

University of West Bohemia
Faculty of Mechanical Engineering

Study program: N2031 Mechanical engineering
Field of study: 2301V007 Industrial Engineering and Management

DISSERTATION

The effect of training in Virtual Reality on hand movement precision

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Academic year 2020/2021

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I declare that I have prepared this dissertation independently, using the professional literature and sources listed in the list that are part of this dissertation.

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Special thanks

I would like to express my deepest thanks to all members of the Department of Industrial Engineering and Management of the University of West Bohemia in Pilsen who helped me in my journey to accomplish the writing of this dissertation work. I'm extremely grateful to supervisor doc. Ing. Pavel Kopeček, CSc., for his professional guidance led me through the whole process from start to finish, and also a lot of patience that was of key importance to get the job done. I would also like to extend my deepest gratitude to consulting specialist doc. Ing. Petr Hořejší, Ph.D., who helped with his professional insight into the field and gave valuable advice and ideas that made it possible to enrich the work with different aspects that would otherwise not come to fruition. I'm also grateful to a colleague of mine Ing. Marek Bureš, Ph.D., who I had pleasure working with and who gave his valuable support, constructive criticism and practical suggestions throughout the time that helped improve this work in great measure.

ANOTAČNÍ LIST DISERTAČNÍ PRÁCE

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PRACOVIŠTĚ VEDOUcíHO	ZČU – FST – KPV	
DRUH PRÁCE	Disertační práce	
NÁZEV PRÁCE	Vliv tréninku ve virtuální realitě na přesnost pohybu rukou	

Fakulta: Strojní
 Katedra: Průmyslové inženýrství a management
 Rok odevzdání: 2021

Počet stránek (A4 a ekvivalentů A4)

Celkem	122		Textová část	122		Grafická část	0
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STRUČNÝ POPIS ZAMĚŘENÍ, TÉMA, CÍL POZNATKY A PŘÍNOSY	Hlavním bodem práce bylo použití VR k zjištění jeho výhod při nácviku konkrétně přesnosti pohybu rukou / rukama a poté vyhodnocení jeho účinku jak pro VR, tak pro přenos do RW výsledků. Za tímto účelem byla vytvořena simulace VR, byl také připraven RW materiál a pro cca. jeden měsíc se školení zúčastnilo 16 účastníků. Výsledky naznačují pozitivní výsledek ve většině aspektech VR, ale pouze částečný přenos tréninkových výhod do RW. Důvody, proč tomu tak může být, jsou popsány v práci a jsou uvedeny návrhy na duplikování studie s různými proměnnými, aby se pokusily dosáhnout různých výsledku, pokud je to možné.
KLÍČOVÁ SLOVA	Virtuální Realita, Přesnost, Trénink, Simulace, Experiment.

SUMMARY OF DISSERTATION SHEET

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TYPE OF WORK	Dissertation	
TITLE OF THE WORK	The effect of training in Virtual Reality on hand movement precision	

Faculty: Mechanical Engineering
 Department: Industrial Engineering and Management
 Submitted in: 2021

Number of pages (A4 a eq. A4)

Totally	122	Text part	122	Graphical part	0
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BRIEF DESCRIPTION of the TOPIC, GOAL AND RESULTS	The main point of the work was to use VR to find out its benefits on training specifically precision of hand/hands movement and then evaluate its effect both for VR and transfer to RW results. For that purpose, a VR simulation was created, RW material was also prepared and for approx. one month, 16 participants were taking part in the training. Results suggest positive outcome in most aspects in VR but only partial transfer of training benefits to RW. The reasons why this could be so are described in the work and suggestions are given to duplicate the study with different variables to try and achieve different results if possible.
KEY WORDS	Virtual Reality, Precision, Accuracy, Training, Simulation, Experiment.

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List of abbreviations

<i>AI</i>	Artificial Intelligence
<i>AR</i>	Augmented Reality
<i>BCI</i>	Brain Computer Interface
<i>BGE</i>	Blender Game Engine
<i>CAVE</i>	Cave Automatic Virtual Environment
<i>CVE</i>	Collaborative Virtual Environment
<i>CS</i>	Cyber Sickness
<i>CAD</i>	Computer Aided Design
<i>3D/2D</i>	Three-Dimensional/Two-Dimensional
<i>EEG</i>	Electroencephalography
<i>FOV</i>	Field of View
<i>HFA</i>	High Functioning Autism
<i>HMD</i>	Head Mounted Display
<i>LCD</i>	Liquid-Crystal Display
<i>LED</i>	Light-Emitting Diode
<i>MS</i>	Motion Sickness
<i>MR</i>	Mixed Reality
<i>OLED</i>	Organic Light-Emitting Diode
<i>PRO</i>	Professional
<i>PC</i>	Personal Computer
<i>RPG</i>	Role Playing Game
<i>RW</i>	<i>Real World</i>
<i>SSQ</i>	Simulation Sickness Questionnaire
<i>UE</i>	Unreal Engine
<i>USB</i>	Universal Serial Bus
<i>VR</i>	Virtual Reality
<i>VRE</i>	Virtual Reality Environment
<i>VE</i>	Virtual Environment
<i>VTE</i>	Virtual Training Environment
<i>VRLE</i>	Virtual Reality Learning Environment
<i>VIMS</i>	Virtually Induced Motion Sickness
<i>OHL</i>	One Hand Line
<i>OHC</i>	One Hand Circle
<i>OHS</i>	One Hand Sinewave
<i>BHL</i>	Both Hands Line
<i>BHC</i>	Both Hands Circle
<i>BHS</i>	Both Hands Sinewave

Introduction

The purpose of this work was to evaluate the effects of routine training in Virtual Reality simulation. The training was conducted both, in Virtual Reality and Real World. RW tests took place twice, on the first day of the experiment and on the last, whereas Virtual Reality training took seven repetitions. As some work in industry/manufacturing (and not only) requires manual routine/specific hand movement actions, it is important to know if Virtual training can be used to help workers quickly and safely adapt to new working scenarios.

Some part of the work also covers the topic of Cyber Sickness, which is one of the problems that VR faces. Thanks to the research done on this subject, it was possible to create a VR simulation and design it in such a way, that would allow minimize any potential CS difficulties during the tests.

For VR simulation high quality 3D models were used, similar in size and look to those in the RW. To prepare those models as well as the experiment simulation itself, various 3D software tools were used, such as Blender and Unity3D game Engine. A simple scenario was presented to participants, where they could perform the tests right away, without learning how Virtual Reality environment and devices work. VR environment was a simple room with minimal visual noise, to reduce potential Cyber Sickness while the experiment in the RW took place in the office room in usual conditions.

Overall 16 young participants took part in the experiment procedure, which lasted around one month. The participants were attending the test sessions twice a week, and those sessions were taking no more than 20 minutes on average. This time requirement allowed participants to perform all the tasks and not get fatigued at the same time.

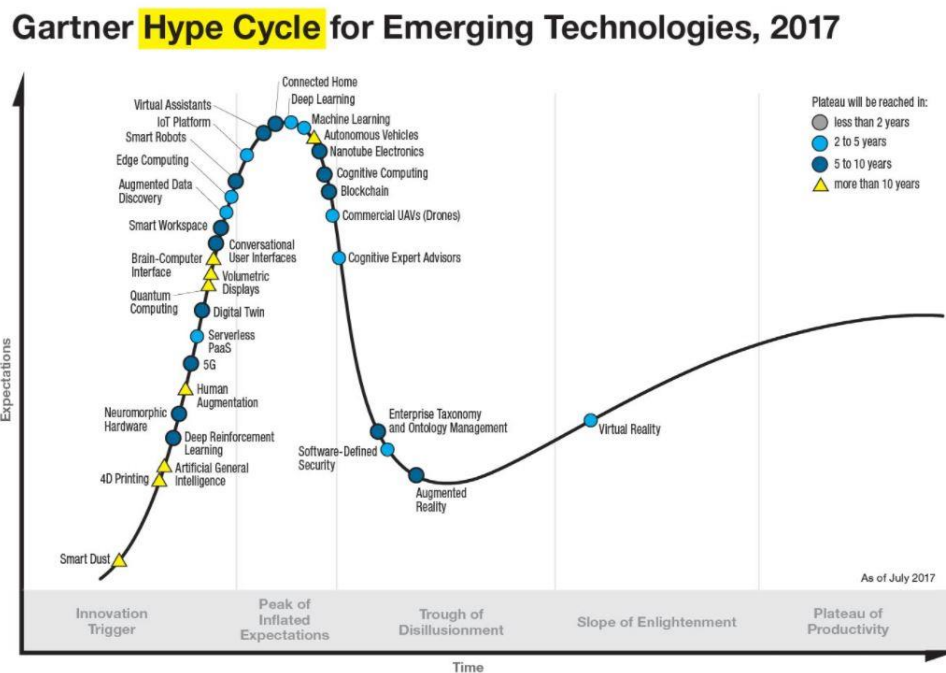
Participants had to repeat specific movements of an object form (line, circle, sinus) both in VR and RW with one hand as well as two hands while equipped with specific tools. Later, once all the data is gathered, comes the analysis of the actual distance between the drawn objects and required location of those objects in the scenes, using math calculations of distances between points. After exporting and analyzing the data in Excel, the results suggest positive progressive effect of VR training specifically in VR context, but only partial effect on RW results. Thus, suggesting that in order to achieve the transfer of skills from VR to RW, more factors need to be taken into consideration. The results and reasons of those outcomes are discussed later in this work in discussion sections.

1 Characteristics of solved topic

Nowadays Virtual Reality technology is used in different areas of life for various purposes. Virtual reality is the most immersive type of reality technology which creates an artificial environment to inhabit. This immersive, computer-generated environment blocks out the sensory input from the outside world; and uses the visual and auditory cues to make the virtual world seem quite real. It is immersive because of its simulated setting that manages to trick your unconscious mind to start treating this illusion as real.

It is used in training, education, psychology, etc. Studies carried out in this field suggest that training in virtual environments can replace the hours spent in the RW. This comes very handy when training in real environments is impossible due to high risk or cost. Although this technology is still in its infancy, it is confidently gaining momentum and in the near future, many people will be dealing with VR on a frequent basis, be it watching movies in VR, playing games or improving skills for their profession.

The image (Fig. 1) presents Gartner's Hype Cycle, which tracks the stages of emerging technologies, starting from early innovation to their wide adoption. As it is shown, VR is at Slope of Enlightenment, which means that more and more organizations understand the benefits this technology can bring, thus funding many new projects.



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Gartner.

Fig. 1 Gartner Hype Cycle [1]

One of the topics that frequently comes up about Virtual Reality is Cyber Sickness (CS). This is something similar to Motion Sickness (MS), as the symptoms are similar, but one is caused in virtual world, another in the real one. Various applications and suggestions try to measure and combat those symptoms of CS and most of the experiments are carried out in some kind of simulators, such as flying simulator, driving simulator, surgical simulator, etc. Alternatively, another variant of such environment is maze.

This subject of CS is very important and will be discussed in separate chapter further in the work. Thanks to performed research on CS, the process of creating a VR simulation and experimentation phase itself were considered accordingly. And as expected, after removing/reducing every known factor (time limitations before getting sick, unnecessary movements in VR, visual noise, etc.) that could somehow cause CS problems during the tests, no difficulties occurred during the whole experimentation phase from start to finish.

The main point of the work is to perform an experiment in VR/RW and find out if precision/accuracy and time factors change and if so by how much and in which direction.

It is important to note, although, from theoretical standpoint there is some difference between the terms of accuracy and precision, in this work, they are used interchangeably with the same context.

1.1 Accuracy and Precision [1]

Accuracy and precision are alike only in the fact that they both refer to the quality of measurement, but they are very different indicators of measurement. Accuracy is the degree of closeness to true value. Precision is the degree to which an instrument or process will repeat the same value. In other words, accuracy is the degree of veracity while precision is the degree of reproducibility.

What does accuracy mean?

If a measurement is accurate, it means that it agrees closely with the accepted standard for that measurement. For example, if we estimate a project's size to x and the actual size of the finished project is equal to or very close to x , then it is accurate, but it might not be precise. The closer a system's measurements to the accepted value, the more accurate the system is considered to be.

What does precision mean?

A measurement that is precise means that it agrees with other measures of the same thing. In the sense of project scoping, let's take an estimation of workload as an example. If we estimate the size of several projects and they, in the end, are all close to or equal to what we predicted, then we can start to get a sense of the precision of our estimates. But first and foremost, each project needs to be as accurate as possible.

As noted prior, despite the differences, this work uses these two terms with the same context.

1.2 Professions that require high detail of performance [2]

People with good hand-eye coordination handily use their visual senses to assess a situation, then use their hands to execute the given task. Good dexterity, attention to fine details and depth perception also play vital roles in your level of hand-eye coordination. Those with good hand-eye coordination can find these skills quite beneficial in certain manual dexterity jobs and lines of work.

1.2.1 Manual Dexterity Jobs in Production

Some professions require high precision of hand to eye coordination more than others. These types of jobs don't necessarily look the same but they share one major requirement, which is precision of work performance.

This work focused on just one way of measuring precision measurements of hand movements using one specific type of simulation but the types of training simulations for each different job should definitely have their own variants/styles of simulation.

Some of the examples of such professions that require high hand to eye coordination/precision are brought below.

Physicians and Surgeons

Physicians and surgeons are responsible for diagnosing and treating patients with injuries and illnesses. Good hand-to-eye coordination is important while both visually assessing a patient's condition and providing treatment. Good dexterity is vital for surgeons who work with precision instruments and sharp tools, such as scalpels and needles. In some cases, good hand-to-eye coordination can mean the difference between life and death. For a surgeon working in a tightly compacted area, one slip of the knife could sever a major artery.

Airline and Commercial Pilots

Good hand-to-eye coordination is vital for pilots who must operate controls, monitor systems, assess weather conditions and navigate the aircraft. In addition to manual dexterity, pilots must also have excellent depth perception so they can not only clearly see objects, but also determine the distance between them. They need good eyesight to read instruments, then react to changing conditions. Commercial pilots may specialize in areas such as crop dusting, firefighting, rescue operations, aerial photography and charter flights.

Automotive Service Technicians and Mechanics

Automotive service technicians and mechanics have significant manual dexterity skills which they use to inspect, repair and maintain motor vehicles. Both automotive service technicians and mechanics spend a lot of time working with their hands. Job duties include inspecting, disassembling, assembling and repairing parts, as well as testing systems. Having a steady hand, good eyesight, and dexterity are all vital when using hand tools, and taking apart engines

and transmissions. Utilizing sophisticated diagnostic equipment and computers is also a regular part of the job.

Metal and Wood Workers

When it comes to metal working, its operations include: Cutting, Folding, Welding, Machining, Punching, Shearing, Stamping, Casting.

A metal worker monitors, adjusts, and controls various basic or elaborate machines to cut, cast, or mold metals. The dexterity levels required for this type of job is pretty high as the risk of injury could be significant, depending on the type of machine a worker is working on. This occupation is infinitely important to create countless parts used for building small items like automobile tools or large parts to build a bridge.

Metal workers usually use metal working hand tools which require high precision of movements to use them. Metalworking hand tools are hand tools that are used in the metalworking field. Hand tools are powered solely by the operator.

Woodworking is the activity or skill of making items from wood, and includes cabinet making (cabinetry and furniture), wood carving, joinery, carpentry, and woodturning. In some ways, wood working is similar to metal working as it shares some of the processes, such as cutting, carving, smoothing, etc.

2 The Overview of Virtual Reality

This chapter presents the research on the topic of VR. Starting with the History of VR, following the comparison between Virtual Reality and Augmented Reality (AR) technologies and several case studies on them. Then the benefits of VR and AR are explained. Important aspect of VR called 'Sense of Presence/Immersion' is described, which is very important as it directly affects the way subjects feel in Virtual Environments (VEs). Furthermore, various positive outcomes of using VR in different areas/applications are presented. Lastly, some negative aspects of VR technology are described, which will then lead to the next chapter – Cyber Sickness.

2.1 History of Virtual Reality

The first traces of Virtual Reality came from the world of science fiction. Stanley G. Weinbaum's 1935 short story "Pygmalion's Spectacles" is recognized as one of the first works of science fiction that explores VR. It describes a google-based VR system with holographic recording of fictional experiences including smell and touch [4]. Furthermore, if we go back to the early 1950s, it was the time when Morton Heilig developed the Sensorama, a multisensory simulator with wind and scent production, vibratory sensation and 3D display [5][6].



Fig. 2 Morton Heilig's Sensorama [7]

It was an arcade-style theatre cabinet that could simulate all the senses, not just sight and sound. It included stereo speakers, stereoscopic 3D display, fans, vibrating chair and smell generators, that would allow nearly full immersion inside the short films that Morton Heilig edited himself. Next Heilig's invention was the Tele sphere Mask in 1960, which was the first example of a head-mounted display. The headset provided stereoscopic 3D and wide vision with stereo sound but was non-interactive and without motion tracking. In 1987 Jaron Lanier, founder of the visual programming lab through his company developed a range of virtual

reality devices, which include the Data glove and the Eye Phone head mounted display. These inventions led to major breakthroughs in developments in this area.

Around that time, in 1968, Ivan Sutherland, a leader in computer graphics developed the "Sword of Damocles", one of the first Head Mounted Displays (HMDs), which overlaid computer graphics onto the RW, today known as augmented/mixed reality systems [5][6].



Fig. 3 The Sword of Damocles by Ivan Sutherland [8]

NASA also had big influence on the evolution of VR technology as they worked on developing HMDs for their astronauts [6]. Throughout 1990s we began to see VR devices to which the public had access. In 1993 SEGA announced the Sega VR headset for the Sega Genesis Console, that prototype glasses supported head tracking, stereo sound and LCD screens in the visor. Next was Nintendo Virtual Boy in 1995, a 3D gaming console that was promised to be the first ever-portable console that would display true 3D graphics. Despite low prices, it was a commercial failure due to lack of colors in graphics and lack of software support. As to the modern times, in 2010, the first Oculus Rift prototype saw the light, in 2014, Sony announced PlayStation VR, a VR headset for PlayStation 4 video game console, and Google announced Cardboard, a do-it-yourself stereoscopic viewer for smartphones. In 2015, HTC and Valve Corporation announced the VR headset with controllers.

2.2 Virtual Reality vs Augmented Reality

There is also another technology called Augmented Reality (AR), which is not the same as VR. The difference between those is that AR simulates artificial objects in the real environment, while VR creates a simulated environment to inhabit. VR and AR technologies can be categorized as immersive VR, non-immersive VR, AR and mixed reality [9].

Both technologies have great potential in almost every industry, and each of them has different objectives. Although in some cases they can be used for the same cause/idea, the results will always be different, for example, assembly of objects can be shown with both technologies, but in different ways. Both will bring benefits if used as intended.



Fig. 4 Virtual Reality vs Augmented Reality [10]

In immersive VR, the RW is completely occluded from the field of view (FOV) and the user has a stronger feeling of presence in that VE [9]. Examples of immersive VR are Oculus Rift and HTC Vive. In non-immersive VR, the user remains aware that they are viewing a VE [9]. The examples of non-immersive VR systems are Samsung Gear VR and Google Cardboard. In AR, the virtual objects are like holograms, transparent in the RW in daylight, whereas in mixed reality (MR), virtual images appear solid to the user in daylight [9]. Examples of AR are Meta and DAQRI. Examples of MR are Microsoft HoloLens and Magic Leap. The integration of these technologies in different practices (i.e., clinical practice) and commercial success is dependent on various variables, which are: affordability, flexibility, wear ability, usability, immersion, mobility and vision [9][11]. VR and AR have the potential to enhance the learning environment in comparison to traditional learning. It is mentioned that 3D learning can increase learner's motivation/engagement, improve spatial knowledge representation, improve contextualization of learning and develop superior technical skills [12].

2.3 Benefits of Virtual Reality

In the modern time Virtual Reality (VR), technology became very popular and is used in many different areas such as entertainment, military, healthcare, education, engineering etc. VR is a simulated environment that is created with computer technology and presented to the user in such a way, that user starts to feel like in real environment. A Simulation is a model of a RW where user has the ability to interact with the environment [13]. Simulations are helpful and useful as they provide realistic context in which individuals can explore, experiment and see immediate results as they create models of their own or try theories on the modelled concept [14]. Depending on the amount of senses simulated in VR, such as vision, hearing, touch, balance, even smell, the immersion level in the artificial world can vary.

Thanks to modern technological advance of computer hardware and software, it became possible to incorporate 3D Virtual Reality in innovative applications of teaching, training, and learning [15][16][17]. Virtual environment or virtual world is a computer-generated 3D representation of real or fictional environments. A user can interact in such an environment

independently in the same pace; one would experience events in the RW [18]. VR has the ability to support realistic and immersive simulation and enables transfer of taught skills in VR into real contexts as well as provide multi-user, embodied and interactive active learning [19]. VR is believed to be a promising tool for training and complex problem solving, which requires weighing multiple variables and situational decision making [19][20][21][22].

