunk 2077									
Img. Comp. 11	472	70.6%	29.4%	272	62.9%	37.1%	67	46.3%	53.7%
Img. Comp. 12	473	43.8%	56.2%	271	43.2%	56.8%	70	51.4%	48.6%
Img. Comp. 13	473	71.2%	28.8%	270	76.7%	23.3%	69	76.8%	23.2%
Img. Comp. 14	474	75.1%	24.9%	273	79.5%	20.5%	69	68.1%	31.9%
Img. Comp. 15	472	60.8%	39.2%	274	60.6%	39.4%	70	52.9%	47.1%
Game averages	**472.8**	**64.3%**	**35.7%**	**272**	**64.6%**	**35.4%**	**69**	**59.1%**	**40.9%**
Metro Exodus									
Img. Comp. 16	471	55.0%	45.0%	274	54.0%	46.0%	70	35.7%	64.3%
Img. Comp. 17	473	25.2%	74.8%	274	32.8%	67.2%	70	37.1%	62.9%
Img. Comp. 18	473	37.0%	63.0%	273	35.5%	64.5%	70	50.0%	50.0%
Img. Comp. 19	472	18.9%	81.1%	274	28.1%	71.9%	70	40.0%	60.0%
Img. Comp. 20	471	22.9%	77.1%	273	25.6%	74.4%	69	33.3%	66.7%
Game averages	**472**	**31.8%**	**68.2%**	**273.6**	**35.2%**	**64.8%**	**69.8**	**39.2%**	**60.8%**
	n total	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**
Total averages	472	48.1%	51.9%	273	49.5%	50.5%	69	48.9%	51.1%

By observing the results from Table 7, it can be recognized that survey participant age does not change the total averages more than a 1.4%. It can be concluded that all the age groups are within margin of error. Margin of error can be calculated for each age group by using a calculator by SurveySparrow (2021). Margin of error can be calculated by using the overall and game specific ray tracing on results as sample proportion, n total as sample size and confidence level of 95. For age group 20-29 margin of error is 4-5%, for age group 30-39 margin of error is 5-6% and for age group 40-49 it is 12%.

In the game specific results, it can be observed that age groups 20-29 and 30-39 differ only by a maximum of 3% in all game averages, which is well within margin of error. There seems to be quite large difference between age group 40-49 and the other age groups taken into Table 7. The results differ by a maximum of 8%, which is nevertheless within margin of error since the survey participant amount in age group 40-49 was relatively low. From these results it can be concluded that age does not affect the perceived image quality of real-time ray tracing in video games.

4.4 Result based on background question 3

Background question asked participants whether they knew what ray tracing is. Detailed results for every answer option can be found in Table 3. To reiterate the results, 77.9% believed they knew what ray tracing is, 11.8% had heard about it before but did not believe to know and 10.3% did not know. The results based on the background question 3 are presented in the following Table 8 - Result based on background question 3. To make it easier to discuss the results, group who knew what ray tracing is, was named group 3a, group who did not know, but had heard about it was named group 3b and group who did not know was named group 3c.