2.4 Benefits of Augmented Reality

Looking at Gartner's Hype Cycle (Fig. 1), we can see that AR technology repeats the path of VR and now is at the stage of "Through of Disillusionment", which means that interest in AR has decreased, as experiments and implementations fail to deliver, but as long as providers of this technology improve their products, investments will continue and in the near future, AR will be used widely as well.

AR technology has been used in various fields, such as manufacturing, gaming, robotics, medicine, machine repair, flying simulators, entertainment and education [23]. This technology connects computer world and human world [24], allowing users to see computer generated virtual objects supplemented to a RW [25][26], giving an illusion to the user as if the virtual rendering is part of its real environment.

Studies show that AR has the ability to enhance the teaching and learning experience [25][27]. Comparing student learning with and without AR, it was found that AR improved collaboration and long-term memory retention, increased motivation and content understanding [28]. Furthermore, a study showed that an assembly with AR instructions were much more effective than paper instructions [29]. Overall, AR proved to be effective when used in lab experiments [30][31][32], mathematics and geometry [33][34][35], geography and ecology [36][37][38][39] and scientific issues [40][41][42].

2.5 Virtual Reality and Augmented Reality Practical Use Cases

VR as well as AR can both be used in many different scenarios for specific purposes. Sometimes the combination of these two can be used as well, but in some cases, each by itself might be the only option to use. First, it is important to set a goal that needs to be achieved, and then it will be easy to understand which technology to use to reach that goal. Below, several case studies from each technology are introduced, that show the capabilities of these tools.

2.5.1 VR Cases

EON Reality Aviation Maintenance Trainer [43]

Pilots and ground crew have to check every part of an aircraft each time before takeoff for safety reasons. As training would require impractical number of planes to inspect in order to acquire necessary skills, a simulation could be used instead. Thus, EON Reality decided to develop a realistic and detailed immersive VR pre-flight and maintenance simulator. The trainee would approach the plain in that VRE and make the same manipulation as in real environment, but at the same time having the opportunity to do it as many times as needed

and when needed, with no cost. This VR case allowed trainees to learn faster, remember longer and make better decisions.

Assembled Electronic Solutions (AES) product concept simulation in VR [44]

With the help of CASIM2 project, which is a collaborative project with 3 partners: University of Birmingham, the Manufacturing Technology Centre (MTC), Rolls-Royce and also partly funded by the European Regional Development Fund, AES decided to test the concept product in a simulated environment using CAVE VR Suite at the MTC. Using CAD model, AES was able to precisely visualize and analyze the 3D prototype, including modelling of ultra-sonic functionality on early stages of design process without actually creating expensive physical scale models. The CAVE is also a great tool for collaborative work, which allows better communication with clients in order to display project and make the right changes. This resulted in reduced process time, significant cost and timesavings.

Audi Virtual Training Car [45]

Audi equipped its Audi A4 model with a VR Oculus headset for the driver, for driving simulation in realistic scenarios to show how the emergency braking assistant Audi pre-sense city works. This can help demonstrate the effectiveness of the Audi assistance systems to customers convincingly and in rich detail. With the headset, the driver can experience the intervention by the emergency braking assistant in a very realistic simulation in the test car that is actually driving, while the driver watches simulated driving scenarios.

The main idea is to allow the salespeople to experience the effectiveness of Audi pre-sense city under realistic conditions so they can authentically communicate the systems' advantages to the customers. After training roughly 5000 participants, Audi is now upgrading the simulation to portray additional assistance functions in a wide range of driving situations.

Temasek Polytechnik and EON Reality solution for enhanced training in VR [46]

To overcome lack of student attention in class, the cost required to provide physical equipment, limited pieces of equipment to train on as well as improve academic performance, learning and motivation in Aerospace Engineering, Temasek Polytechnik and EON Reality partnered to create a series of applications designed to enhance training for aerospace students.

These applications can increase student engagement through interaction, improve knowledge retention and enhance overall learning experience. Virtual Reality Gas Turbine Engine (GTE) allows students to learn the fundamentals of GTE operations and operations that are more advanced. Furthermore, students have the possibility to access these modules anytime and anywhere, allowing students to practice on their own schedule, revisit subject matter and clarify concepts outside a lecture setting through VR, which would be impossible if physical engines were needed.

2.5.2 AR Cases

Boeing solution for reducing production time using AR [47]

The Boeing Company is an American corporation that designs and manufactures airplanes, rockets, rotorcraft and satellites worldwide. The complex task of wiring, the length of which is around 130 miles for every new Boeing 747-8 Freighter, made the company decide to use smart glasses and the Skylight platform from Upskill to develop an application that would help reduce production time. Until that moment, technicians used “phone books” full of diagrams to do their work, as well as laptops, but had the same problem of constant look-away interruptions as workers got directions and had to cross-check diagrams and schematics. After beginning a pilot program and replacing those laptops and phone books of papers, Boeing cut its wiring production time by 25% and reduced error rates effectively to zero.

Land Rover showrooms for new vehicles using AR [48]

With the announcement of a new model “New Discovery Sport”, Land Rover has unveiled innovative AR technology to support its launch and bridge the gap between announcement and vehicle arriving in showrooms. Customers can visit Land Rover retailers to find out more about the new model. Using Durovis Dive headset, which contains an iPhone 5S preloaded with an app, visitors will be able to look at an activation marker on the floor after which they will be immersed in a detailed photo-realistic 3D model of the new car. Customers will be able to walk around the vehicle, to get a full sense of the size and scale of the car. At specific points, different animations will appear, demonstrating new features. When arriving to driver’s door, the door opens and a user can have a look inside the vehicle as well.

IKEA Place AR Application [49]

The world’s largest furniture retailer recently made available the new AR application that will let people experience and experiment with IKEA virtual products in their homes. Using these applications, clients will be able to see in true scale the appearance of different virtual models (sofas, armchairs, coffee tables, etc.) in their homes. It will help try out different products, colors, styles - simply make buying decisions more unsophisticated. In order to use this application, users will need to have iOS 11.

2.6 Sense of Presence/Immersion in VR

Sense of presence is defined as “a state of consciousness”, the psychological sense of being in the VE [50][51][52][53][54]. It is noted by various authors that sense of presence reduces social distance between learners and improves skill acquisition and knowledge transfer by permitting multiple perspectives and situated performance [22][53][55][56]. It was noted that sense of presence in virtual learning environments increases learner’s motivation and engagement in learning process and potentially learning outcomes, by enabling focused and realistic interactions with learning materials and activities [57][58][59].

A similar concept related to sense of presence is immersion – degree of “the subjective impression that one is participating in a comprehensive, realistic experience” and “the semi-

voluntary experience of being transported into an alternate context for an extended duration” [21][60]. Previous research suggests that higher levels of immersion are associated with higher levels of presence [53][61][62]. The psychological perception of being inside a virtual world is known as presence [63]. Among many factors affecting user’s feeling of presence, one is the content of the virtual world [64]. Immersive experience can be created via the sensory and environmental fidelity in 3D VE, engagement with virtual objects and activities, and emotional experience activated through realistic scenarios in virtual world [22]. VR has been implemented as a promising learning tool both for formal and informal learning contexts in a variety of educational activities [17][65]. It was also reported that immersive VR could provide a VE to simulate teaching challenges and thus act as a pedagogical tool for the collaborative/cooperative teaching/training program [66].

It has been noted that haptic feedback increases the sense of presence in VEs [67]. Haptic feedback is usually described as incorporating both kinesthetic (coming from muscles, joints and tendons) and tactile (coming from nerve receptors in the skin) information [68][69][70]. Haptic feedback can be very useful and have positive effect on task performance. For instance, it is said that tele operators benefit from haptic feedback when manipulating remote objects [71][72]. Various studies have been conducted within collaborative virtual environments (CVE) to find out how haptic feedback influences performance. In one study a person was asked to hand over an object to another person within a CVE, which resulted in faster task completion, higher sense of presence and participant’s belief in superiority of such actions, compared to those without haptic feedback [73][74]. Similar study that also used CVE, where two people collaboratively had to move a virtual ring along a virtual wire without touching a wire, showed that performance was significantly better using haptic feedback and sense of presence was increased as well [75][76][77]. Lastly, another study within a CVE in which two participants had to lift a virtual box together, suggests that haptic feedback evokes a greater sense of co-presence [78].

VR is characterized with representational fidelity, learner interaction, support of psychological sense of presence, immersion and multi-user environment for embodied interactions [12]. Prior studies note that immersive VR learning environment also enhances situated learning through simulation of realistic contexts and providing contextualized learning activities [79][80][81], thus improving performance transfer from learning environment to the real-world setting [82][83]. Nowadays flight simulators are used widely both for entertainment and training purposes, as they provide realistic environments to the extent that flight training hours can be replaced by corresponding simulator hours [84]. Several unique affordances of an immersive VR learning environment include: (I) virtual agents/avatars that act like real personalized and interactive learning partners that sometimes cannot be easily arranged in a real-world, (II) unlimited variations of 3D VR environments, and (III) possibility to transfer sensory representations to improve virtual learning actions[22][79].

2.7 Virtual Reality in training and education

VR simulations prove to be effective not only for educational purposes but also in situations, where human lives can be at risk or it could be hard and costly to check with a high precision, whether some changes are worthwhile to introduce to the real environment.

Interactivity is the most fundamental aspect in learning. It is mentioned that both, providing a learning environment and interaction with PCs may promote a better understanding of things [85]. Despite many studies in this area, there is still controversy about the real effects of VR on learning and cognition, but preliminary results indicate that the use of VR can increase learning performance [86], facilitate usability and enhance interaction [87], help to reconstruct and navigate through non-existent environments [88], help disabled learners with knowledge accessibility [89], etc. Serious games tend to be used often in formal education and with sufficient support are shown to be highly motivational and effective in learning complex tasks [90][91].

VR Technology can be of great use for emergency service personnel such as police, ambulance, fire fighters and army, as they have to be prepared for various operations at all times, thus continuous training is crucial for their success and security. But training in real environment is sometimes impossible, due to cost or complexity and the good alternative that comes handy is virtual training environment, which allows training for such complex collaborative tasks [92][93]. Thus, if the situation does not predispose for real life training practice due to danger, cost or effort, emergency service personnel can profit from virtual training to train for scenarios in real environment [94]. Often VR training is the only option that is possible [95]. Some studies suggest that virtual training environments can be used successfully for training specific skills, such as spatial perception, route learning or the reactions in certain emergency situations [94][96][97][98]. There is also evidence that 3D presentation of visual information in virtual environment promotes better collaborative decision-making compared to 2D presentation [99]. Virtual Training Environments (VTEs) keep learners motivated and engaged in learning process [100] and have also been proven to be very useful in pedagogical contexts [101]. VTEs allow wide variety of learning styles and support collaborative knowledge building and reflective thinking [101] as well as experiential learning [102]. To enhance the effects of training, adequate instructions can be adapted to pre-training, during-training and post-training phase [103]. Some authors suggest debriefings during and/or after a training session, where individuals reflect on the training, to foster transfer of such complex team tasks [104]. It is also mentioned that virtual team performance resembles team performance in reality [105]. Team performance is dependent on whether procedures are established within a team, how conflicts are resolved and if collaboration occurs [105].

Many authors highlight the need for realistic virtual training, where training simulation holds information overload and pressure during an operation, especially when the training is meant for crisis management [106]. It is important for the emotional state to be invoked during training and it should be as close to emotional state trainees would confront during and actual operation as possible, because of the strong effect of emotions on decision-making, learning and problem-solving [106]. Similar research suggests that virtual training for action forces such as military or fire fighters should provide first-person experiences and situated learning without time for conscious thoughts, but with the possibility of gaining knowledge [95]. The levels of immersion or presence in the virtual environment seem to be crucial for the development of first-person experiences and the knowledge gained is then "direct, personal, subjective and often tacit" and can be transferred to the RW [107]. It is noted that first-person perspective can improve learning in virtual environment [108]. In addition, it is suggested that mental representations acquired in a VTE might be similar or close to representations of real objects [96]. Experiences that individuals build in virtual environments can then become

recallable and used successfully in the RW [109]. Some authors mention that in order to maximize the transfer of skills from virtual training to reality, the context of the virtual training task should be as close and similar to the task in reality as possible [110]. In addition, structuring virtual learning according to psychological factors along with fidelity to real equipment plays big role in knowledge transfer [111]. As virtual simulations or games allow exploration of realistic scenarios, learning and performance can be enhanced [104]. There is a promising potential of VTEs in educational curriculum [112].

It is important to note that assessing the level of relevance and value of training to trainees to find out the usefulness of training content to them is crucial [113], as this kind of information can help predict the transfer of knowledge and the impact of training on job performance [114]. Learning measures alone cannot be used to show whether gained knowledge will be applied, but a positive attitude towards the training makes it more probable that transfer will be successful [114]. If trainees accept training and see personal relevance for their job, they will have higher motivation to learn [115].

One of the most common types of VR training are flight simulations. Pilots train in VR simulation, in order prepare themselves for various scenarios that can occur in real life, such as bad weather, broken engine etc. Professional pilots train mostly in special cockpits built for immersive/realistic training. This study suggests that using a VR headset and a couple of handles for training, the experimental results show the feasibility of the UAV flight training system [116].

One other benefit of VR training is cost efficiency. Wherever it's required to prototype a product for visualization, train staff in difficult scenarios or any other task that could cost a company money, VR seems to be a very good option to avoid high costs. A study even suggests that VR training (HTC Vive) even yielded better results in learning efficiency of a bimanual gearbox assembly task compared to traditional learning as well as using Google Cardboard [117].

2.8 Virtual Reality for people suffering social impairments

One of the uses of VR can be helping those with autism to lessen social anxiety and frustration and improve academic and social skills. Individuals with autism suffer impairment in social functions which leads to difficulties in social interactions, communication and emotion recognition [118][119]. Despite their good academic performance, social communication barrier can lead to frustration [119][120] and this in turn can worsen academic performance due to low self-esteem, even though their intellectual abilities are average or above that [121]. VR can be used for social training and provide safe and unlimited contexts to practice social scenarios that are most commonly encountered in our everyday life [122][123][124] and as a result, social anxiety can be reduced [125]. Additionally, it is noted that computer technology is often highly motivating and rewarding for those suffering with ASD (Autism Spectrum Disorder) and especially children with HFA (High Functioning Autism) [126]. Various studies suggest that VR environments can help individuals with autism disorders improve social problem solving and social understanding (i. e., knowing when to initiate conversation, what other person feels, choosing appropriate seat) [127][128][130].

A research suggests using biofeedback adaptive VR environment to reduce pain and anxiety of patients who have/are going to undergo surgical operation. The research focuses on utilizing affective computing techniques to develop and deliver an adaptive virtual reality experience based on the user's physiological response to reduce pain and anxiety and as the early results suggest, VR as a great potential in the management of pain and anxiety during pre and post-operative care [129].

2.9 Virtual Reality and Medicine

The fact that VR systems can allow users to explore immersive 3D environments from any location at any time could have a profound impact on science education [131]. VR allows exploration of hidden phenomena, distant locations and manipulation of otherwise immutable objects [132]. For instance, VR gives the possibility for medical students to explore delicate internal organs that would otherwise require cadaver (corpse) dissection [133]. VR can be a promising replacement to cadaver dissection for learning anatomy and practicing surgical procedures [134]. Direct manipulation of objects in virtual environment may promote development of “embodied”, multi-modal mental representations of represented objects [135]. Embodied learning allows students to practice via simulations or mental imagery when there is no physical opportunity [135]. The ability to imagine and mentally manipulate anatomical structures is a crucial skill that medical students must have [136]. VR and computer models represent a good alternative for medical students and other professionals to practice their skills when access to patients or cadavers is limited [137].

A VR multi-user tool/serious game is a great opportunity to collaborate/cooperate with other medical staff to prepare for critical cases such as anaphylactic shock, which as stated is rare to eventually occur within a regular curricular term of vocational training. This way, paramedics can perform training any time, with anyone and mostly everywhere, where there are capable devices present [138].

In the events of the year 2020, when COVID-19 broke out and many of the usual activities that humans got used to became very difficult to do, dangerous or simply impossible, studies suggest VR has use cases for this situation that can help people in many ways. VR proves to be an effective tool that can help handle this situation by spreading awareness, improving communication between people, and help in physical rehabilitation and pain management of an infected patient during the treatment proces [139].

VR can even be used to train how to properly keep hand hygiene to prevent healthcare-associated infections. The study suggests that when feedback about microorganism transmission and infectious outcomes are introduced visually, this enhances associative learning and increasing intrinsic motivation to perform hand hygiene [140].

As lockdowns and social isolation were introduced to reduce the amount of infected people, one of the most common tasks that people perform now is online shopping. This saves a lot of time as well as protects from getting infected. A research suggests that VR can be effectively used for online shopping with addition to product visualization and immersion [141].

Another common activity during the pandemic became online teaching and education. Although live training is almost always better compared to online training, it was suggested that VR can be used for such cases as the immersion from VR could improve overall activity and efficiency of the training/education. The research in progress, explores some of the issues in the use of virtual reality in the context of remote and virtual laboratories and discusses some of the challenges and opportunities of porting existing practical labs and simulations into a virtual reality environment [142].

2.10 Studying motivation and Virtual Reality

Many games have been developed using 3D images with which users need to interact in order to learn certain tasks. Interaction and immersion are the key elements when it comes to making learning process more enjoyable. 3D animations can be used to teach students various procedures and mechanisms for carrying out specific tasks [143]. Furthermore, some VR environments can support multiple user collaboration/cooperation, where students learn together and from each other [144]. This is a good way to increase their motivation for studying. It was noted, that text-based learning content often leads to boredom and can prevent students from understanding the subject [145]. It is also noted that in many different contexts video is a more effective form of learning compared to books [146].

Student motivation is vital as it has a direct influence on his/her desire and dedication to accomplish specific task [147]. Motivation is a major cognitive factor influencing learning and thus the better-motivated students can learn with higher efficiency [148]. There is a research suggesting that 3D full immersive Virtual Reality Learning Environments (VRLE) will increase learner 's interest and motivation towards learning process more compared to 2D animated environments [149].

It has been argued by some authors that emotions play big role in learning. Some suggest that different emotional states induce different kinds of thinking [150], and others mention that a slight positive mood effects thinking in a positive way as well, thus leading towards greater creativity and flexibility in problem solving [151]. Thanks to today 's knowledge and technologies, VR environments can be created and filled with various interesting elements, making it motivational and fun for students to explore, thus making the learning process more fruitful.

2.11 Reaction Time Experiments

Measurement of reaction times is one of the fundamental concepts in cognitive psychology. Typically, reaction time (RT) is measured as the time between the onset of a stimulus or response cue and a participant's response (often a button presses, but may be vocal, motor responses, or other behaviors). Comparing RTs between different tasks (or different conditions of the same task) can reveal the time required for processing or performing some part of the task.

You also have "reflexes" too. Reflexes and reactions, while seeming similar, are quite different. Reflexes are involuntary, used to protect the body, and are faster than a reaction. Reflexes are usually a negative feedback loop and act to help return the body to its normal functioning

stability, or homeostasis. The classic example of a reflex is one you have seen at your doctor's office: the patellar reflex.

According to [152] there are three kinds of reaction time experiments. In simple reaction time experiments, there is only one stimulus and one response, where participants respond as quickly as possible anytime a stimulus appears. With this type, no other mental processing (e.g., discrimination, response type) is required. In recognition reaction time experiments, more commonly called the go/no-go task, there is some stimuli that should be responded to (the 'memory set'), and others that should get not response (the 'distractor set'). The last one is choice reaction time experiments, in which participants see two different stimuli, and each stimulus is associated with a particular response, a user must give a response that corresponds to the stimulus, such as pressing a key corresponding to a letter if the letter appears on the screen. Note that this is different than go/no-go tasks because it requires responses to all stimuli, not just one.

Reaction time has been widely studied, as its practical implications may be of great consequence, e.g. a slower than normal reaction time while driving can have grave results. Many factors have been shown to affect reaction times, including age, gender, physical fitness, fatigue, distraction, alcohol, personality type, intelligence, drugs, illness, etc. [152]. Multiple studies have shown the positive effect of training in VR on reaction times, such as marksmanship [153], karate-kumite [154], baseball [155] etc. It was also noted that reaction times can vary depending on distance and size of the object [156], emotional state of a person [157] and shooter-gaming experience [158].

Some of the best examples of using RTs to quantify the speed of mental processing are the Sternberg mental scanning experiments [159]. In those studies, participants were shown a sequence of numbers one at a time. Then, they were shown a single digit and asked whether that digit appeared in the study sequence. Sternberg found that RTs increased as the length of the study sequence increased: the more numbers the participants had to remember, the longer it took to determine if the test digit had appeared in the sequence. In fact, the increase was linear. For every additional digit in the study sequence, RTs increased by about 40 ms. Thus, Sternberg argued, the time to "scan" one element in short-term memory was about 40 ms, and the increased RTs with larger sets were directly attributable to the participant "scanning" through more numbers in their short-term memory. A similar example of the use of RTs comes from mental rotation experiments [160], in which the time required to mentally rotate a stimulus is linearly related to the amount of rotation performed.

2.12 The Obstacles of Virtual Reality

There are various obstacles to VR 's success, some of those are: cost of devices, quality of content, potential risk for eyesight, VR sickness etc. Here we shall focus our attention on the issue of Cyber Sickness (CS). CS occurs during the exposure to a VR and it's symptoms are very similar to the ones of Motion Sickness (MS). The symptoms include headache, nausea, vomiting, fatigue, postural instability, disorientation, etc. This sickness is a natural reaction to an unnatural environment and it happens due to the mismatch between sensory inputs. When those inputs do not agree, that is when you start feeling sick. In traditional MS the mismatch occurs because you feel movement in your muscles and your inner ear, but you don't see it,

like it happens on the ship. With CS, it is the opposite, you see movement on the screen, but you don't feel it. Below in the chapter is a research on the Cyber Sickness, which was used to plan the future of the experiment in order to mitigate any potential difficulties caused by this issue.

3 Cyber Sickness – Symptoms and Causes

This chapter focuses mainly on Cyber Sickness research, its effects and outcomes. When working with Virtual Reality applications, it is important to understand, that, eventually, the problem of Cyber Sickness arises, and it is very helpful to know where it's coming from and how to combat it if possible. As Cyber Sickness is very similar to Motion Sickness, there are many aspects that they share, thus making it possible to lend some solutions from much known Motion Sickness to Cyber Sickness. In addition, this topic could be very important for Augmented Reality technology as well. Although, not much has been done on that front and it cannot be said for sure what kind of connection there is between Cyber Sickness and Augmented Reality, there is still a chance, that solutions provided for Virtual Reality could potentially help with possible Cyber Sickness problems in Augmented Reality as well. The research provided below was used as basis in order to prepare the training simulation in such a way, that would minimize potential Cyber Sickness problems during the training process.

There are a wide variety of research conducted in the field of VR on simulator sickness: simulator sickness in different types of moving images [161], comparison of one-screened and three-screened display types [162][163], relationship between age and sickness level [164], and gender effect on simulator sickness [165][166]. Research on VEs has provided converging evidence that being placed in a VE with an HMD can lead to MS [167]. Previous studies suggest that a twenty-minute exposure to VREs can increase CS symptoms in over 60% of participants [168]. It has been found that exposure to VEs and simulators caused 30% of exposures result in nausea, up to 40% in eyestrain, as well as the experience of numerous other symptoms of motion sickness including headache, dizziness/vertigo, loss of postural stability, drowsiness, salivation and sweating [169]. Numerous factors are related to the susceptibility and severity of visually induced motion sickness (VIMS) [170][171][172], including the sensation of illusory self-motion [173][174][175], gender [176], age [177], or personality factors like neuroticism and anxiety [178]. Due to many factors contributing to the cause of simulator sickness both from technological and individual standpoints, it is very difficult to predict [179]. It has been noted that psychological conditions such as anxiety can significantly increase when simulated motion increases [180]. Based on the theories of sensory conflict [181] and neural storage [182], changes in visual stimulus could cause sensory conflicts between different modalities (vision, touch, etc.) which in turn could evoke different levels of virtually induced motion sickness.

Little is known on the subject of virtual environment effects on symptoms of CS, thus, a new system describing VE systems, the Virtual Environment Description and Classification System (VEDACS [183]) was proposed. VEDACS describes VEs in terms of 42 variables, which are then divided into seven categories: (1) environmental dimensions, (2) visual complexity, (3) the motion of objects, (4) the tasks that users perform, (5) the provision of help/assistance, (6) the provision of sound, and (7) global measures such as the amount of time that each person spent in a VE.

It has been suggested that the size of the monitor and the resulting display angle can also influence the severity of VIMS [184][185]. Often head-mounted devices are used for displaying virtual environments and they are known to cause motion sickness [186][187]. A research

conducted to analyze simulator sickness score using a video game in VR with an HMD, notes that sickness occurred in all participants who played the game for a maximum of 50 min [188]. Similar research suggests that sickness occurred both, in users who played a game on a standard TV screen and those with a HMD [189]. One study, targeted at finding out effects of immersion in VRE using a 20 m experiment, concluded that remarkable effects of immersion could not be found under such a short duration condition [190]. Other research suggests that the duration of exposure might be a causal factor in postural disequilibrium and that exposure of less than 3 h would not be sufficient to induce an outstanding detriment in postural steadiness [191]. According to the sensory conflict theory [192][193][194], anything that strengthens the non-veridical visual stimulus should increase MS.

According to various studies, VEs, high-latency that can result from low framerates can lead to reduced sense of presence [195], impaired task performance, reduced user response [196][197] or simulator sickness [198]. It has been determined by some authors [199] that the critical end-to-end latency is at 17ms, but other authors [200] found this threshold to be even lower. When rotating head in virtual environment with head mounted display on, adaptation to a newly displayed scene has to happen and due to the delay in visual image, during the process of adaptations, some users may develop motion sickness and show postural disequilibrium [201][202].

It is noted that VR environment influences automatic nervous system and equilibrium [203]. Sensory conflict theory states that when there are conflicting visual and vestibular inputs disequilibrium occurs, which results in MS [204]. When sensory conflict happens, the instability of persons standing positions occurs [205] and the influence of this instability may appear in humans walk after the righting reflex occurs [206]. A reflex corrects the orientation of the body when it is taken out of its normal upright position. Various studies note that CS can affect 50-80 % of people, depending on the quality of the digital content and how it's presented [207]. In addition, some studies show that women are more susceptible to MS than men, and those with a history of migraines or concussion also suffer a higher chance of getting motion sick [208]. Also, the older subjects are more susceptible to Simulator Sickness than younger subjects [209][210].

Some authors suggest that major contributor to MS is the duration of motion with visuals [211]. Others argue, that consumer HMDs require ideal frame rates in order to reduce/prevent the discomfort of MS [212]. Various researchers believe that decreasing Field of View (FOV) tends to decrease VR sickness, though at the cost of sense of presence [213]. A few authors came to a conclusion that a wide FOV display can maximize "immersion" in VE, whereas narrow one may hinder sense of presence [214][215]. As a result of increased FOV, users exhibited more postural instability, which has been suggested to be a surrogate measure for simulator sickness [216][217]. Differences in FOV have been related to navigation and memory differences [218][219][220]. Larger FOV can improve spatial awareness as well as increase sense of presence and consequently may help exhibit better memory structure of that VE [221]. Various methods, such as brain wave readings [222], behavioral metrics [223], and self-reported measures [224][225][226], have been employed over the years in order to measure users sense of presence in VEs.

In some research, it is noted that 3D video yields higher discomfort levels than 2D video [227]. There is an interesting conclusion made by some authors, stating that the highest value of sickness occurs during rotation along roll axis and that the results were highly consistent [228]. A study was conducted to analyze Visually Induced Sickness during day-night driving sessions, which showed that sickness level in night sessions was much higher than in morning sessions. In addition to that, it was proved that sleep deprivation might strengthen the symptoms [229]. It is interesting to notice that in traditional motion sickness studies, younger subjects were found to be more prone to sickness than older subjects [230], whereas in others, many older visitors appeared to suffer from effects of CS more than younger subjects [231].

It has been noted that some users might exhibit symptoms of CS, both during and after VR experience [232][233]. Cyber sickness is different from motion sickness in the way that the user is stationary, but has a compelling sense of motion as the visual imagery changes [234][235]. Vection or otherwise illusions of self-motion and sickness can be caused by watching changing moving scenes in VE [236]. In addition, it is found that users spending more than 20 min in VE experience progressively more sickness symptoms [237]. Studies suggest that both exposure duration and repeated exposures are significantly linearly related to sickness outcomes [238]. The repetitive watching of the same video image reduced subjective score of motion sickness in 8 of the 14 participants [239]. Some authors found that scene oscillations produce vection and promote cyber sickness significantly [240]. Simulation Sickness Questionnaire (SSQ) has been found to be valid and reliable subjective measure tool for both simulator sickness and side effects experienced in VEs [241][242]. It is interesting to note, that motion sickness after immersion in VRE is much greater when both pre and post questionnaire are given rather than when only posttest questionnaire is used [243].

Some previous studies suggest that the discomfort of MS can cause self-control ability decline and lead to serious traffic accident fatalities [244]. Moreover, as it was mentioned that the discomfort of all motion related sicknesses might even last for the entire day [245]. This adds some risk to using VR, as many people are very susceptible to VR Sickness and have to cope with that discomfort after their experience with it through the rest of the day, during which fatal accidents may occur and not only during driving a vehicle. For this reason, some studies are conducted to determine a set of MS indicators that would predict the occurrence of a person's MS as soon as possible [246]. Specifically, they use electroencephalography (EEG), as among other imaging technologies, it outperforms the other methods in terms of portability and temporal resolution, which refers to the precision of a measurement with respect to time.

Currently there is a debate concerning VR technology and VR sickness. Some argue that the problem of VR sickness is inherent from this technology itself and as long as there is mismatch between what is visually perceived and what is physically sensed, fixing the VR display properties does not address the root cause [247]. Particular study indicates that the weight of the HMD devices themselves play big part in causing VR sickness [247]. The 1994 US Navy study reported that techniques such as biofeedback, relaxation training, and counseling had an estimated 40 to 85 % success rate in helping reduce susceptibility to motion sickness [247]. Motion sickness drugs for the most part claim to prevent, not treat, motion sickness [247]. It is suggested that a visible horizon has a mitigating effect on MS [248][249][250].

Researches were conducted to find out the effect of virtual and real walking in virtual environment and the results seem controversial. A study found that during the task requiring a navigationally complex environment and for a long period, it is preferable to use simulated walking [251]. On the other hand, another study reported that natural walking caused less motion sickness than simulated walking in one out of two experiments involving a virtual maze[252]. During a similar research, no differences were found in simulator sickness between real walking and several virtual travel techniques in a small virtual room [253]. Furthermore, no differences were found between real walking, gaze-directed and pointing-directed travel techniques in a complex 3D maze [254].

4 Hardware and Software for Virtual Reality

In this chapter, we shall discuss hardware and software requirements for this project. Head Mounted Devices (HMDs), both mobile and tethered will be presented. The description of two main tethered HMDs and their technical characteristics will be shown. The software part contains the description of several game engines most suitable for this research. Multiple case studies of each game engine will be presented, showing their capabilities in creating serious games, simulators, etc.

4.1 Virtual Reality Headsets

Modern VR headsets can be either Mobile or tethered. Mobile headsets are simply shelling with lenses where you place your smartphone. The lenses separate the screen into two images, turning your smartphone into a VR device. Of course, the visual experience of such headset will depend on which smartphone you use. Because phones are not designed specifically for VR, they can't offer the best picture even with special lenses and they are considerably underpowered compared to PC or game console-based VR. Mobile VR headsets are Google Daydream View and Samsung Gear VR. They use only motion sensors, are quite inexpensive, and can offer interesting VR experience to their users.



Fig. 5 Google Daydream, Sony PlayStation, Samsung Gear VR [255]

Tethered headsets like Oculus Rift, HTC Vive and PlayStation VR are physically connected to PCs, in the case of PlayStation VR; it is connected to a PlayStation 4. For now, only tethered headsets can allow complex experiences, but in the future, when devices will be lighter and more powerful, headsets will become wireless, leaving the same functionality as the tethered ones. The use of built-in motion sensors and an external camera tracker, drastically improves both, image fidelity and head tracking. Although it is necessary to mention that in order to run smoothly with these VR headsets, very powerful PCs are required.



Fig. 6 HTC Vive with controllers and sensors [256]

HTC Vive in its comprehensive package includes a headset, two motion controllers and two base stations for defining a “whole room” VR area. The headset uses “room scale” tracking technology, allowing a user to move in 3D space and at the same time, using motion-tracked controllers interact with the environment. It tracks your movements in a 10-foot cube instead of from your seat. The headset contains a gyro sensor, an accelerometer and a laser position sensor, which work together to track the position of your head. It comes with two wireless infrared Lighthouse cameras, which are placed in the corners of a room and follow the headset’s 37 sensors (70 in total, including controllers as well). In result, a user can freely move around while the device will track precisely each move he/she makes. Headset also has a front-facing camera that allows users to move around their real-world environments without removing the headset.



Fig. 7 Oculus Rift with controllers and sensors [257]

Oculus Rift is another Virtual Reality headset. It has rotational and positional tracking. The positional tracking called “Constellation” is performed by a USB stationary infrared sensor that reads the lights emitted by infrared LEDs that are integrated into the headset. The sensor usually sits in front of user, be it on desk or monitor. This creates 3D space where you can walk, sit or stand. Headset has built-in magnetometer, a gyroscope and an accelerometer, all of which combine to accurately track the headset across all three dimensions.

Specifications of Oculus and HTC Vive are very similar. They use OLED display, have same resolution 2160x1200(both eyes combined), refresh rate of 90Hz, and field of view 110 degrees. Although tracking area of HTC Vive is much larger. The prices of devices are as follows, including headset with controllers, Oculus Rift price goes up to 700\$, whereas HTC Vive up to 900\$.

4.2 Game Engines

4.2.1 Unity3D Game Engine

Unity is a cross-platform game engine developed by unity Technologies, the primary use of which is developing games and simulations for computers, consoles and other mobile devices. This game engine supports 2D and 3D graphics, drag and drop functionality and scripting with C# in MonoDevelop .NET Framework 2.0. The combination of low learning curve for beginners, active ecosystem of asset and plugin creators, rapid development speed and its cross-platform integration that supports 25 platforms (Windows, iOS, Android, Linux, etc.), makes this game engine dominate the industry.

Many studies were conducted using this game engine for simulation purposes and it was suggested to use Unity3D for serious game training for crane operators to teach safety procedures and methods of crane operations [258]. This game engine was also used in developing a Brain Computer Interface (BCI) simulated application that could be used as feedback training system providing effective feedback of vision and hearing [259]. The benefits of realistic physics in game engines allows simulating various environments that are similar to the RW, this allowed to develop a virtual education assistance system with simulated river ecosystems with 3D visualization to help learn the river environments [260]. Furthermore, as game engines are very common in-flight simulators or emergency simulators, a study using Unity3D suggested using this engine for security serious game to train specialists through supervised situational scenarios, focusing on social level security and safety actions such as floods and fires [261].

One study incorporated virtual environment with teaching ISO/IEC systems and software engineering and as a result, there was a significant difference between those who played this game and those who participated only in paper-based learning sessions [262]. The group who played the game got greater knowledge compared to the other group.

Additionally, using Unity3D, a serious game for nurses was developed to train for first aid key survival technique and as a result, those who underwent the practice in this game performed better compared to those who did not [263].

Lastly, due to the unlimited variations of scenarios Unity3D game engine can provide, it was used with Oculus Rift headset to make a virtual navigation in the ancient Egyptian funerary rituals to explain the meaning of the various pictograms and hieroglyphs [264].

4.2.2 Unreal Engine

The Unreal Engine is a game engine developed by Epic Games, primarily developed for first-person shooters but also has been successfully used in a variety of other genres, including stealth, MMORPGs, and other RPGs. With its code written in C++, the Unreal Engine features a high degree of portability and is a tool used by many game developers today. This engine supports game scripting in C++ as well as Blueprints Visual Scripting system, which doesn't require scripting knowledge.

Although, learning how to work in Unreal Engine is not straight forward as in Unity3D, it is still one of the most popular game engines used nowadays. Due to that fact, many scientific studies on serious games or other research activities were conducted using it. For example, using this engine, researchers were able to create a serious game to diagnose attention disorders in a virtual classroom [265]. In the next study, a serious military game was targeted on evaluation of cadets 'knowledge on ethics and laws of war using RPG style game [266].

A virtual mine system simulation was created to promote the productivity, efficiency and safety in modern coalmines [267]. Furthermore, in the study, researchers developed a visual impairment simulator game, that would reproduce the appearance of a series of visual impairments [268].

Additionally, using Unreal Engine, a nuclear power plant simulator was created to educate and train personnel for the operational and emergency scenarios of a plant [269]. Lastly, the study presented an evacuation planning game in emergencies [270].

4.2.3 Panda3D

Panda3D is an Open Source game engine, a framework for 3D rendering and game development for Python and C++ programs. It includes graphics, audio, I/O, collision detection, and other abilities relevant to the creation of 3D games.

Due to above, this game engine was used for various studies conducting serious game simulations in different areas. Panda3D was used for: teaching introductory programming to computer science students [271], creation of an intelligent game engine for the at-home rehabilitation of stroke patients [272], construction of a Virtual Environment for teaching driving [273], a simulation environment for accounting education and training [274], creating a simulation for children with autism to promote collaboration and social interaction [275].

4.2.4 Blender Game Engine

The Blender Game Engine is a component of Blender, a free and open-source comprehensive 3D production suite, used for making real-time projects, from architectural visualizations and simulations to games. The game engine was written in C++ as a mostly independent component, and includes support for features such as Python scripting and OpenAL 3D sound blender.

Some of the research conducted using this game engine are - a simulation for teaching arithmetic to primary schools students [276], reconstruction and navigation through cultural

heritage [277], 3D visualization of archaeological sights [278], underwater simulator for robotics applications in high depths [279], real-time simulation of production systems [280].

4.2.5 3DVIA Virtools

3DVIA Virtools owned by Dassault Systèmes offers a development environment to create 3D real-time virtual reality applications and services, targeted at system integrators, game studios and corporate end-users.

Different simulation applications were created with this tool, some of which are: a forest knowledge education game [281], an application of dynamic virtual reality faces for the assessment and training of facial emotion recognition ability for people with social impairments [282], a simulation to improve the safety of construction plant operators [283], an application for treatment of generalized anxiety disorders [284], a virtual environment for assisting interior lighting and design education [285], a virtual reality based system for nuclear safeguards applications [286].

4.2.6 OGRE3D

OGRE (Object-Oriented Graphics Rendering Engine) is a scene-oriented, real-time, flexible 3D engine written in C++ designed to make it easier and more intuitive for developers to produce applications utilizing hardware-accelerated 3D graphics. The class library abstracts all the details of using the underlying system libraries like Direct3D and OpenGL.

Although, OGRE3D is not specifically a game engine, but it can be, if integrated with other libraries for sound, networking, AI, collision, physics, etc. Various studies performed with this tool are: an educational game for learning programming languages [287], an implementation of 3D visualization applications based on physical-haptics principles to perform rehabilitation tasks [288], a serious game for surgical training [289], a game-based training system for submarine safety and spatial awareness [290].

Summary

Nowadays, there are a multitude of game engines available for creating some kind of simulation, game, etc., but in this chapter, the most suitable for this project game engines were presented. Although, many game engines are open source and freely available for use, specifically for this research, Unity3D was chosen to create a virtual environment experiment. The main reason for this choice is the PRO license available for this tool, but at the same time, it is one of the best game engines available nowadays and with frequent updates and improvements that the developers produce, makes Unity3D reliable for the long run.

5 Summary of research part and thesis

The reviewed literature on Virtual Reality and Augmented Reality in this work suggests various use applications of these technologies in different areas, be it training for specific skills, education, medicine, etc. Studies suggest that Virtual Reality could be very helpful for these purposes as it has the possibility to motivate and ease the training/learning process, enable collaborative work, reduce risks for life through realistic VR simulators, help people with health issues, etc. Although, as any other technology, it has its' own negative side effects, and one of the big ones is Cyber Sickness. In addition to being unable to fully recognize the experience gained in Virtual Environment, it can cause some serious temporary health issues, depending on how prone a person is to this feeling and how often and long this experience lasts. Thanks to the indepth research and understanding some parallelism between Motion Sickness, the simulation and experiment process in this work was performed in such a way, that would maximally reduce any potential Cyber Sickness aspects that could happen during the testing period.

As Virtual Reality is very popular for training, and any type of simulation can be created for these purposes, this information was a sufficient basis to use VR and create a simulation in which participants would be tested for their skills progress in VR and transfer to the Real World.

The type of training that was chose was base on tracking user hand precision over multiple sessions, where they had to perform specific movement tasks with their hands. These data would be collected and user hand movements would be compared later with the actual position/path of what they had to perform.

This type of training could be beneficial for example in metal work/wood work, where workers have to use ex. saw or manual laser cutter and perform very precise movements, which can at times be very risky, thus performing them correctly is not only cost effective but also risk safe.