***Table 8** - Result based on background question 3*

Choose the image that looks better to you									
Do you know what is ray tracing	**3a) I know what is ray tracing**			**3b) I have heard, but I Don't**			**3c) No, I do not.**		
	n total	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**
Control									
Img. Comp. 1	703	87.8%	12.2%	105	70.5%	29.5%	94	57.4%	42.6%
Img. Comp. 2	702	78.5%	21.5%	106	71.7%	28.3%	93	61.3%	38.7%
Img. Comp. 3	702	51.7%	48.3%	106	50.0%	50.0%	94	51.1%	48.9%
Img. Comp. 4	705	73.2%	26.8%	106	66.0%	34.0%	93	58.1%	41.9%
Img. Comp. 5	702	55.3%	44.7%	105	56.2%	43.8%	93	54.8%	45.2%
Game averages	**702.8**	**69.3%**	**30.7%**	**105.6**	**62.9%**	**37.1%**	**93.4**	**56.5%**	**43.5%**
Shadow of the Tomb Raider									
Img. Comp. 6	704	19.3%	80.7%	107	31.8%	68.2%	94	22.3%	77.7%
Img. Comp. 7	703	30.0%	70.0%	107	32.7%	67.3%	94	42.6%	57.4%
Img. Comp. 8	704	21.9%	78.1%	107	24.3%	75.7%	94	24.5%	75.5%
Img. Comp. 9	700	17.9%	82.1%	106	7.5%	92.5%	94	11.7%	88.3%
Img. Comp. 10	706	59.6%	40.4%	106	50.9%	49.1%	94	56.4%	43.6%
Game averages	**703.4**	**29.7%**	**70.3%**	**106.6**	**29.4%**	**70.6%**	**94**	**31.5%**	**68.5%**
Cyberpunk 2077									
Img. Comp. 11	701	68.6%	31.4%	106	55.7%	44.3%	93	54.8%	45.2%
Img. Comp. 12	704	44.9%	55.1%	107	42.1%	57.9%	93	47.3%	52.7%
Img. Comp. 13	701	77.9%	22.1%	107	57.0%	43.0%	94	50.0%	50.0%
Img. Comp. 14	705	78.6%	21.4%	107	62.6%	37.4%	94	66.0%	34.0%
Img. Comp. 15	705	61.8%	38.2%	107	57.0%	43.0%	94	57.4%	42.6%
Game averages	**703.2**	**66.4%**	**33.6%**	**106.8**	**54.9%**	**45.1%**	**93.6**	**55.1%**	**44.9%**
Metro Exodus									
Img. Comp. 16	704	55.4%	44.6%	107	49.5%	50.5%	94	42.6%	57.4%
Img. Comp. 17	706	30.9%	69.1%	107	22.4%	77.6%	94	20.2%	79.8%
Img. Comp. 18	705	35.5%	64.5%	107	44.9%	55.1%	94	51.1%	48.9%
Img. Comp. 19	705	21.7%	78.3%	107	30.8%	69.2%	94	25.5%	74.5%
Img. Comp. 20	705	26.7%	73.3%	105	16.2%	83.8%	93	25.8%	74.2%
Game averages	**705**	**34.0%**	**66.0%**	**106.6**	**32.8%**	**67.2%**	**93.8**	**33.0%**	**67.0%**
	n total	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**
Total averages	**704**	**49.9%**	**50.1%**	**106**	**45.0%**	**55.0%**	**94**	**44.0%**	**56.0%**

From Table 8 it can be observed that survey participant knowledge about ray tracing affects the total averages by 5.9%. To check if the result is valid, margin of error can be calculated for each group by using a calculator by SurveySparrow (2021). Margin of error can be calculated by using the overall and game specific ray tracing on results as sample proportion, n total as sample size and confidence level of 95. For group 3a margin of error is 3-4%, for group 3b margin of error is 9% and for group 3c it is 9-10%. It can be concluded that total results are still within margin of error and margin of error is high due to the low number of respondents for the specific answer option.

In the game specific results, it can be observed that game specific total averages in Shadow of the Tomb raider and Metro Exodus differ only by a maximum of 2.1% between groups, which is well within margin of error. However, in Control and Cyberpunk 2077, differences between groups are more significant. In Control groups 3a and 3c differ by a maximum of 12,8% which is not within margin of error anymore while groups 3a and 3b are still within margin of error because they differed by 6.4%. In Cyberpunk 2077 group 3a differs from groups 3b and 3c by 11.3-11.5% which also is not within margin of error. Thus, there seems to be limited support to conclude that people who don't know what ray tracing is and occasionally people who are not sure what ray tracing is, do not perceive the ray traced images to be better as often as others who do know what ray tracing is.

4.5 Result based on background question 4

Background question 4 asked participants whether they had seen ray traced graphical effects in video games. Detailed results for every answer option can be found in the Table 4. To reiterate the results, 68.1% had seen ray traced in video games before, 19.3% did not know and 12.6% had not seen ray tracing in video games before. The results based on the background question 4 are presented in the Table 9 - Result based on background question 4. To make it easier to discuss the results, group who had seen ray tracing in video games was named group 4a, group who did not know was named group 4b and group that had not seen ray tracing in video games was named group 4c.