Additionally, this kind of training could be beneficial for surgeons, as they perform very delicate surgical operations that require very stable hand precision and movement. Thus, training for hand stability and movement could be of good use in surgical area as well. Based on the literature, the main thesis is:

- Using Virtual Reality, it is possible to create realistic scenarios.
- Virtual Reality can help in training, education and health care.
- The more realistic the context of the 3D environment, the more sense of presence.
- Cyber Sickness effects majority of population and can cause health issues.
- VR can be used in different areas of work sector.
- Using Virtual Reality, it is possible to increase a person's skill and transfer it to the Real World.
- The resulted skill after training would potentially be greater than before the start of the training process.

6 Used scientific methods

This chapter on used scientific methods briefly lists the basic scientific approaches and methods that are included in the work. Each chapter lists separate method which was used mainly in the practical part of the dissertation. Specifically, these are experiment and statistics. The application of these methods led to the confirmation or refutation of the established hypotheses of the dissertation.

6.1 Empirical methods

Empirical research methods evaluate the researched object or phenomenon using sensory sensations and perceptions using technology, to capture even the finer nuances. These methods can detect specific unique properties of researched objects and phenomena in reality. Usually these methods are divided according to the method of their implementation into:

- observation
- measurement
- experimentation. [292]

Observation

The observation may take place without contact between the observed and the observer, so-called non-participatory observation, when it can be completely anonymous for the observed. On the other hand, when close observation is involved there is active participation between observer and observed, but this method is up to the entity's willingness to cooperate [291]. The observation was used to understand and learn the methodology of measuring hand movement precision training/change in VR and RW. This type of experimentation and training is impossible to perform without close cooperation between observer and participant, thus an observed training lasting around one month of intensive sessions was performed.

Measurement

Measurement is a special type of observation. This is an accurate description of certain important characteristics and properties that will be used to compare and classify the observed objects. When measuring, we use technical means with predefined and defined units and quantities. Measurement is most often used to determine length, weight, speed, price, movement, densities, temperatures, etc. [293]. Within the dissertation, the measurement was part of the practical part. Once all the data was collected from training sessions (precision and time of performance), this data, both from VR and RW was moved to pre-prepared Excel templates with defined macros that would allow precise calculation (given specific formulas for each variant of drawn shape) of variables and later allow its usage for statistical part.

Experimentation

An experiment is a procedure carried out to support, refute, or validate a hypothesis. Experiments provide insight into cause-and-effect by demonstrating what outcome occurs when a particular factor is manipulated. In this experiment, 16 participants took part in testing and training their performance for hand precision in VR and RW. The complete time required just for the test was around one month. The preparation of the experiment design, simulated VR environment, VR/RW material, gathering data, calculation and preparation of statistics required additional multiple months of research and work.

6.2 Logical methods

Logical methods use the principles of logical thinking and logic itself. Very often divided into "paired methods":

- abstraction - concretization
- analysis - synthesis
- induction - deduction.

However, in scientific research, these methods are often intertwined and complementary, which often makes that connection synergetic [292].

Abstraction - concretization

Abstraction is a thought process in which we notice and pick from various objects only their essential characteristics and at the same time we do not consider the insignificant ones. Thanks for this in the process, we create a conscious model of the object containing only these significant characteristics that allow us to find answers to the questions that we ask ourselves. Concretization is the opposite of abstraction. When concretizing, we look for the occurrence of the subject object or phenomenon from a certain group and we apply the characteristics of this class of objects to it or phenomena [292]. In order to meet the goal of the dissertation, it was necessary to perform concretization. The main purpose was to concentrate on two factors, speed and accuracy of performed task and find the connection/influence between those factors in given experimental tasks.

Analysis - synthesis

The analysis represents the distribution of the given factors into other smaller parts, which are then examined. The main thing is to distinguish between important and insubstantial parts and to deal with them in more detail. Synthesis is the opposite process to analysis, because it groups parts into whole. It deals with research of individual forms, which are then combined into a whole using certain procedures. [292]. The data from the experiment was grouped into two categories, precision data and speed data. These were then calculated and compared for each session on the graph charts. This would essentially show the correlation between those two components of training.

Induction - deduction

Induction refers to the formation of a general conclusion from the acquired knowledge of details. It represents a link from individual findings to general courts. On inductive conclusions often, there is a subjective approach and experience, therefore their validity is limited. Deduction is the opposite of induction, we come here from general conclusions to individual judgments. Deduction is always based on true assumptions, we use them to examine the individual and as yet undiscovered cases. [292] Induction and deduction are the content of the final chapters of the dissertation. By analyzing the graphs after performing statistical analysis, we can clearly deduct multiple informative conclusions. Such as benefits of the given training, required amounts of training, and more.

6.3 Statistical methods

For statistical evaluation specific statistical tests were used. Those tests can be divided to parametric and nonparametric tests. Parametric are those for which we must know the distribution of data, they usually assume a normal distribution. Nonparametric do not require this assumption. The following three tests were used:

1. Jarque-Bera test.
2. Paired-sample t -test.
3. Wilcoxon signed ranked test.

Jarque-Bera test [294]

In statistics, the Jarque–Bera test is a goodness-of-fit test of whether sample data have the skewness and kurtosis matching a normal distribution. The test is named after Carlos Jarque and Anil K. Bera. The test statistic is always nonnegative. If it is far from zero, it signals the data do not have a normal distribution.

The Jarque-Bera Test, a type of Lagrange multiplier test, is a test for normality. Normality is one of the assumptions for many statistical tests, like the t test or F test; the Jarque-Bera test is usually run before one of these tests to confirm normality. It is usually used for large data sets, because other normality tests are not reliable when n is large (for example, Shapiro-Wilk isn't reliable with n more than 2,000).

The data could take many forms, including:

- Time Series Data.
- Errors in a regression model.
- Data in a Vector.

A normal distribution has a skew of zero (i.e. it's perfectly symmetrical around the mean) and a kurtosis of three; kurtosis tells you how much data is in the tails and gives you an idea about how "peaked" the distribution is. It's not necessary to know the mean or the standard deviation for the data in order to run the test.

Paired-sample t-test [295]

The paired sample t-test, sometimes called the dependent sample t-test, is a statistical procedure used to determine whether the mean difference between two sets of observations is zero. In a paired sample t-test, each subject or entity is measured twice, resulting in pairs of observations. Common applications of the paired sample t-test include case-control studies or repeated-measures designs. Suppose you are interested in evaluating the effectiveness of a company training program. One approach you might consider would be to measure the performance of a sample of employees before and after completing the program, and analyze the differences using a paired sample t-test. (The paired sample t-test, sometimes called the dependent sample t-test, is a statistical procedure used to determine whether the mean difference between two sets of observations is zero. In a paired sample t-test, each subject or entity is measured twice, resulting in pairs of observations. Common applications of the paired sample t-test include case-control studies or repeated-measures designs. Suppose you are interested in evaluating the effectiveness of a company training program. One approach you might consider would be to measure the performance of a sample of employees before and after completing the program, and analyze the differences using a paired sample t-test.)

The Paired Samples t Test compares the means of two measurements taken from the same individual, object, or related units. These "paired" measurements can represent things like:

- A measurement taken at two different times (e.g., pre-test and post-test score with an intervention administered between the two time points)
- A measurement taken under two different conditions (e.g., completing a test under a "control" condition and an "experimental" condition)
- Measurements taken from two halves or sides of a subject or experimental unit (e.g., measuring hearing loss in a subject's left and right ears).

The purpose of the test is to determine whether there is statistical evidence that the mean difference between paired observations is significantly different from zero. The Paired Samples t Test is a parametric test. This test is also known as:

- Dependent t Test
- Paired t Test
- Repeated Measures t Test

The variable used in this test is known as: Dependent variable, or test variable (continuous), measured at two different times or for two related conditions or units.

Wilcoxon signed rank test [296]

The Wilcoxon test, which can refer to either the Rank Sum test or the Signed Rank test version, is a nonparametric statistical test that compares two paired groups. The tests laid the foundation for hypothesis testing of nonparametric statistics, which are used for population data that can be ranked but do not have numerical values.

The tests essentially calculate the difference between sets of pairs and analyzes these differences to establish if they are statistically significantly different from one another.

The Wilcoxon test is a nonparametric statistical test that compares two paired groups, and comes in two versions the Rank Sum test or the Signed Rank test. The goal of the test is to determine if two or more sets of pairs are different from one another in a statistically significant manner. Both versions of the model assume that the pairs in the data come from dependent populations, i.e. following the same person or share price through time or place.

The types of questions that the Wilcoxon Test can help us answer include things like:

- Are test scores different from 5th grade to 5th grade for the same students?
- Does a particular drug have an effect on health when tested on the same individuals?

Versions of the Wilcoxon Test

- The Wilcoxon Rank Sum test can be used to test the null hypothesis that two populations have the same continuous distribution. The base assumptions necessary to employ this method of testing is that the data are from the same population and are paired, the data can be measured on at least an interval scale, and the data were chosen randomly and independently.
- The Wilcoxon Signed Rank test assumes that there is information in the magnitudes and signs of the differences between paired observations. As the nonparametric equivalent of the paired student's t-test, the Signed Rank can be used as an alternative to the t-test when the population data does not follow a normal distribution.

7 Goals and Hypothesis

In this chapter, the main purpose of this work is described and the plan by which it will proceed.

7.1 The goal

The goal of this work is to evaluate the effect of Virtual Reality on training hand movement precision and compare the first session with all consequent ones, to find out either a positive(improving) or negative(worsening) result trend. Additionally, RW test would be conducted, that would measure near similar actions on the paper, mainly to find out whether Virtual Reality training has any effect on RW practices. Both, RW test and VR test will be conducted in one handed mode as well as two handed mode, as an additional comparison of the effect of complexity on the trends. Ultimately, we want to find out, whether VR improves results in VR and/or in RW as well. A comparison between the first and the last sessions will be made.

7.2 VR applications in Industry/Manufacturing

This work is done in order to prove/disprove whether using Virtual Reality technology/simulations could be beneficial for Industrial Engineering and using such training simulation as hand movement precision. As different tasks require different training, we decided to specifically evaluate how a person's cognitive ability to learn specific movement patterns change during VR training.

Industrial engineering is an engineering profession that focuses on the optimization of complex processes, systems, or organizations by developing, improving and implementing integrated systems of people, money, knowledge, information, equipment, energy and materials [297]. Very often companies use VR for their staff for various reasons, such as maintenance or assembly. According to [298], VR can be used in manufacturing for developing new products, training, factory layout planning, repair operations and the benefits that come with it are increased efficiency, cost and time savings, improved worker safety, better manufacturing process and etc.

There are multitude of studies that suggest methodologies and explore the potential of using immersive VR applications for training/learning in industry/manufacturing, for example: discussing factors that can help create better learning content and context for a better understanding of learning instructions [299], a suggestion on VR maintenance system creation approach [300], methodologies and experiences when creating and implementing VR training platform for operators and maintenance staff [301], a combination of VR and AR to create a complete and robust process that can better address complex training tasks [302], discussions about benefits of using VR for education and creative learning in engineering [303], the latest findings in key areas of AR and VR application to manufacturing [304], an overview on Virtual manufacturing and potential applications[305][306]. Most of them come out with the data that supports the notion, that VR has a positive impact on trainees.

Furthermore, apart from researching the potential of VR for training, there are already numerous use cases that have already existed for quite some time, suggesting that VR training has a big positive impact and its usage is visible in almost every field imaginable. For example, according to [307], VR found its way in welding training system from Lincoln Electric for muscular memory and motor patterns; Siemens Virtual Twin maintenance system and UPS truck driving safety training. According to EON Reality training solutions [308], there are tremendous amounts of VR/AR use cases in various fields, but focusing specifically on manufacturing and industry, they present such examples as forestry services training, waste management training, VR maintenance training, VR industrial planner and etc.

This experiment slightly resembles the experience from welding simulator from Lincoln Electric, but cannot be completely compared as the circumstances and devices are different. But them using it for training suggests a positive impact overall.

7.3 Hypothesis

The following hypothesis were stated for this research.

Hypothesis for VR experiment

H1: Distance reducing trend (increasing drawing accuracy) for VR testing is to be expected;

H2: Time reducing trend (increasing drawing speed) for VR testing is to be expected;

H3: One handed test would be more accurate than two handed in VR;

H4: One handed test would be faster than two handed in VR.

Hypothesis for real world experiment

H1: Accuracy increasing trend for RW tests (on paper) is to be expected;

H2: Time reducing trend (increasing drawing speed) for RW tests (on paper) is to be expected;

H3: One handed test would be more accurate than two handed on paper;

H4: One handed test would be faster than two handed on paper.

7.4 Steps of this research

The following steps are foreseen in order to reach the stated goal.

- Create a simple VE with minimum objects, to focus on the simulation. A simple room with sufficient lighting;
- Three one hand simulation scenes (line, circle, sine) for capturing hand movement precision;
- Three two handed simulation scenes (line, circle, sine) for capturing hand movement precision;

- Each simulation will have 4 precision capturings for each shape object per session, for averaging later on;
- Create data capturing algorithm inside Unity3D game engine on the backend (Scripted in C# and saved in Json format), for exporting and analyzing in further steps (in Excel);
- Convert data from Json format to Excel using any free online converter;
- Analyze data of each scene;
- Find the trendlines using averages of all participants;
- Compare one hand mode results to two hand mode results;
- Find out whether VR training has any effect on participants in VR (only VR);
- Find out whether VR training has any effect on participants in RW scenarios (transfer from VR to RW), otherwise, does VR improve RW results;

8 Pilot projects

In this chapter, a simulation created in Virtual Environment using Unity3D, on which the author of this thesis worked as an examination part of study, will be presented.

8.1 Car assembly Simulation

This simulation was part of the study process and made for examination purposes. It was made using Unity3D, both in CAVE with InterSense tool and Oculus Headset. Using this game, it's possible to assemble cars' wheels, screw or unscrew the bolts, interact with car - open or close the doors, observe it from different angles and from the inside as well. Finally, after assembling the car completely, it is even possible to take the car for a test drive in a vast environment. This can also be used for future psychiatry tests for people who are afraid to drive in real car. They can try combating their fears in a controlled driving simulator.

Free 3D models from different sources were imported to Unity3D game engine and aligned accordingly.



Fig. 8 Wheel Assembly Part

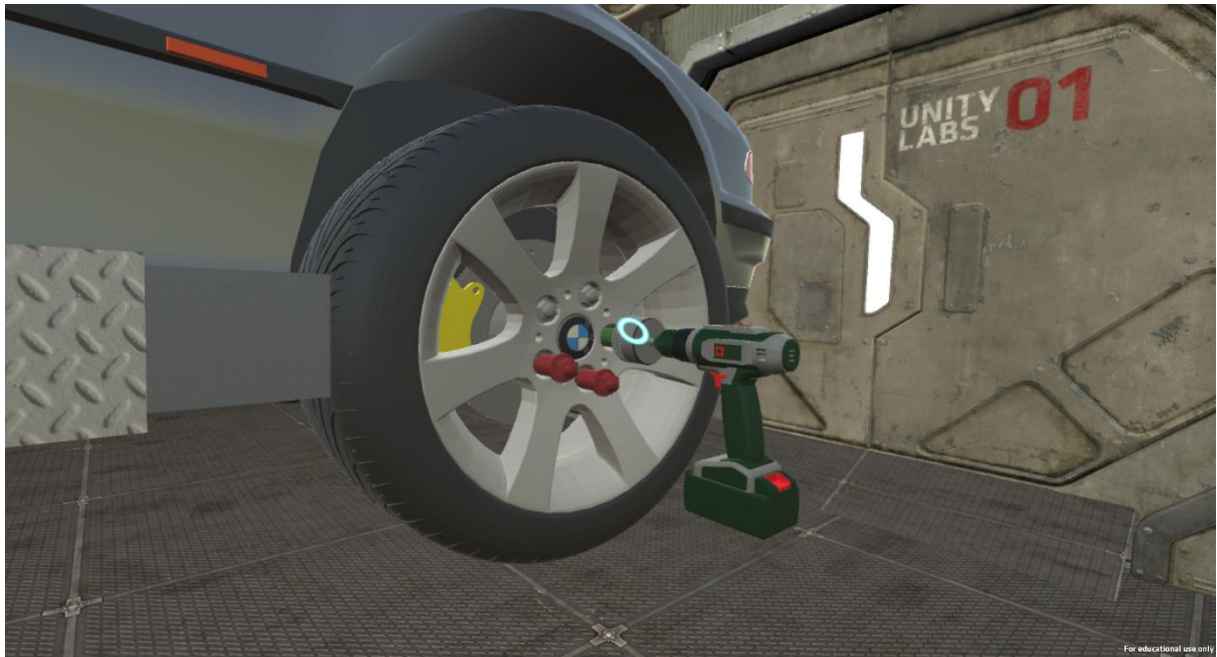


Fig. 9 Screwing Bolts on Wheels

8.2 Cyber Sickness experiments

A group of students including the author, conducted the Maze simulator test, where a subject had to collect balls for 10 minutes. In this simulator, subjects had to repeatedly collect red and green balls, and after the mark of 10 minutes proceed to questionnaires and standardized Pegboard tests to evaluate the effect of Cyber Sickness on their physical abilities. The experiment was performed with Oculus Rift DK2, in CAVE with InterSense IS-900, with just a PC and monitor and lastly a control group.

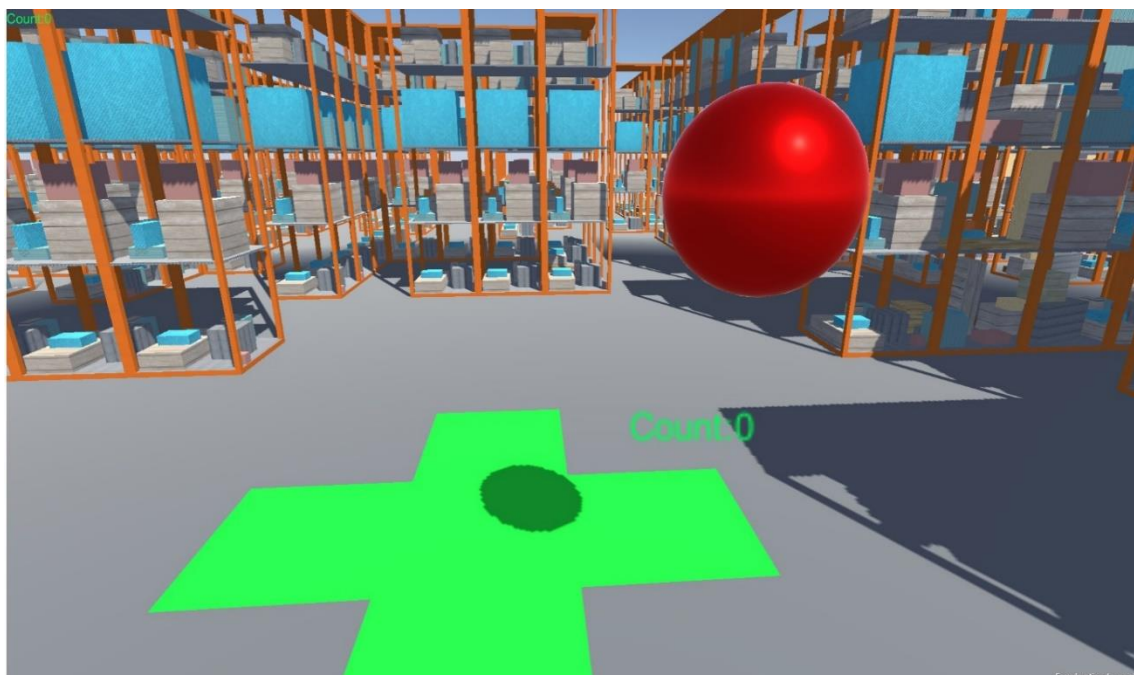


Fig. 10 Virtual Reality Maze game for Cyber Sickness experiment

9 General Information on Experiment

The purpose of this experiment was to measure the effect of VR training sessions both on VR performance (drawing shapes in VR) and RW results (drawing shapes on paper). This way the hand movement precision over time was measured. Participants were asked to draw shapes with high precision as well as highest possible speed. The balance of those two parameters was completely up to them.

In this experiment 16 participants had to draw the shape of line, circle and sinus wave both on paper and in Virtual Reality, for measuring the change in precision and speed. Each participant participated 7 times in total, and attended the experiment 2-3 times a week. So, in total, the experiment lasted around one month.

Paper experiment was conducted only twice, on the first day and on the last. That would give us the idea if VR training improves results on paper, in the RW, while training in VR. But that was only one of the interests, as it was needed to measure the improvements in VR sessions as well. In VR, consequent sessions would be compared to previous ones and give us the trend, which would either improve or worsen the results for precision and/or speed.

Participants were all young, healthy and in good state. They were chosen from the department of physical education and sport, with the age ranging between 19-28. On the first day, their gender, main hand, age and experience with VR was written down in the form of abbreviation, that would look like this "MP23N". Which stands for:

M - Muž (Man), Alternatively Z – Žena (Woman)

P - Pravák (right hand as main), Alternatively Levák (left hand as main)

23 - Age

N – No previous experience with VR, Alternatively A – Had some previous experience with VR

The shapes that were chosen for the tests were a line, circle and sine wave. When creating testing material, it was important to make sure that the measurements of digital models coincide with the ones in the RW. First, line/circle/sine shapes were drawn in GIMP software for the A4 format paper, after that 3D models of the same shapes were created in Blender software with exact measurements/sizes. This size of shapes was very convenient as in the end, participants didn't have to walk to draw the shapes in VR, everything was done in only standing pose.

The parameters of the shapes are:

- Line length 26 cm;
- Circle radius 10 cm;
- Sinus amplitude of 5 cm and 2 periods of 10 cm each.

The types of simple movements that resemble repeating the shape of line, circle or sine wave can be seen in some workstations in different industries. We decided not to increase the level

of complexity by creating some difficult to repeat shapes that would take participants unfamiliar with VR much longer to get used to. We wanted them to perform the test right from the get go, and training them with those shapes seemed sufficient, as the complex movements are usually composed of multiple simple tasks.

Shapes were repeated with one hand(main) as well as both hands. In VR, 6 scenes in total were prepared for this experiment, three for one handed drawing (line, circle, sinus wave) and three for two handed drawing (same shapes). Each shape was drawn 4 times before moving to other scene/shape, in order to average out the data in the future for higher reliability.

When conducting the experiment on paper, participants had to draw each shape twice with one hand and twice with both hands, two times less than in VR. This was done once on the first day, and once on the last day.

Due to having only couple of students with some VR experience, there was no need to split statistical data. Also, due to having only few girls, there was no reason to split statistical data between genders as well.

9.1 The difference between One hand mode vs Two hand mode testing

In this test, as mentioned prior, the idea was to analyze the trends and effects of VR on hand movement precision, both in one hand mode and two hand mode respectively. Each VR testing scene was a simple room with a table on which an object and a working tool, either glue gun (one hand) or caulking gun (two hands) was put. Thus, the only difference between one hand test and two hand tests was the tool, which participants would hold either with single controller or a combination of both. The two-hand mode test was meant to increase the complexity and see how that would affect the results compared to a simpler one hand test.

9.2 Considerations for VR simulations

Navigation type

There is a possibility for different types of movement in VR, the most popular are:

- Free movement: The user has the ability to move around the environment. This can be done using gliding option, something similar to what can be achieved with keyboard forward, backward, left and right buttons.
- Controlled movement: The user is moved through the experience, in an 'on-rails' experience where the ability to move the camera is taken away from the user. The user is simply moved to specific precomputed key locations where all the action happens.
- Teleportation-Controlled: The user uses their hand controller (or gaze activated) to travel between teleportation points. All the other area around a user is excluded from the list/layer of potential teleportation location. This option could be used for specific story-telling purposes, where you need to show a user pre-programmed information.

- Teleportation-Free: Basically, as it sounds, a user has the possibility to teleport wherever he/she wants without any restrictions, like in an open world game environment.

The type of navigation technique to choose for your simulation highly depends on the simulation itself. In our tests, participants didn't need to move neither in VR nor in real environment, they were initially placed on the same spot each time, where they would perform all the tests from start to finish, they would move only their hands. The VR environment was designed in such a way, that after setting up the play area in "SteamVR" program, participants were automatically located on the right position in VR but could use free teleportation technique to tweak the positioning if it was not good enough.

"SteamVR" is the ultimate tool for experiencing VR content on the hardware of your choice. SteamVR supports the Valve Index, HTC Vive, Oculus Rift, Windows Mixed Reality headsets, and others.

Health & safety

When it comes to VR, several measures could be taken in order to reduce potential risks. First of all, it is necessary to take into consideration if a user will be moving/walking freely (while not using controllers for locomotion) in VR and consequently in real environment, or he/she will use other navigation techniques while standing on one place. If a user will conduct partial movement (depending on room space and cable/cable-less approach) via walking, the real room environment needs to be cleared out of any dangerous and sharp-edged objects to eliminate dangerous falls. Although if setup of the VR device is done correctly, a user is notified whenever he/she is leaving the pre-computed play area of possible movement in real environment, thus allowing them to stop, re-adjust their positioning both in VR and RW and use other methods of locomotion instead, until they get to a good point in a play area and can use walking as additional/supplementary movement once again.

The immersive nature of virtual and augmented reality can induce stress or anxiety after wearing a full occlusion headset for more than a few minutes. Thus, it is necessary to know ahead if a person suffers from such health conditions and if so, this person should not be allowed for the tests or use such technology to not put their health in danger.

Furthermore, it is necessary to consider activities that the user will do in VR.

- Neck and back strain can be caused by extended periods of tilting that places great pressure on the neck, which may be exacerbated by the additional headset weight. Most of the times, users will feel just neck strain when in standing pose, but in some cases, when simulations make them tilt forward or on the sides, to get/grasp something, back strain can occur as well, which can cause no less discomfort than the neck strain.
- Digital eye strain or computer vision syndrome can occur due to long visual exposure to not only VR content but any other digital exposure as well. It can also be worsened if a user has already weakened eye muscles or other health conditions. Thus, it is

necessary to take into consideration each person's health status and allow only those who are capable to take part in the tests without any risks to their health.

- Visual vertigo is a disorder characterized by symptoms of dizziness, vertigo, unsteadiness, disorientation, and general discomfort induced by visual triggers. Too much objects in front of a person or unbalanced lighting conditions can cause a person to feel significant levels of discomfort. Our VR test environment was very minimalistic, and contained only few objects (tool to hold, table, shape to perform on and room itself) that were required to perform the tasks.
- Audio vertigo is a syndrome in which vertigo and imbalance are triggered by loud noises or pressure in the affected ear. For our tests no audio was used in order to let users focus on a given task.
- Simulator sickness/Cyber Sickness.

In our tests, the duration of the whole process was mainly dependent on the participants ability to perform the tasks at their own speed, which was on average 20 minutes long overall. As to the neck and back strain, although it was necessary to roll the head a bit forward in order to simulate performing the task on the table in VR as in RW, participants could take off the headset to rest if needed or readjust it according to their needs. All in all, all the tests went smooth and there was no particular problem with any of the participants that was difficult to fix.

Interaction

When creating a VR simulation/game, it is necessary to establish from the start what type of interactions users will have in that environment. Some simulations might require zero interaction, where user is just an observer of events, others could use only pointing of controllers and finally simulations, where users might need to use all the buttons on VR controller to fully interact with VR environment, like grabbing objects, opening doors, shooting etc.

Also, it is necessary to make such a system, that will account for both left- and right-hand dominant users. A good option to use during interactions in VR is using vibration of controller, in order to provide feedback to the user when specific actions are performed. Vibration of controller is possible to program thanks to build in vibration motor.

In our tests, participants could switch the controllers depending on their dominant hand and perform the tests as usual, with no difference at all. But because the accuracy of the motion's every millimeter counted, no vibration from VR controllers as a feedback was used, that could potentially add unnecessary noise to the movements and give us incorrect results.

Constraints

Understanding the constraints is first key as it will dictate not only the style, but the level of interaction the user has in the world. For example:

User constraints: When creating a simulation, you need to remember for whom the experience is targeted at. Different individuals have different bodies and, in our case, mainly height. The age of participants also plays a big role on durability during the tests. In the simulations, the main constraint that needed to be considered was participants height, as it would directly affect the amount of tilt that would be required to look down on an object and perform a motion of that shape. The height of a table object in VR was similar to the ones of real environment, which was of 145 cm height. As it turned out, only one participant was tall enough to feel some discomfort while performing the tests and as for others, no notification about height was brought up during the tests.

Hardware constraints: The hardware on which the simulation would run is also another concern that needs to be accounted for. The better the device on which you will run your tests, the smoother the experience for the users. Although having a very powerful Notebook at disposal, the simplicity of the simulation, although being in VR, didn't require very much computer resources. So, the combination of a good pc and a simple simulation, no hardware problems in our tests were experienced.

Graphics constraints: Creating a realistic simulation with good graphics is very important for higher immersion. For the tests, a very popular game engine was used, which is called Unity3D, which has great capabilities for realistic graphics, especially when used with post processing modules that can alter the picture in different ways. The term post-processing is used in the video/film business for quality-improvement image processing methods used in video playback devices, and video players software and transcoding software.

Furthermore, in order to achieve higher immersion, the 3D models, their textures and shapes must be of higher quality as well. Only than the potential of a game engine and post processing could have a significant boost in experiencing higher immersion levels. For our cause, as such tools like caulking gun and glue gun are very usual objects, there was no difficulty in finding these models or parts of them for free on the web. When those models/objects were downloaded, the next part was altering their components to look as similar as possible with the real ones, so that the users wouldn't feel much disconnect when performing VR tests and real-world tests with real tools.

Physical constraints: What is the scale in the world, and how will it impact the user's experience? Feelings of enclosed space may induce claustrophobia, or conversely agoraphobia in large spaces. The VR environment was a minimalistic medium-spacious room, which didn't cause any of such problems in any participant.

The real-world room space for participants to stand in was 2x2 meters, but for our tests, there was no need to walk, they had only to stand on one spot and perform all the tasks from there. Positioning of VR objects was done in such a way, that after creating a "Play area" (2x2 meters space in real space), all participants would always stand on a specific spot each time, and the objects in VR would always match their view. In very minor cases when it was not as correct as initially planned, participants could easily and quickly re-adjust their position in VR using a teleportation technique or simply walk a step or two to the desired spot.

Duration of the simulation

As it was already discussed, duration of the simulation could have significant effect on user's health/physical condition. Some individuals start feeling dizzy when using VR instantly, whereas others might feel fine for much longer, and it also depends on the type of the simulation they are immersing in. Duration of one session for each of the participants was around 15-20 minutes depending on their ability to perform the tests, as they had full control over the speed and accuracy they were performing the tests with.

Difficulty of the simulation

When creating the simulation for users that had no prior experience with VR and/or gaming, the difficulty level of the tests needed to be taken into consideration. Due to having simple tasks and comfortable ergonomic HTC Vive controllers, most participants could quickly grasp the correct way of performing the tests, that required only pressing and releasing only one button, as well as moving their hand in a given shape objects form. They only needed few minutes of practice on their first day of trial, and on the consecutive days, participants could perform the tests right from the get go.

Tracking stations/ HTC Vive base stations

It is very important to position the tracking stations correctly on the opposite sides of the wall. The distance between them, the angle at which they are rotated and height play important role in tracking the deadest and controllers.

The tests required exceptional tracking quality, as even the smallest loss in tracking could result in unwanted jitter in the movement in VR. This problem was mostly solved by positioning the participant in such a way that their body wasn't obstructing the controller's movement. They were instructed to use only the working hand and have another hand down, so that tracking stations could track the working controller all the way from start to finish. Although two handed mode was a bit tricky, still the results were very positive. Both positioning and rotating participants in the room correctly for tracking stations to have unobstructed view was very crucial to achieving high quality results.

But if sometimes the jitter occurred, as every test was manually observed by the tester, the test results were not counted and the simulation was restarted until all the required data was gathered with correct measurements.

10 VR experiment

10.1 Software and Hardware

VR simulation was created using Unity3D game engine. And the tests were run on VR ready Acer Predator notebook, with Intel Core i7-6700HQ @ 2.60GHz, 16gb Ram and Nvidia GeForce GTX 1060-6gb.

As for the VR headset, HTC Vive Pro was used, which has the resolution of 1440 x 1600 pixels per eye (2880 x 1600 pixels combined), 90 Hz refresh rate and 110 degrees Field of view. All this allowed participant to have as comfortable experience in VR as it could get.



Fig. 11 Acer Predator VR Ready notebook and HTC Vive Pro with controllers

10.2 The design

The environment in VR was a simple cubicle room with no extra objects in it, in order to not distract participants with unnecessary visual noise. Apart from the room itself, the only 3d models available in the scene were a table of 1.05 m height, an object (line, circle, sinus) of reference to draw on, the model of glue gun or caulking gun, depending on the scene, which was either one handed version or two handed. Line, circle and sinus wave had a green color with medium transparency on them, whereas drawing was done with solid yellow color with Unity3D's line renderer.

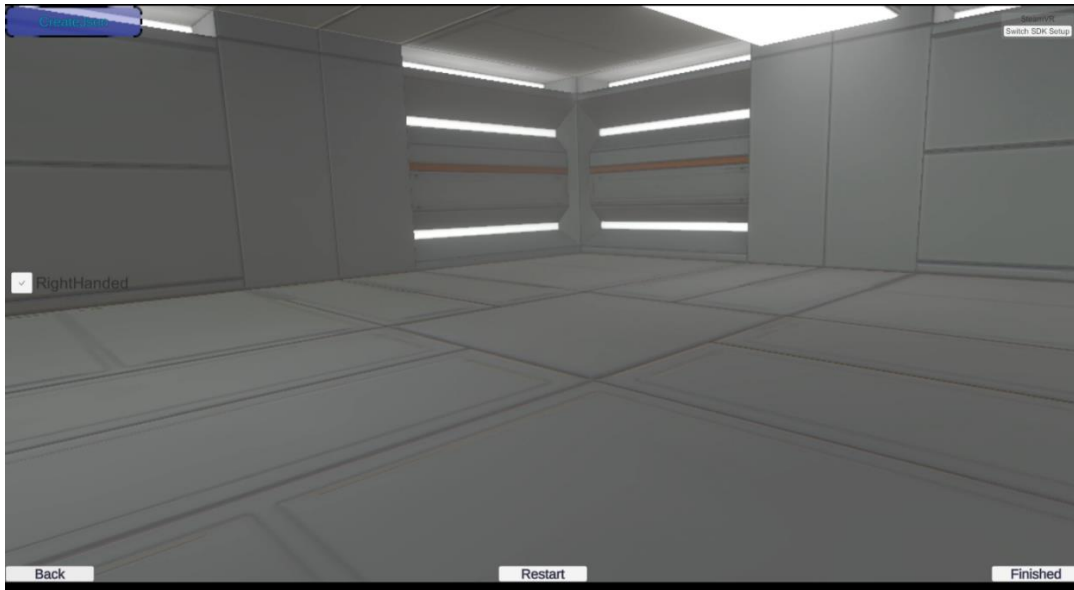


Fig. 12 Empty Virtual Reality Environment



Fig. 13 Space for VR testing with visible tracking stations on the wall sides

10.3 3D Models

The models of glue gun and caulking gun were first downloaded from the web and slightly adjusted in Blender software for my experiment.



Fig. 14 Glue gun model in 3D Viewer

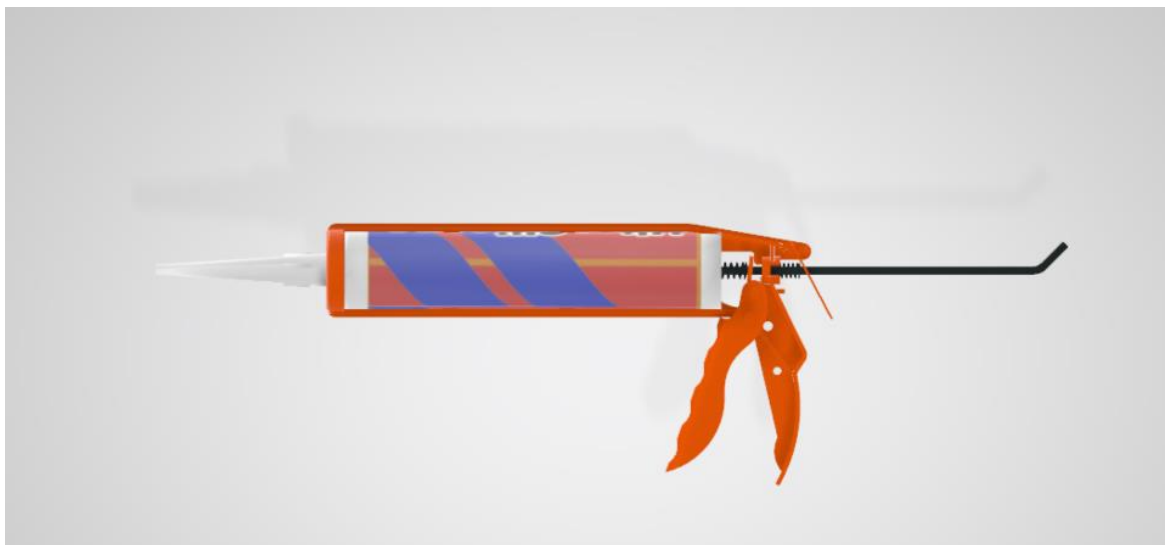


Fig. 15 Caulking gun model in 3D Viewer

10.4 Shape models

Line, circle and sine wave models were modeled in Blender software using curve objects and were very thin, in order to create a strict movement, pattern that participants had to follow. The thinner the objects were, the less would be scatter in precision.

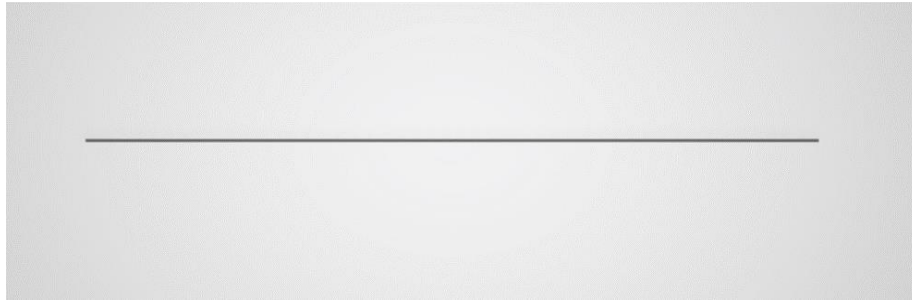


Fig. 16 Line model in 3D Viewer (default grey/unchanged color)

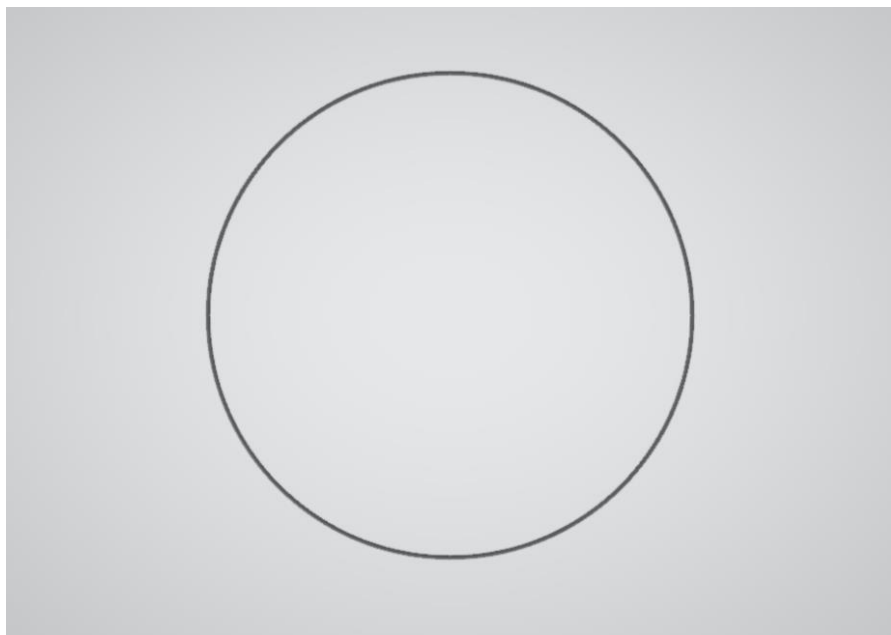


Fig. 17 Circle model in 3D Viewer (default grey/unchanged color)

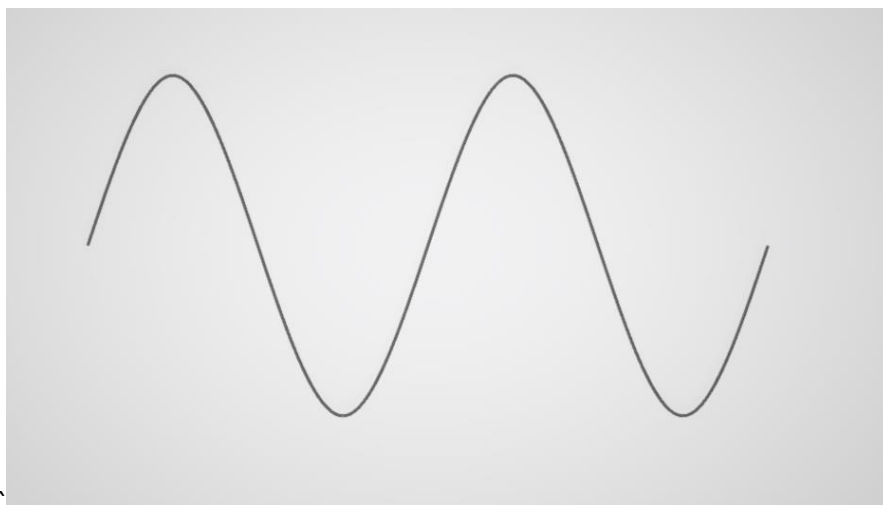


Fig. 18 Sinus wave model in 3D Viewer (default grey/unchanged color)

10.5 Procedure

The complete one-day session lasted around 20-25 minutes depending on participants abilities. Each of them was instructed to draw with the glue gun (one hand) and caulking gun (both hands) inside of the shape, which was on the table, as precise and as fast as possible, but it was completely up to them which of the two aspects (precision or speed) they would choose over the other. They just needed to do it the best way they could or they thought they could.