***Table 9** - Result based on background question 4*

Choose the image that looks better to you									
Have you seen real time ray traced graphical effects in video games?	**4a) Yes I have.**			**4b) I do not know.**			**4c) No I have not.**		
	n total	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**
Control									
Img. Comp. 1	617	89.3%	10.7%	173	62.4%	37.6%	114	75.4%	24.6%
Img. Comp. 2	617	79.3%	20.7%	173	64.2%	35.8%	113	76.1%	23.9%
Img. Comp. 3	619	52.5%	47.5%	172	48.3%	51.7%	113	50.4%	49.6%
Img. Comp. 4	620	75.6%	24.4%	172	57.6%	42.4%	114	64.9%	35.1%
Img. Comp. 5	617	56.4%	43.6%	171	56.1%	43.9%	114	47.4%	52.6%
Game averages	**618**	**70.6%**	**29.4%**	**172.2**	**57.7%**	**42.3%**	**113.6**	**62.8%**	**37.2%**
Shadow of the Tomb Raider									
Img. Comp. 6	618	19.4%	80.6%	174	28.2%	71.8%	115	20.0%	80.0%
Img. Comp. 7	617	29.5%	70.5%	175	39.4%	60.6%	114	31.6%	68.4%
Img. Comp. 8	619	21.5%	78.5%	175	26.3%	73.7%	113	21.2%	78.8%
Img. Comp. 9	616	16.7%	83.3%	172	12.2%	87.8%	114	17.5%	82.5%
Img. Comp. 10	619	58.5%	41.5%	174	55.2%	44.8%	115	62.6%	37.4%
Game averages	**617.8**	**29.1%**	**70.9%**	**174**	**32.3%**	**67.7%**	**114.2**	**30.6%**	**69.4%**
Cyberpunk 2077									
Img. Comp. 11	619	69.5%	30.5%	171	54.4%	45.6%	112	61.6%	38.4%
Img. Comp. 12	618	44.0%	56.0%	173	46.2%	53.8%	115	46.1%	53.9%
Img. Comp. 13	617	77.1%	22.9%	173	55.5%	44.5%	114	73.7%	26.3%
Img. Comp. 14	620	78.4%	21.6%	174	66.7%	33.3%	114	72.8%	27.2%
Img. Comp. 15	620	61.3%	38.7%	174	56.3%	43.7%	114	65.8%	34.2%
Game averages	**618.8**	**66.1%**	**33.9%**	**173**	**55.8%**	**44.2%**	**113.8**	**64.0%**	**36.0%**
Metro Exodus									
Img. Comp. 16	617	56.1%	43.9%	175	42.3%	57.7%	115	55.7%	44.3%
Img. Comp. 17	619	30.7%	69.3%	175	22.3%	77.7%	115	27.8%	72.2%
Img. Comp. 18	618	35.4%	64.6%	175	46.3%	53.7%	115	40.0%	60.0%
Img. Comp. 19	618	21.7%	78.3%	175	29.7%	70.3%	115	21.7%	78.3%
Img. Comp. 20	618	26.1%	73.9%	173	24.3%	75.7%	114	22.8%	77.2%
Game averages	**618**	**34.0%**	**66.0%**	**174.6**	**33.0%**	**67.0%**	**114.8**	**33.6%**	**66.4%**
	n total	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**	**n total**	**RT On (%)**	**RT Off (%)**
Total averages	**618**	**49.9%**	**50.1%**	**173**	**44.7%**	**55.3%**	**114**	**47.8%**	**52.2%**

From Table 9 it can be observed that survey participant's previous experience about ray tracing in video games affects the total averages by a maximum of 5.2%. To check if the result is valid, margin of error can be calculated for each group by using a calculator by SurveySparrow (2021). Margin of error can be calculated by using the overall and game specific ray tracing on results as sample proportion, n total as sample size and confidence level of 95. For group 4a margin of error is 3%, for group 4b margin of error is 7% and for group 4c it is 8-9%. It can be concluded that total results are still within margin of error.

In the game specific results, it can be observed that game specific total averages in Shadow of the Tomb raider and Metro Exodus differ only by a maximum of 3.2% between groups which is well within margin of error. However, in Control and Cyberpunk 2077 differences between groups are more significant. In Control total averages, groups 4a and 4b differ by 12.9% which is not within margin of error anymore and groups 4a and 4c are still scarcely within margin of error. In Cyberpunk 2077 total averages, group 4a differs from group 4b by 10.3% which is not within margin of error, while groups 4a and 4c differ by 2.1% which is within margin of error. Hence there seems to be limited support to conclude that people who don't know whether they have seen ray tracing in video games, do not perceive the ray traced images to be better as often as others who have seen ray tracing in video games before.

4.6 Open feedback analysis

Last question in the survey was completely optional text box where participants could write any feedback they wanted to give or anything else that came up in their mind during the survey. From 912 participants, 163 answered this question. The answers can be generally dived into feedback and general comments. The answers were analyzed mainly focusing on the feedback, since it is important for potential future surveys.

Main feedback for the survey were that some of the images were not from the exact same camera angle, comparison from video could have been easier and more valid, survey did not work well enough on some mobile devices and there was at least one suggestion that side by side image comparison would have been easier than the slider tool used in the survey. There were also multiple suggestions that "I am not sure which image is better" or "The images

look the same to me" should have been an answer option. These options were not in the survey because with adequate number of survey participants, image comparisons which looked the same to respondents or which respondents could not decide which is better, should have results close to 50% on both images.

It is a valid criticism, that not all the images were from the exact same camera angle, and this was due to limitations caused by some of the game's photo modes, which made it difficult to take images from the exact same camera angle. Still, this did not appear to cause complications for the survey's results, since results showed clear preference for one of the two answer options in games (Shadow of the Tomb Raider and Metro Exodus) which had the biggest problems with different camera angles. This should still be a consideration in future surveys and remedied if possible.

There were many suggestions to use video as comparison method instead of still images inside a slider tool since it should make it easier to detect the difference and it should reflect the act of playing the game better. This is a valid suggestion and should be considered for future surveys. In this survey videos were not used since still images should be enough to let the participant make conclusion on which image was perceived to be better and still image comparison should be faster than making the participant watch a video. As discovered by Punter et al. (2003), it is important to not make the survey too long which could affect the respondents motivation to finish the survey negatively.

Suggestion for using side by side image comparison instead of a slider tool, which could reveal one image on top of the other was tested during the development of the survey. This was however rejected, because of technical reasons related to the survey platform. If two images would have been aligned side by side, both images would have been excessively minuscule, and comparison was deemed to be too difficult to perform this way. This led to the search for a slider tool, which would enable rendering of two images in the space of one and let the survey participant to compare the images by sliding the images on top of each other.

Survey received mixed feedback about mobile device support. Some answers said that the survey worked on mobile devices, while others said that it did not work at all or they almost finished the survey, but the survey did not work to the end on their device. In future surveys mobile device support should be tested comprehensively or respondents should be warned that the survey may not work on mobile devices and your mileage may vary.

Other feedback for the survey were more general feedback, which did not directly or at all contain suggestions on how to improve the survey. Most of the general feedback were good luck or you'll do great wishes for the writer of the thesis and a few interesting research topic comments were also encountered. There were also a few comments which could be classified as spam, which is understandable since this was anonymous and publicly accessible survey. Additionally other commenters wished they had ray tracing capable graphics card, and some wondered what the ecological impact of real time ray tracing will be since they hypothesized that real time ray tracing would further increase the power consumption of graphics cards.