Participants would be handed HTC Vive Pro controllers and placed in a specific location/area in the real environment, so that the tracking stations could follow hand movement of participants throughout the whole experiment, to avoid any jitter or freeze. Despite having best conditions, this could still happen sometimes, so the drawing on which the tracking was jittery had to be erased and be redone again. The drawing started on button press and finished on button release.

Once the VR scene started, participants would be spawned right in front of the table, as everything was positioned (both in VR and RW) in a way to make the experience for participants as comfortable as possible. The drawing was done using Unity3D game engines line renderer component, that would draw points on the position of glue gun or caulking gun edge when VR controller movement changed and the button was pressed. The distance at which the points could be drawn was adjusted in such a way, that when drawn, the points were so close to each other, it created an illusion of a continuous drawing line of yellow color. If the distance was adjusted for higher values, such as 1 cm, the points would be drawn 1cm apart from each other while participant held controller and drew in VR, with this big distance between points, there would be no continuous line, but simply points in 3D space. Additionally, the more points there were, the more accurate data that could be gotten. In this experiment, the distance was less than a millimeter. The smaller the distance between point centers, the more points would be drawn. Because it's easy to do calculations with that data, it was not a concern to reduce the distance between the points' centers to a very small amount and having many of them.

Big distance between points



Small distance between points



Fig. 19 Big distance between points' centers vs small distance

Below are shown the images for each simulation. These images are taken during the drawing process, where you can see from the perspective of a participant. The green statically positioned shape is the one, participants had to draw inside and the yellow is the one they actually drew.



Fig. 20 OHL Drawing

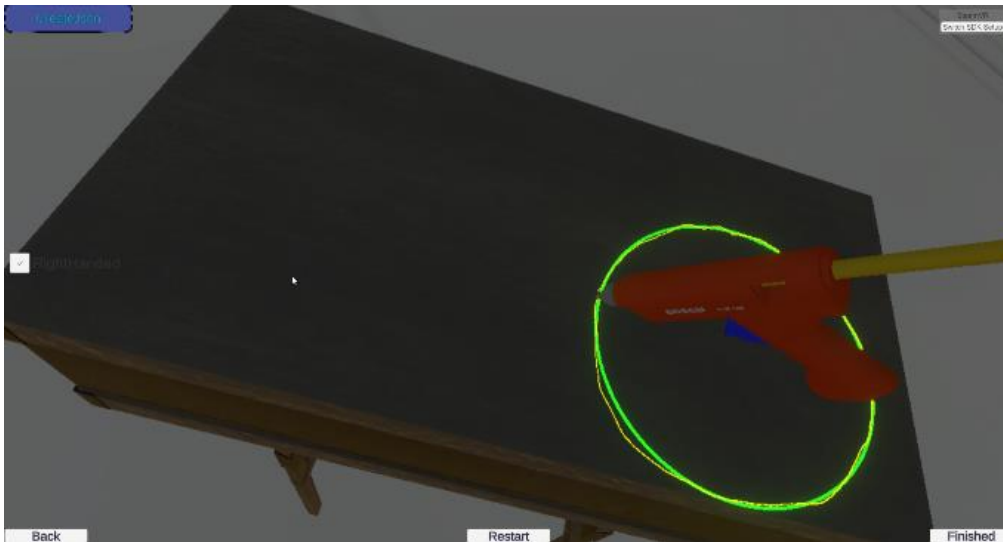


Fig. 21 OHC Draing

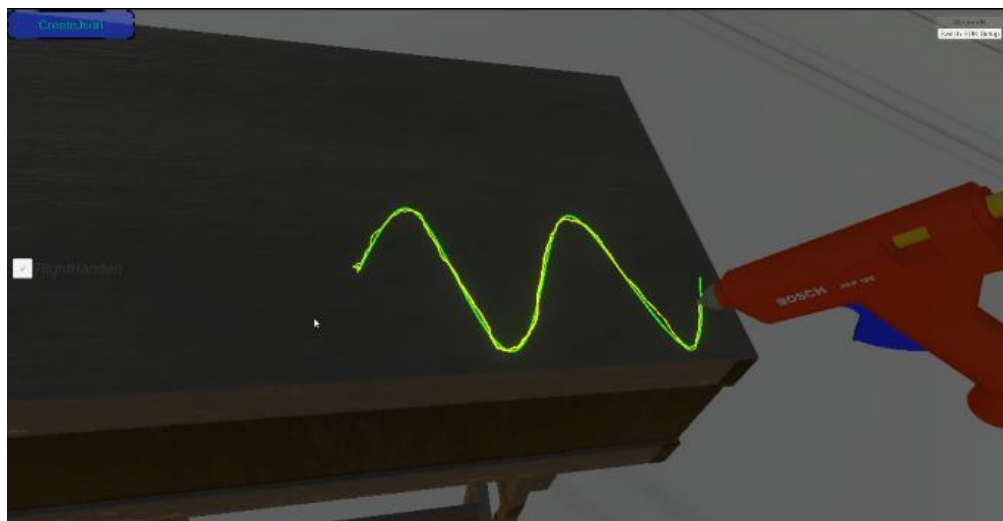


Fig. 22 OHS Drawing

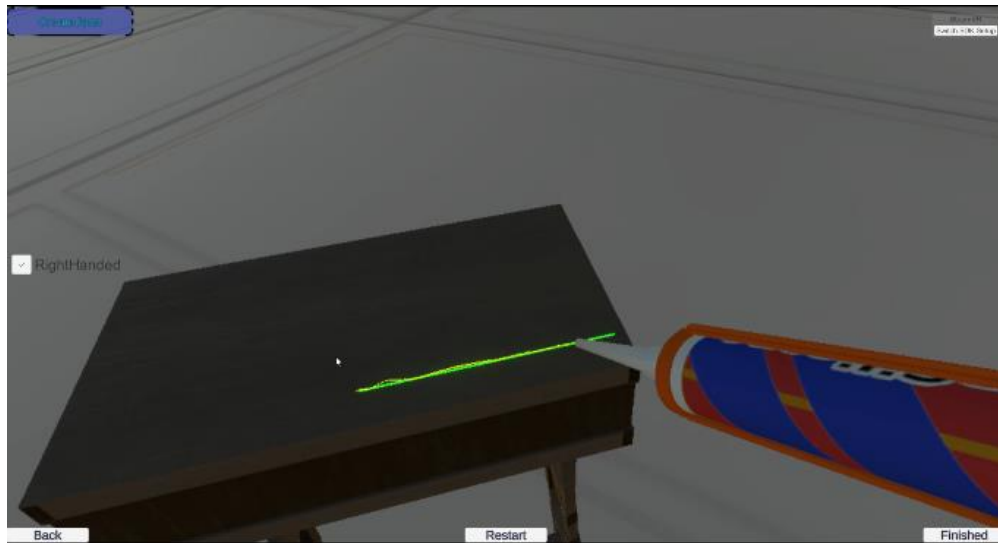


Fig. 23 BHL Drawing

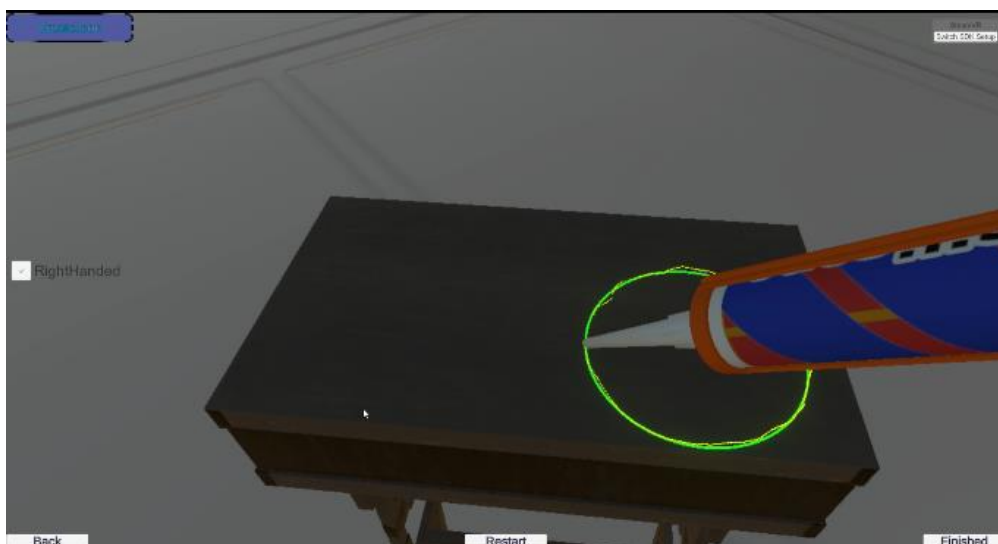


Fig. 24 BHC Drawing

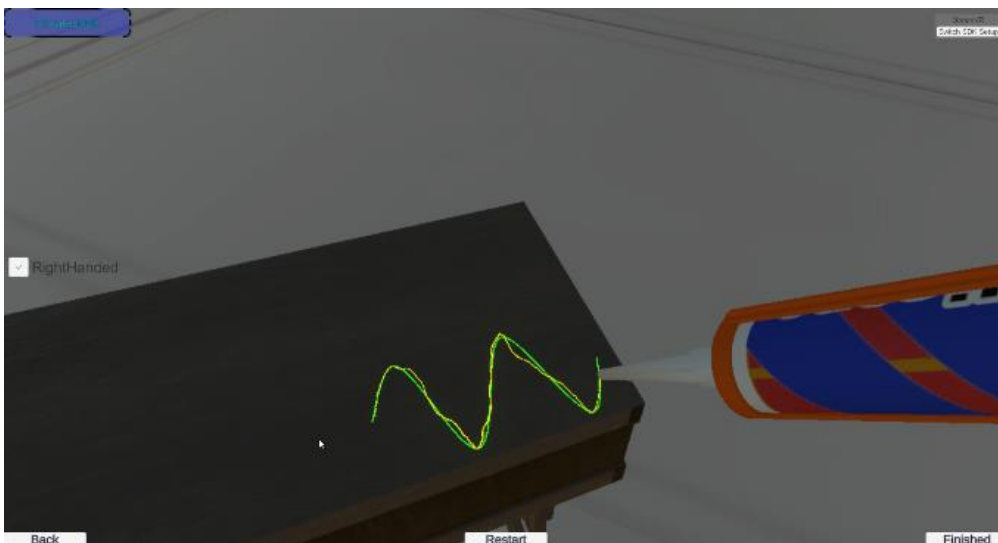


Fig. 25 BHS Drawing

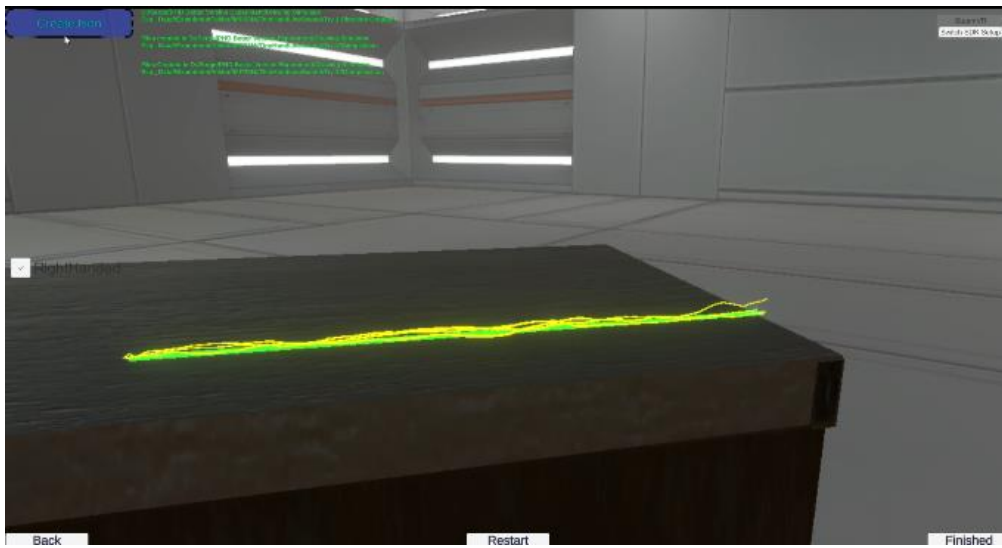


Fig. 26 Line drawing result



Fig. 27 Circle drawing result



Fig. 28 Sinus drawing result



Fig. 29 Participant during VR test

Each test was controlled and observed and once participant finished the test, another scene would be manually opened, till all of them were finished. Final data was exported in the form of a Json file that contained information about drawn points in 3D space, for calculating the distance to the actual shape, that participants had to draw on, which was on the table.

```
{  
  "pointNumber": 197,  
  "vectorPosition": {  
    "x": 0.5038178563117981,  
    "y": 1.0592365264892579,  
    "z": -0.4701833426952362  
  },  
  "isTouchingObject": true,  
  "objectName": "Sine",  
  "hitColliderCountTrue": 69,  
  "timeSpent": 6.395934104919434  
},
```

Fig. 30 Exported points data snippet from Unity3D in Json format

This small snippet of data from Json file shows information only about the first 2 points of the drawn line. For each shape, the amount of points varied, due to shape length, but on average, for line it was around 200 points, for circle 500 points, and for sine wave 400 points. Here are shown x, y, z Unity3D coordinates of each point, which was used for distance calculations between drawn points and the actual shape that was on the table. Additionally, other data was gathered, such as collision with the object info, the name of the collided object, proportion of collided points with shapes in the whole drawn line and time spent from the start of drawing (when controller button is pressed) till finish (when controller button is released).

In the end, only x, y, z coordinates and time data were used for final calculations and comparisons, all other remaining data was left unused.

10.6 How the raw data was gathered and saved for VR

During the testing, when participants had to repeat/draw the exact shape object (line, circle or sinus) that was presented in front of them on the table, the Vector3 positions (x, y, z) of points in a line renderer, a Unity3D object, were collected to be saved later with other data.

Apart from this data, there were other arguments that were gathered during the performing process. Those held custom information for each of the point inside a line renderer, such as a Boolean variable that checked if anything was hit at all by the glue gun edge/caulking gun edge, the objects name that was hit (if hit at all), and the time that was spent for each shape to be drawn, counted from pressing a button till it was released (HTC Vive controller). All these arguments were gathered in a separate list of custom class type (C#).

Once all four repetitions of the same process were completed, before moving to a new Unity3D scene/test (overall six), the data gathered in the temporary list was converted into Json file format and exported in a specified folder with specific naming, in accordance to each participants representation in the experiment, for example. The data path to which json files were saved could look like the following: "Desktop/Experiment/participant_name/experiment_type/session_number". Json file format is very commonly used for such cases, when its needed to send/receive chunks of text data from one source to another, additionally there are many applications that support this file format so it makes it to be easily imported.

10.6.1 JSON Definition

JavaScript Object Notation (JSON, pronounced /'dʒeɪsən/; also /'dʒeɪsɒn/) is an open standard file format, and data interchange format, that uses human-readable text to store and transmit data objects consisting of attribute–value pairs and array data types (or any other serializable value). It is a very common data format, with a diverse range of applications, such as serving as a replacement for XML in AJAX systems. JSON is a language-independent data format. It was derived from JavaScript, but many modern programming languages include code to generate and parse JSON-format data. The official internet media type for JSON is application/json. JSON filenames use the extension. json.

10.6.2 Converting raw json data to Excel using third party applications

Converting the data from json format to Excel was a pretty easy task, due to these tools being very popular, many such converters, free and paid, exist that work easily between these software's. In this project were used free online json-excel converters as they answered our simple needs. After data conversion, Excel was presented as several columns and rows of that data, where each parameter (Position of points, time spent etc) were given on their own column and each row represented next value. This converted data then was simply copied and pasted into a pre-prepared template for calculation.

10.6.3 Moving the raw Excel data into a pre-prepared template for calculations

As precision calculation for each of the shapes (line, circle sinus) required different techniques of measurements of the distances between points and those shapes, there were prepared three Excel templates with macros that would automate the calculation for each column once the data was pasted inside and specific key was pressed. This operation of conversion and copy-pasting was done for each of the file (movement/drawing capture), which were done four times for each shape by every participant on each session. So, simply put, for just one session per participant, there were 24 json files generated that needed to be converted, copy-pasted into the template and calculated via an Exell macro.

10.7 Calculations

When all the participants finished the experiment, the data that was exported in the format of Json files, was converted into an Excel format and copied into a prepared template. In order to calculate the distance between points and shapes (line, circle, sine), each shape calculation required separate template, as the formulas are different for each of them.

	A	B	C	D	E	F	G	H	I
1	pointNumber	vectorPosit	vectorPosit	vectorPosit	isTouching	objectName	hitCollider	timeSpent	
2	1	0.4317479	1.0596660	-0.5374339	FALSE		0	0.0	
3	2	0.4320558	1.0589103	-0.5366010	FALSE		0	0.1668144017457962	
4	3	0.4311432	1.0592337	-0.5369809	FALSE		0	0.233209490776062	
5	4	0.4303274	1.0595567	-0.5374661	TRUE	Sine	1	0.2777699828147888	
6	5	0.4291670	1.0602304	-0.5367459	TRUE	Sine	2	0.33321520686149599	
7	6	0.4286767	1.0602988	-0.5351713	TRUE	Sine	3	0.4552820026874542	
8	7	0.4285319	1.0603507	-0.5340994	TRUE	Sine	4	0.4776703119277954	
9	8	0.4275293	1.0608899	-0.5333362	TRUE	Sine	5	0.5559384226799011	
10	9	0.4265895	1.0607389	-0.5327079	TRUE	Sine	6	0.7108497619628906	
11	10	0.4265615	1.0603677	-0.5316910	TRUE	Sine	7	0.7667561173439026	
12	11	0.4261764	1.0599159	-0.5304850	TRUE	Sine	8	0.8332480192184448	
13	12	0.4258157	1.0592552	-0.5292265	TRUE	Sine	9	0.8885524868965149	

Fig. 31 Snippet of converted Json data in Excel

10.7.1 Line

In Unity3D game engine, y axis coordinate corresponds to up and down movement. When calculating line equation, we need to know 2 points the line passes through. Due to line shape being on the same height level (y axis) and only x and z axis being varied, it was impossible find 3D line equation in canonical form. Thus, only x and z coordinates of the line to find 2D line equation were used.

Simply put, calculations were made by creating a right-angled triangle and calculation the distances. First step would be projecting perpendicular line from each drawn points y axis to the line shape y axis. The absolute length of that difference would be one of the catheters of the triangle. Now when 3D complexity is eliminated, second step would be using 2D line equation to find distance between each point's new coordinates (in 2D, while y axis is eliminated) and the line, so that we could find another catheter. Third and final step would be finding hypotenuse by using two catheters we found before, this would give us the distance between each point and the line shape in 3D. No matter if the point was higher or lower (y axis) than that of the line, still the absolute value of that length was used.

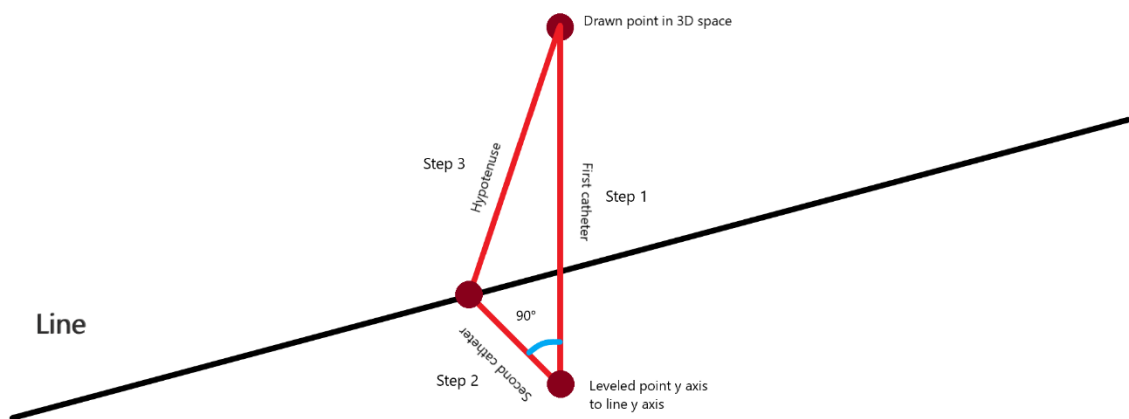


Fig. 32 Complete process of distance calculation between a point and line

Given the 2 points the line passes through, the 2D line equation is shown below.

$$1.6x - y - 1.003 = 0$$

To find distance between point $M(M_x, M_y)$ and the line, we must use formula:

$$d = \frac{A * M_x + B * M_y + C}{\sqrt{A^2 + B^2}}$$

In Excel template, all these steps were performed using a macro. The numbers were still in Unity3D scale format, where 1 unit corresponds to 1 meter. Later, after all the calculations were finished, numbers were converted to mm. As described before, participants drew shapes on each session 4 times in VR, to average it out later for higher accuracy. The Excel file contained 4 sheets, one for each drawing on each session. Once all the steps and averaging for each sheet were performed, the average of time and distance were calculated between all 4 sheets again for the final Results sheet already in mm. Lesser distance meant higher precision.

Overall Time		Leveling PointY to LineY	New PointY to Line 2D	Drawn Point to Line Distance 3D	Average Distance
		-1.06	-0.7071	1.274204	

Fig. 33 Line template sheet calculations/steps

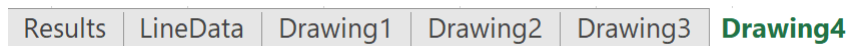


Fig. 34 4 Separate Drawing sheets in Excel

Data to use from this color Data is an average of 4 drawing per session. 1 Day/Try = session. Session = 4 drawings of each shape) // // //	
Results	
Average Time	#DIV/0!
Average Distance(mm) from the Line to a drawn point(Closest)	#DIV/0!

Fig. 35 Results sheet

```

Attribute VB_Name = "Module1"
Sub AutoFill()

Dim ws As Worksheet
For Each ws In ThisWorkbook.Worksheets
    If ws.Name <> "Results" And ws.Name <> "LineData" Then
        ws.Range("J2") = ws.Range("H" & Rows.Count).End(xlUp).Value
        ws.Range("N2").AutoFill Destination:=ws.Range("N2:N" & ws.Range("A" & Rows.Count).End(xlUp).Row)
        ws.Range("Q2").AutoFill Destination:=ws.Range("Q2:Q" & ws.Range("A" & Rows.Count).End(xlUp).Row)
        ws.Range("T2").AutoFill Destination:=ws.Range("T2:T" & ws.Range("A" & Rows.Count).End(xlUp).Row)
        ws.Range("X2") = Application.Average(ws.Range("T2:T" & ws.Range("A" & Rows.Count).End(xlUp).Row))
    End If
Next ws
End Sub
    
```

Fig. 36 Line Template Macro

10.7.2 Circle

The same way as in the Line calculations, we eliminate 3D factor by projecting the y axis of the point to the y axis of the circle, using perpendicular line. The absolute value of the difference would give us one catheter of a right-angled triangle, this is the first step. Once the new 2D coordinates of each point were established, the distance between each point and circle center was calculated. Then we would have to do a simple operation of reducing from radius (10 cm) of the circle that second distance value, the absolute value of which would give us the distance between the new 2D coordinate of a point to the circle circumference, which is the second

step. This would give us the length of the second catheter of the triangle. Once, both catheters were found, the third step would be finding hypotenuse, which would be the distance between a point and circle circumference in 3D space.

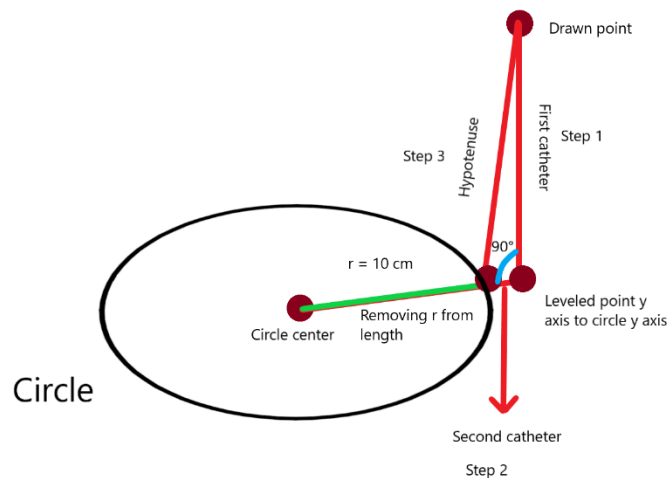


Fig. 37 Complete process of distance calculation between a point and circle circumference

The Excel template with macro for circle calculations is identical to the line template, thus, duplicate images will not be shown in this section.

10.7.3 Sinewave

When it comes to sinus calculations, due to change of position and rotation of the sinus shape in Unity3D world (for better positioning and VR tracking), it became a bit more complicated to do the distance measurements. For that purpose, the third parametric value was brought into the calculations. To calculate the distance between points and sinus wave we need the formula of the sinus first. This was done using GeoGebra mathematic software, that allowed us to insert default parameters, find the function and then rotate to the amount it was rotated inside Unity3D world (43.61°).

Knowing the coordinates that sine wave intersects after rotation, it was possible to calculate the rotated version of the same sinus wave, but this time, with new parametric value as shown below. Here red circle indicates the world center in Unity3D and the blue segment of the sinus, indicates the position and length in the same world.

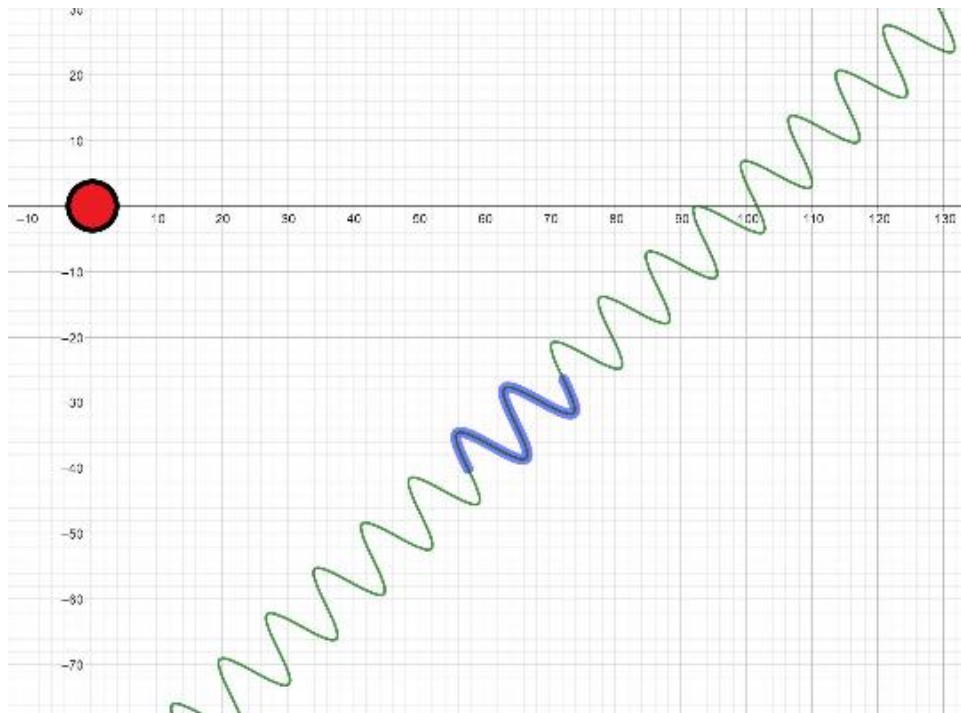


Fig. 38 Rotated Sine Wave in Geogebra Software

Although here the function is shown with x and y parameters, taking into consideration Unity3D world specifications, as y axis corresponds for up/down movement and the shapes y axis were unchanged the whole time, here, y axis was replaced by z axis for calculations.

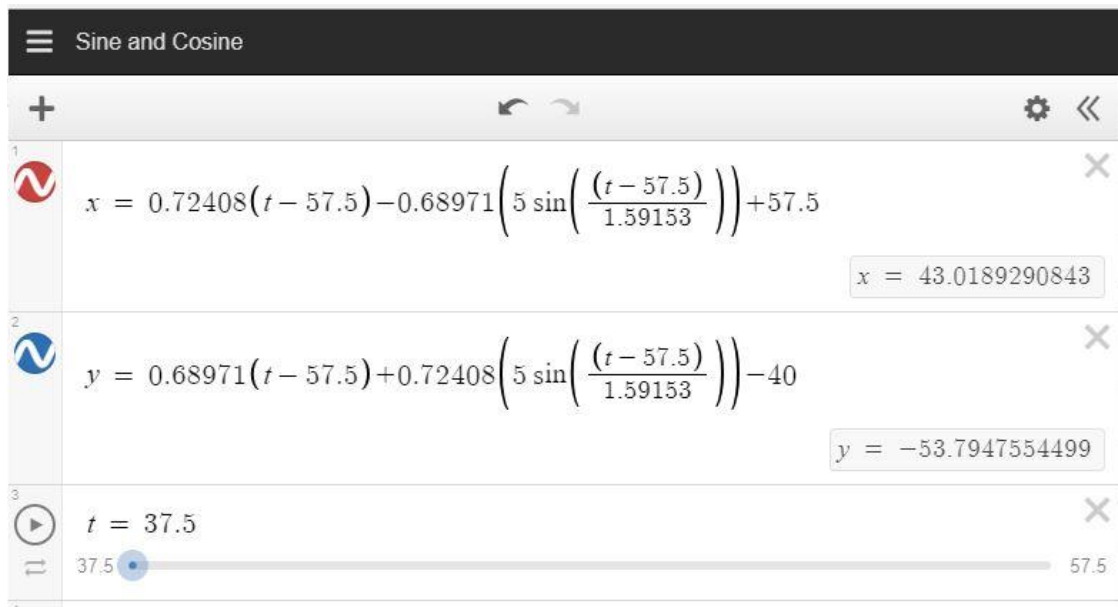


Fig. 39 Function after repositioning and rotation of sine wave object

Parametric value range that was found to be the most precise, is between 37.5 (where sine wave starts) and 57.5 (where sine wave ends). Small increments of 0.0005 to the parametric value allowed us to have 400 points on the sinus wave that could be used to find the closest distance between each point of a drawn line to one of the coordinates on the sine wave.

Simply put, each point of a drawn line (of yellow color drawn by participants) would iterate through each point on a sine wave (calculated through parametric value inside new rotated sine function using macro) and try to find the closest point and when found, write inside a designated cell in Excel the distance value. The process would finish when the last point stopped iterating through sine wave points, created with parametric values.

To illustrate this method, below is the image showing one of the drawn points (yellow) finding the distance between the points (red, overall 400 in the span on the sinewave) on the sine wave created by changing parametric value.

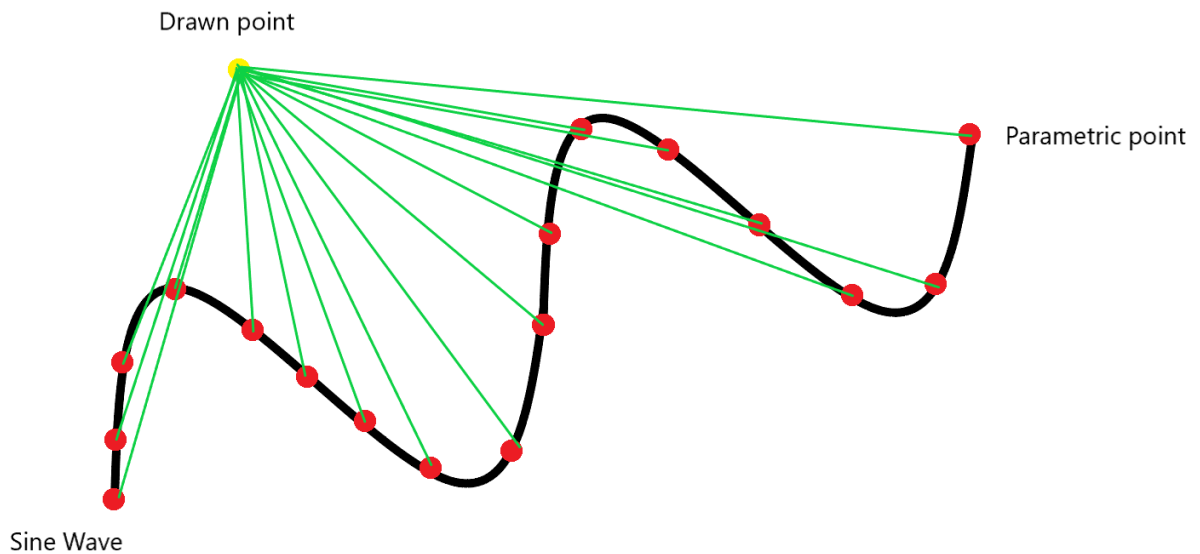


Fig. 40 Sine wave distance calculations using parametric values

In order to do all these calculations, a macro in Excel was used, that would grab a point, iterate through each new point on a sine wave generated by a new parametric value, find closest point, and when finished, grab another point and do it again, until running out of all drawn points. The rest of the sheets are identical to the other templates, thus avoiding using duplicate images.


```
Attribute VB_Name = "Module1"

Sub AutoFill()
Attribute AutoFill.VB_ProcData.VB_Invoke_Func = "r\n14"

Dim i As Integer
Dim j As Integer

Dim distance3D As Single
Dim smallestDistance As Single
smallestDistance = 1

Dim ws As Worksheet

For Each ws In ThisWorkbook.Worksheets
    If ws.Name <> "Results" And ws.Name <> "SineWaveData" Then
        ws.Range("O2") = ws.Range("H" & Rows.Count).End(xlUp).Value
        For i = 2 To ws.Range("A" & Rows.Count).End(xlUp).Row
            smallestDistance = 1
            For j = 2 To ws.Range("J" & Rows.Count).End(xlUp).Row
                distance3D = Sqr((ws.Cells(j, 11).Value - ws.Cells(i, 2).Value) ^ 2 + (ws.Cells(j, 12).Value - ws.Cells(i, 3).Value) ^ 2 + (ws.Cells(j, 13).Value - ws.Cells(i, 4).Value) ^ 2)
                If distance3D < smallestDistance Then
                    smallestDistance = distance3D
                End If
            Next j
            ws.Cells(i, 19).Value = smallestDistance
        Next i
        ws.Range("M2") = Application.Average(ws.Range("S2:S" & Rows.Count).End(xlUp).Row))
    End If
Next ws

End Sub
```

Fig. 41 Sine calculation template Macro in Excel

10.8 VR experient results

Once all the data was calculated and exported to a separate template that would hold it, the next step was to identify the trend in precision and speed. Below is just an example of one Excel sheet that holds precision and speed information from all participants in only one type of simulation (overall 6).

Participant	One Hand Circle (sec/mm)													
	Try 1	Try 2	Try 3	Try 4	Try 5	Try 6	Try 7	Try 1	Try 2	Try 3	Try 4	Try 5	Try 6	Try 7
1	5.3	6.9	8	8.5	7.4	7.4	6.3	15.3	14.1	5.2	6.4	7.1	5.2	6.3
2	5.5	7.8	9.6	7	7.7	7.7	7.2	15.3	17.1	7.8	5.4	6.5	4.9	5
3	6.2	6.2	6.1	4.3	5.7	7	4.6	12.8	7.5	5.7	5.7	6.3	8	7
4	23.3	24.9	22.8	24	16.7	11.6	9.3	19.9	19.8	14.7	11.4	16.1	11.4	9.1
5	15.1	19.8	16.1	13.1	11.9	11.9	8.7	9.2	13.5	8.2	6.5	5.2	6.6	5.2
6	10.5	11.1	10.4	8.1	8.1	6.7	7.3	6	5.7	5.7	4.2	9.3	7.3	5.4
7	12.2	4.1	11	8.3	5.4	6.1	6	9.3	8	12.1	4	7	7.5	4.8
8	7.6	7.2	8.8	7.5	5.5	5	4.6	32.8	8.8	4.1	6.2	7.9	7.1	6
9	16.9	14.1	12	8.8	9.1	11.5	8.6	7.3	6.2	9.3	4.9	6.9	4	5.6
10	14	17.8	17.1	14.1	19.2	15.1	15.7	15.9	4.3	4.5	3.8	3.6	3.6	2.5
11	7.9	5.9	5.6	5.6	6	7.7	6.6	10.5	4	4.8	4.9	3.9	4	4.5
12	17.9	10.4	9.9	16.5	12.7	11.2	8.1	5.6	4.6	3.8	3.1	4.1	4.9	3.5
13	10.6	14.5	11.6	11.7	14.5	9.7	11.1	8.9	8	8	7.4	4.5	6.9	6.7
14	18.1	12	15.6	16	15.6	12.6	7.6	20.2	9	8.7	19.9	8.5	20.6	4
15	13.3	16.5	17.1	18.1	15.4	17.5	18.5	3	2.6	2.8	2.3	2.9	2.7	2.9
16	13.1	16	11.1	8	9.1	11.1	10.2	2.7	2.5	2.7	3.7	3.4	3.4	3.7
Avg T/D	12.3438	12.2	12.05	11.225	10.625	9.9875	8.775	12.16875	8.48125	6.75625	6.2375	6.45	6.75625	5.1375

Fig. 42 Data holder for one hand circle simulation with found averages

Once the averages for all sessions were found (yellow color), both data of each simulation type were inserted into a chart, meaning both data, precision and speed, would be shown in one chart. Average (red color) values of time and distance are the average values of all participants together from each session (try) column. This gave the overall trend, which was sufficient for the cause. Although, other ways (box plots, stacked columns) for presenting the data were prepared, the one was decided to show here, line chart with primary and secondary axis, was found to be the most laconic and informative. The result charts show the trends for time and distance. The decrease in these numbers indicates that precision and speed were increasing. In other words, decreasing trend means improvements in speed and precision, whereas increasing one, deterioration.

The first simulation type is OHL – one hand line. Here are presented all 7 sessions with averaged data from each participant for that session. The blue line indicates average time and the orange line, average distance. Additionally, linear trend line with dots is shown as well. As we can see, overall trend of distance and time is decreasing, which means that the speed and precision were improving over time. The average time to draw a line in one hand mode started at ~5 seconds on the first session and ended on a ~3.5 seconds mark on the last session, whereas average distance value started on a ~9.7mm mark and ended on a ~4.5 mm mark.

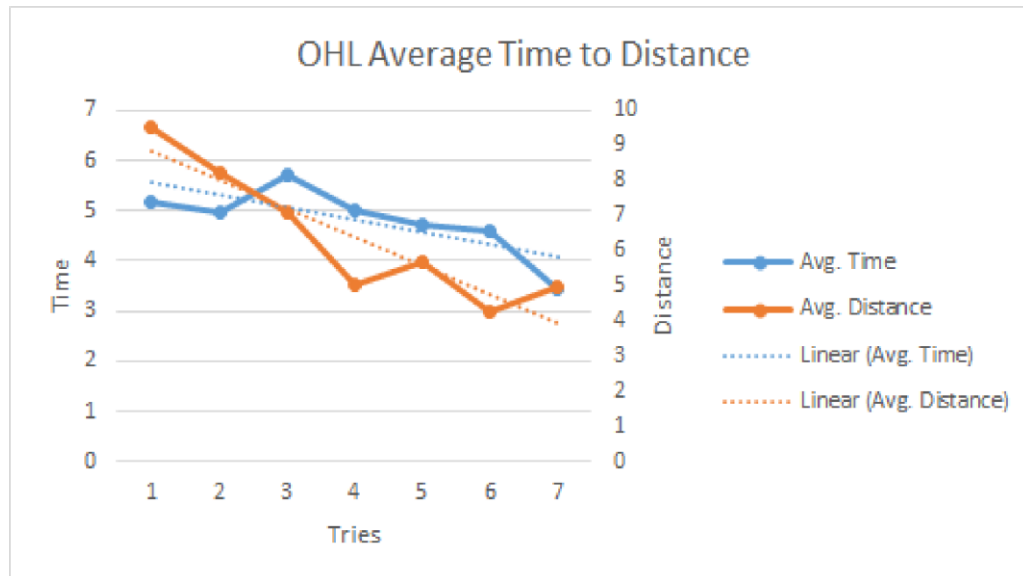


Fig. 43 OHL Avg. time to distance trend

The second simulation type is OHC – one hand circle. As before, here is presented averaged data with dotted trend lines indicating the decrease in distance and time to finish the movement, which means that participants precision and speed were increasing over time. The average time to draw a circle in one hand mode started at ~12 seconds on the first session and ended on a ~6.8 seconds mark on the last session, whereas average distance value started on a ~ 10 mm mark and ended on a ~5 mm mark.