The survey did also reach professional game developers and hobbyist or professional photographers of whom some wrote detailed observations or thoughts about ray tracing or lightning conditions in real life or in video games. For example, there were recollections on how lightning has been implemented in video games before ray tracing and deliberation on does specific visual element in the image make it better when considered as an example from photographers' point of view. For instance, in photography not all reflections or light sources are wanted. There was also deep deliberation on, were the lightning done in the selected games before ray tracing was added to the game, which could mean that artist had already optimized the scenes for non-ray traced lightning and ray tracing version might not have been made with the same sincerity.

5 DISCUSSION

By analyzing only, the total averages, wrong conclusions could be made, since total averages for the whole survey show only negligible support for images with ray tracing off as seen in Table 6. There seems to be large difference on the perceived image quality depending on where ray tracing was applied. In Control and Cyberpunk 2077 ray traced images were on average clearly perceived to be better, while in Shadow of the Tomb Raider and Metro Exodus images without ray tracing were on average clearly perceived to be better.

Research question 1 can be answered with these results. Research question one asked ”Is real time ray tracing in video games perceivable?” and according to these results it is. As previously stated, on game specific averages there was clear preference to images with or without ray tracing. Thus, it can be concluded that ray tracing assuredly is perceivable in video games.

Research question 2 can too be answered with these results. Research question two asked ”Did real time ray traced effects in video games improve the perceived image quality?” and according to these results, it depends on the ray tracing implementation and even on the individual scene. Nonetheless by examining multiple image comparisons from same game, it can be determined on game specific accuracy, did real time ray tracing improve the perceived image quality.

In the case of Control and Cyberpunk 2077 ray tracing is used for mainly reflections and global illumination information. Cyberpunk 2077 supports full global illumination for sunlight and a more limited version for other light sources as in Control (Burnes, 2019b; Makarov and Knapik, 2021). According to the results, these effects in these games seem to be perceived to be better. Environments in those games also have many surfaces where reflections can be rendered. It could be proposed that specific ray traced effects, reflections, are easier to detect from the image comparisons and are also perceived to be better.

In the case of Shadow of the Tomb Raider, ray tracing is only used for shadows (Burnes, 2019a) and by looking at the total game averages, images with ray tracing off were perceived to be better. Thus, it can be proposed that ray tracing only for shadows, is not perceived to

increase image quality. In Metro Exodus ray tracing is used for all lightning in the form of global illumination and there are also ray traced reflections, although the environments of Metro Exodus do not have many places where reflections could be rendered (Burnes, 2021). Game specific total averages for Metro Exodus showed strong support for non-ray traced images. Thus, it can be proposed that global illumination alone with no clear reflections does not make perceived image quality better.

It was also found that there is minor support to propose that whether person knows what ray tracing is or if person has seen ray traced effects in games affects the perceived quality of ray traced images. In chapter 4.4 it was found that that people who don't know what ray tracing is and occasionally people who are not sure what ray tracing is, do not perceive the ray traced images to be better as often as others who do know what ray tracing is. Similar findings were made in chapter 4.5 where it was found that people who don't know whether they have seen ray tracing in video games, do not perceive the ray traced images to be better as often as others who have seen or have not seen ray tracing in video games before.

Since specific ray tracing implementations were perceived to be better, it could be proposed that specific ray tracing features could be used to increase photorealism in VR, which was found to be important by Zibrek et al. (2019). It could also be speculated that as ray tracing implementations mature and further advancements in hardware are made, CGI quality images could be rendered in real time and they would be hard to identify from real photographs as discovered by Lehmuskallio et al. (2019) in the case of offline CGI renders.

One might speculate that AI based solutions for denoising (Huo and Yoon, 2021) could also be used for real time ray tracing in the future as they are already in use with proprietary libraries (NVIDIA, 2017). It should also be noted that even though ray traced global illumination effects were not perceived to be better in this thesis, ray traced global illumination is probably still going to be used as it makes game development iteration faster, since scene lightning can be calculated in real time (Makarov and Knapik, 2021; The 4A Games Team, 2021).

When contemplating these results, it should be noted that this survey had many limitations. First, the survey was quite short and had only five image comparisons per game, which cannot be enough evidence to make irrefutable conclusions. Also, even though the scenes for image comparisons were tried to be chosen as equitable as possible, the fact is that scenes in the image comparisons affect the results in the survey greatly. Finally real time ray tracing is still relatively new technology in the field of video games, and it could be speculated that video games in the future take better advantage of it.

Perceived image quality of real time ray tracing still needs further research. It should be researched with bigger survey data or by different research methods. In the case of human based measuring, i.e. in a survey, videos could be used instead of still images. In addition, as technology and ray tracing implementations get more mature the research topic should be revisited to examine if conclusions as proposed in this thesis have changed.

6 CONCLUSIONS

Ray tracing has been developed since the 1960s and now with the advancements in computer graphics, can be performed in real time. There are already video games supporting real time ray tracing. Perceived image quality of ray tracing in some of these games was researched in this thesis using a survey method. The survey ran for two weeks, and 912 answers were collected.

First research question in the thesis was “Is real time ray tracing in video games perceivable?” and it was found that survey participants generally had a strong preference to one of the answer options which implies ray tracing was perceivable. Second research question was “Did real time ray traced effects in video games improve the perceived image quality?” and it was found that it depends on the ray tracing implementation. Games with clear ray traced reflections were perceived to be better than games with ray traced shadows or focus on the global illumination. Furthermore, there seems to be minor support to propose that people who do not know what ray tracing is or have not seen ray tracing in video games before, display a small preference to non-ray traced images when people who know what ray tracing is and have seen ray tracing before show preference to ray traced images. Yet this observation does not apply when people with ray tracing background indicate preference for non-ray traced images, whereupon all groups generally favor non ray traced images at equal rate.

Limitations in the thesis were focus on the image quality only, still images were used for image comparisons, not all the images were from the exact same camera angle and relatively low amount of image comparisons. The research topic should be researched further with different methods, larger amount of survey questions and as technology makes further advancements it should be researched, has the findings changed when applied to newer video games.

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APPENDIX 1. Graphical settings for image comparison video games

Control Video Settings		
	Ray tracing On	Ray tracing Off
Game version	1.13	1.13
Display mode	Borderless	Borderless
Resolution	2560x1440	2560x1440
Render Resolution	2560x1440	2560x1440
NVIDIA DLSS	Off	Off
Vsync	Off	Off
Brightness	60	60
Quality Preset	Custom	Custom
Far Object Detail (LOD)	High	High
Texture Resolution	Ultra	Ultra
Texture Filtering	High	High
Shadow Resolution	High	High
Shadow Filtering	Medium	Medium
Volumetric Lightning	High	High
Foliage Quality	Medium	Medium
SSAO	On	On
Screen Space Reflections Quality	Disabled with RT	High
Global Reflections	High	High
MSAA	4X	4X
Film Grain	Off	Off
Motion Blur	Off	Off
Ray Tracing Preset	High	Off
Ray Traced Reflections	On	Off
Ray Traced Transparent Reflections	On	Off
Ray Traced Indirect Diffuse Lightning	On	Off
Ray Traced Contact Shadows	On	Off
Ray Trace Debris	On	Off

(continues)

APPENDIX 1. (continues)

Shadow of the Tomb Raider Video Settings		
	Ray tracing On	Ray tracing Off
Game version	1.0.298	1.0.298
DirectX 12	On	On
Resolution	2560x1440	
NVIDIA RTX DLSS	Off	Off
Fullscreen	On	On
Exclusive Fullscreen	Off	Off
AMD FidelityFX CAS	Off	Off
Vsync	Off	Off
Anti-Aliasing	TAA	TAA
Stereoscopic	Off	Off
Preset	Custom	Custom
Texture Quality	Ultra	Ultra
Texture Filtering	16x Anisotropic	16x Anisotropic
Shadow Quality	Disabled with RT	Ultra
Ray Traced Shadow Quality	Ultra	Off
Ambient Occlusion	HBAO+	HBAO+
Depth of Field	High	High
Level of Detail	Ultra	Ultra
Tessellation	On	On
Bloom	On	On
Motion Blur	Off	Off
Screen Space Reflections	High	High
Screen Space Contact Shadows	High	High
Pure Hair	Normal	Normal
Volumetric Lightning	On	On
Lens Flares	On	On
Screen Effects	On	On

(continues)

APPENDIX 1. (continues)

Cyberpunk 2077 Video Settings		
	Ray tracing On	Ray tracing Off
Game version	1.23	1.23
Vsync	Off	Off
Windowed Mode	Fullscreen	Fullscreen
Resolution	2560x1440	2560x1440
HDR Mode	None	None
Quick Preset	Custom	Custom
Texture Quality	High	High
Field of View	100	100
Film Grain	Off	Off
Chromatic Aberration	Off	Off
Depth of Field	Off	Off
Lens Flare	Off	Off
Motion Blur	Off	Off
Contact Shadows	On	On
Improved Facial Lightning Geometry	On	On
Anisotropy	16	16
Local Shadow Mesh Quality	High	High
Local Shadow Quality	High	High
Cascaded Shadows Range	High	High
Cascaded Shadows Resolution	High	High
Distant Shadows Resolution	High	High
Volumetric Fog Resolution	Ultra	Ultra
Volumetric Cloud Quality	Ultra	Ultra
Max Dynamic Decals	Ultra	Ultra
Screen Space Reflections Quality	Psycho	Psycho
Subsurface Scattering Quality	High	High
Ambient Occlusion	High	High
Color Precision	High	High
Mirror Quality	High	High
Level of Detail (LOD)	High	High
Ray Tracing	On	Off
Ray-Traced Reflections	On	Off
Ray-Traced Shadows	On	Off
Ray-Traced Lightning	Psycho	Off
DLSS	Off	Off
Dynamic FidelityFX CAS	Off	Off
Static FidelityFX Cas	Off	Off

(continues)

APPENDIX 1. (continues)

Metro Exodus Enhanced Edition Video Settings	
Game version	v2.0.0.1
Resolution	2560x1440
Aspect ratio	16:09
Quality	Extreme
Vsync	Off
Motion blur	Low
Ray tracing	Ultra
NVIDIA DLSS	Off
Reflections	Hybrid*
VRS	Off
Hairworks	On
Advanced PhysX	On
Tessellation	On
Shading rate	1.0x

*Hybrid reflections contains ray tracing enhanced reflections.

Metro Exodus Video Settings	
Game version	v1.0.0.7
Resolution	2560x1440
Aspect ratio	16:09
Quality	Extreme
Vsync	Off
Motion blur	Low
NVIDIA RTX	Off
Ray tracing	Off
NVIDIA DLSS	Off
Hairworks	On
Advanced PhysX	On
Tessellation	On
Texture Filtering	AF 16X
Shading rate	1.0x

APPENDIX 2. Test system specification

Test System Specification Table	
Processor:	AMD Ryzen 7 3700X
Motherboard:	Asus ROG CROSSHAIR VII HERO (WI-FI)
Memory:	2x16GB DDR4 3600 (16-19-16-36)
Graphics Card	Asus ROG-Strix-RTX2080TI-A11G-Gaming
Cooling:	Noctua NH-D15
Storage:	Samsung SSD 970 EVO Plus 1TB Samsung SSD 860 EVO 2TB
Power Supply:	660-Watt Seasonic Platinum Modular 80+ Platinum
Case:	Fractal Design Define R5 Black
Operating System:	Windows 10 Pro 20H2
Drivers:	NVIDIA 460.79 WHQL

APPENDIX 3. Image comparison images

Image comparison images where uploaded to Zenodo: Kauria Aku. (2021). Perceived image quality of real time ray tracing in video games survey image archive (Version 1). Zenodo. https://doi.org/10.5281/zenodo.5347012

Copy of the original survey can be found at: https://link.webropolsurveys.com/S/AB9152FCA2F65505

It is not known how long it will be active, so it is recommended to use Zenodo-link.