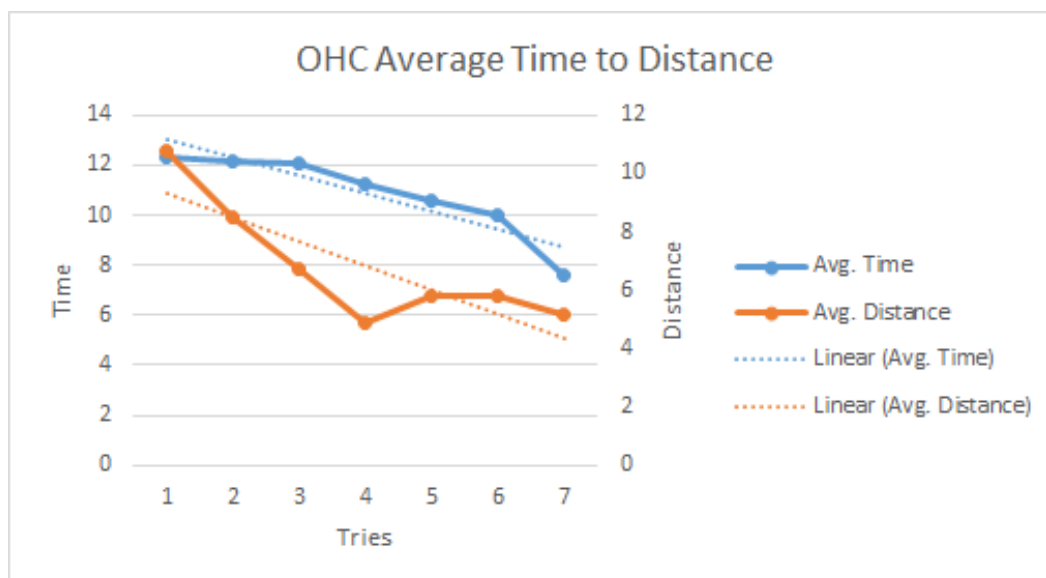


Fig. 44 OHC Avg. time to distance trend

The third simulation type is OHS – one hand sinus. Mostly repeating the pattern of previous simulation trends, there also is some bounce in the middle of the experiment but overall trend is indicating improvements in precision and speed. The average time to draw a sinus wave in one hand mode started at ~11 seconds on the first session and ended on a ~5 seconds mark

on the last session, whereas average distance value started on a ~ 7.5 mm mark and ended on a ~4.3 mm mark.

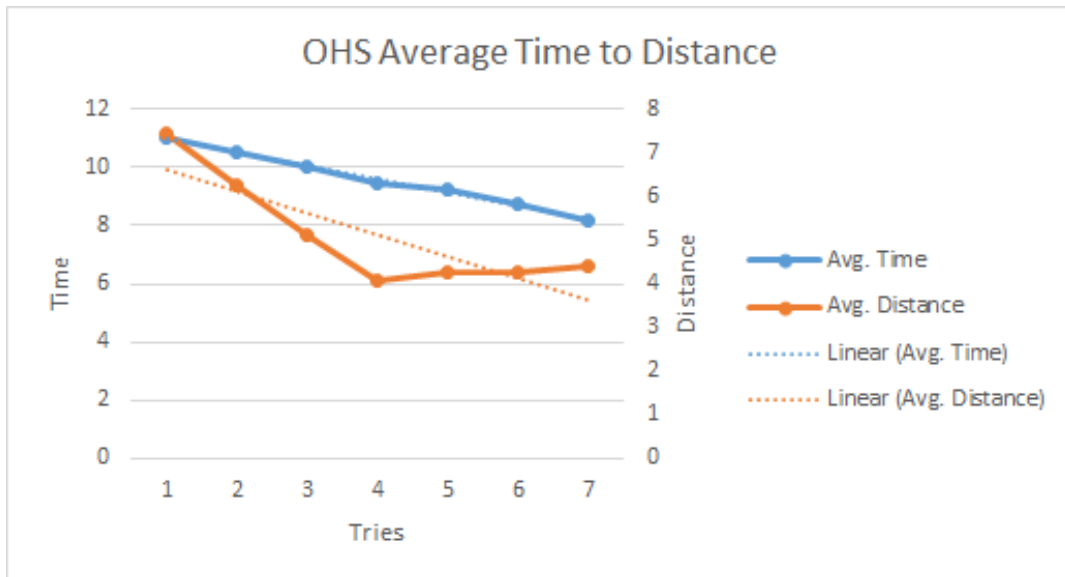


Fig. 45 OHS Avg. time to distance trend

The fourth simulation type is BHL - both hands line. Here average time trend is very gradual whereas distance trend bounced on the 3rd session and then continued gradual decrease. Again, overall trend is indicating improvements in precision and speed. The average time to draw a line in both hands' mode started at ~5.2 seconds on the first session and ended on a ~3.8 seconds mark on the last session, whereas average distance value started on a ~ 10.2 mm mark and ended on a ~6.3 mm mark.

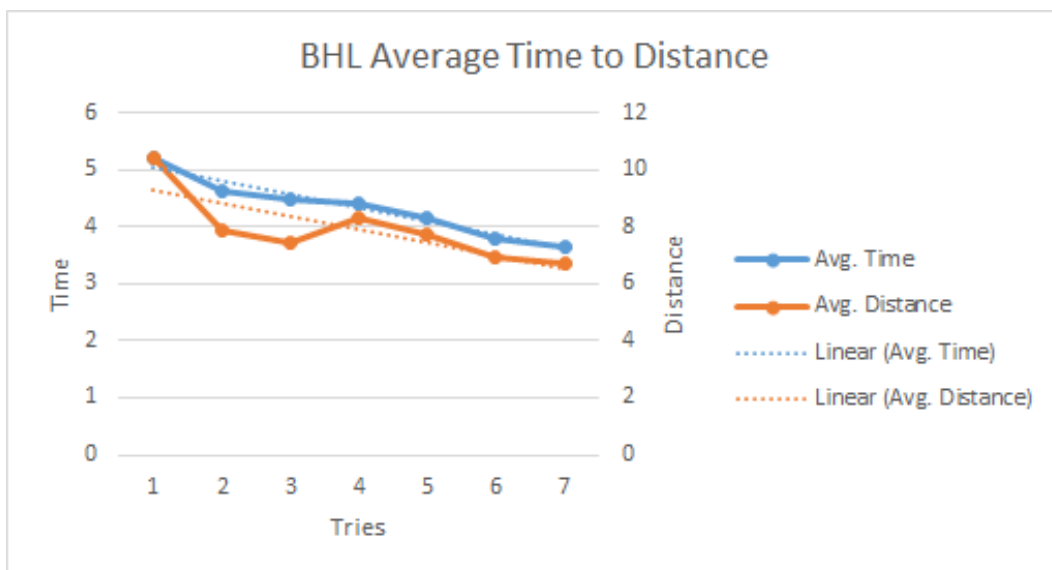


Fig. 46 BHL Avg. time to distance trend

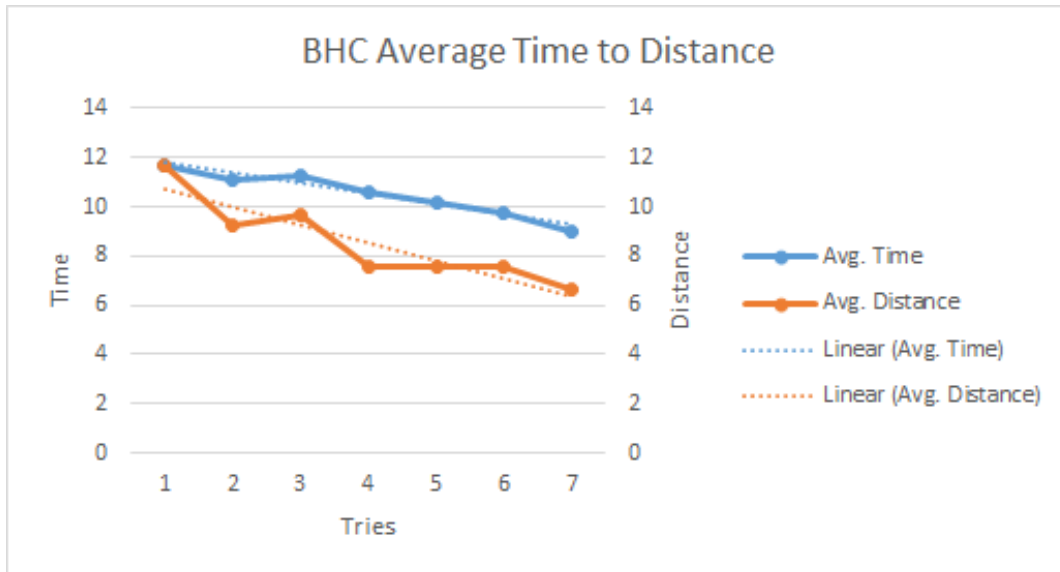


Fig. 47 BHC Avg. time to distance trend

The fifth simulation type is BHC - both hands circle. Here the decreasing trends for time and distance measurements are more gradual and show continuous improvements in speed and precision. The average time to draw a circle in both hands' mode started at ~12 seconds on the first session and ended on a ~8.5 seconds mark on the last session, whereas average distance value started on a ~ 12 mm mark and ended on a ~6.3 mm mark.

The sixth and last simulation type is BHS – both hands sinus. Very similar to other both hands type simulation results, we can clearly see continuous decreasing trends in distance and time, which again indicate improvements in precision and speed. The average time to draw a sinus wave in both hands' mode started at ~11 seconds on the first session and ended on a ~7.5 seconds mark on the last session, whereas average distance value started on a ~ 9 mm mark and ended on a ~7.5 mm mark.

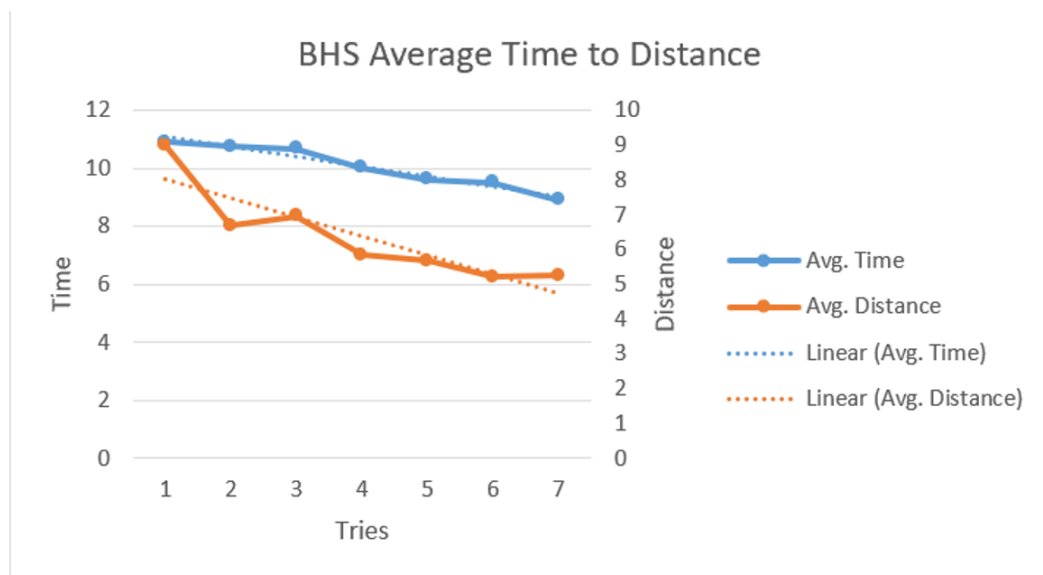


Fig. 48 BHS Avg. time to distance trend

11 Real world experiment

11.1 Equipment

For the experiment on the paper the same models as in VR were used, a real glue gun and a caulking gun. The sizes of real models were very similar to the ones in VR, same as drawings on the paper were similar to the 3D models of shapes in VR. Below are shown the real models of glue gun and caulking gun images.

Although the glue gun uses plastic as a glue that it melts when attached to electric socket, in this experiment pencil lead on the edge of the glue gun was used. This was a much easier solution than using melted plastic and it would allow us to get continuous line on a paper.

The caulking gun had a new unopened silicone tube. Similarly, instead of using silicone for drawing, the cap of a small pencil was inserted inside. This was an easier solution and produce better drawing results.



Fig. 49 Glue gun with pencil lead inside



Fig. 50 Caulking gun with small pencil attached

11.2 Paper/RW material

For each session (overall 2 for paper experiment), 5 A4 format papers were used for each participant.

1. One paper contained 2 lines on one side for one hand drawing (glue gun), and 2 lines on the back of the paper for both hands drawing (caulking gun).
2. One paper with 2 circles on both sides for one hand drawing (glue gun).
3. One paper with 2 circles on both sides for both hands drawing (caulking gun).
4. One paper with 2 sine waves on both sides for one hand drawing (glue gun).
5. One paper with 2 sine waves on both sides for both hands drawing (caulking gun).

Below are the images of the paper material with red colored shapes drawn on them. In addition, you can observe the drawings made by participants with glue gun or caulking gun (using pencil). The first number (ex. 5.7 or 7.3) indicates time to draw in seconds, and the second number (1 or 2), indicates one hand (glue gun) or two hand (caulking gun) test.

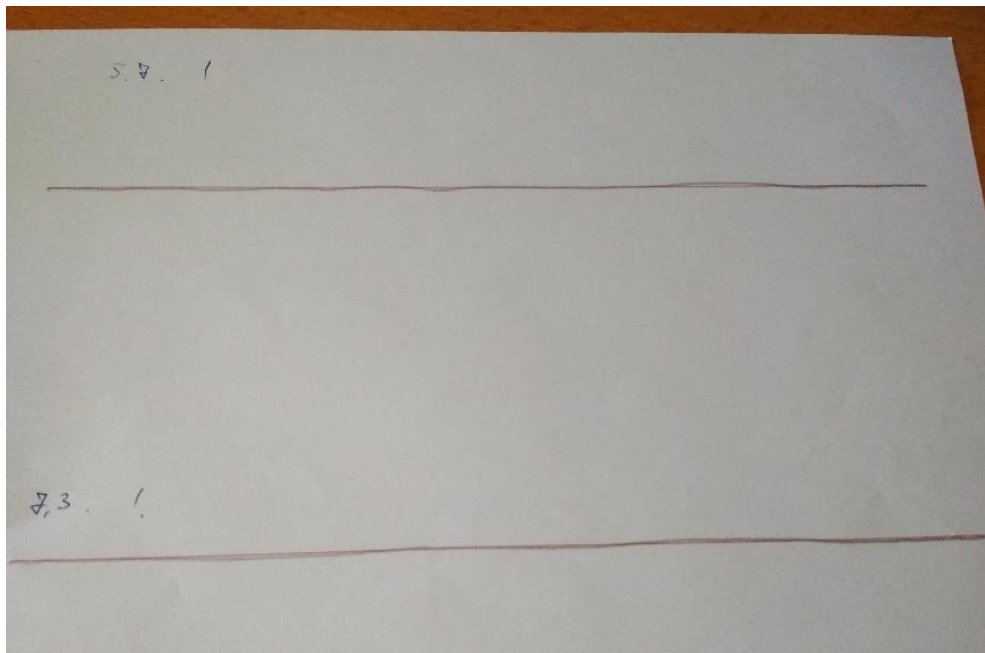


Fig. 51 OHL Drawing (1 handed)

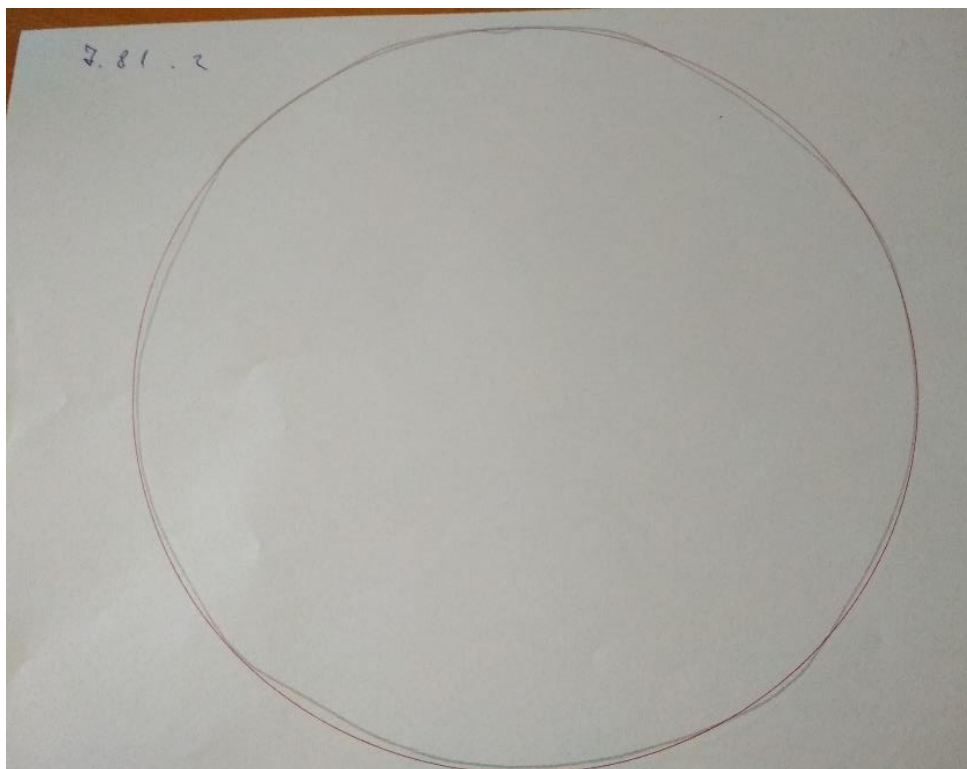


Fig. 52 OHC Drawing (2 handed)

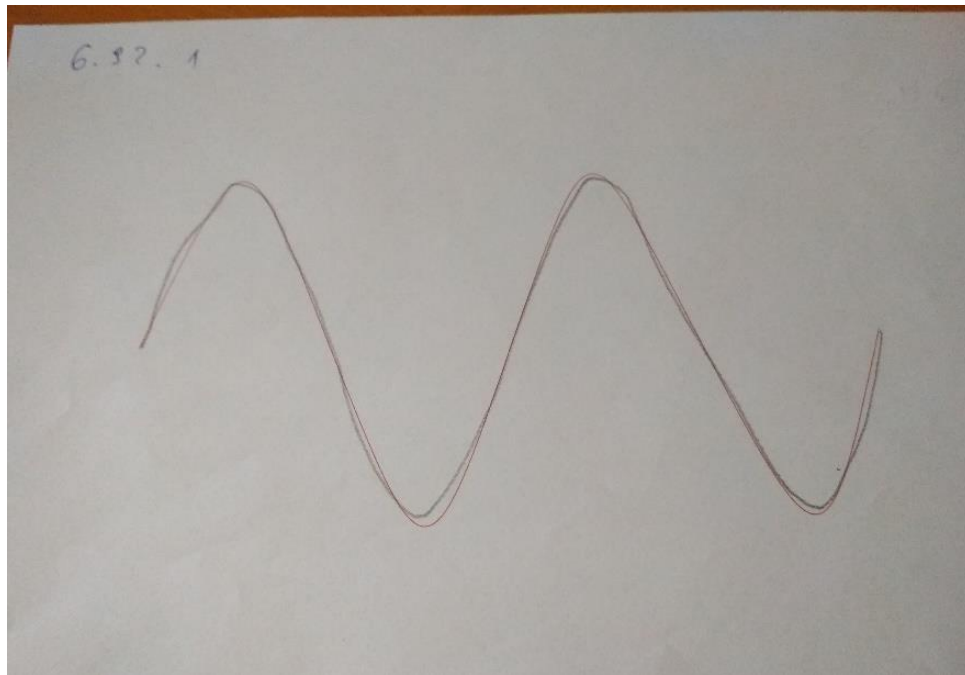


Fig. 53 OHS Drawing (1 handed)

11.3 Design

The design of this testing is very simple, it involved all participants standing and drawing with a glue gun or a caulking gun on the paper that was placed on a table of approximately 0.8 m height.

11.4 Procedure

Participants were positioned near the table where all paper materials and glue gun/caulking gun were prepared. Once a participant was given a tool, he/she would proceed drawing the shape on a paper. All participants were instructed to draw the shapes onto prepared red drawings as fast and precise as possible. Choosing either higher precision or speed was completely up to them. It just needed to be done with their best abilities. During the test, experimenter would hold the paper, so that it stays unmoved and additionally control time with a stopwatch. After each drawing, time to finish the drawing and test type (1 or 2) were written down near each drawing. Then the paper was either changed or turned for continuation of the process till all the drawings were done. Overall, the whole process could take around ~5 minutes, depending on participants decision to go either for speed or accuracy.

11.5 Calculations

Although, experiment on the paper was measuring the same factors as in VR, doing calculations here the same way as with VR data would be a huge challenge or maybe even impossible. For this reason, a different route was chosen. In order to measure accuracy of paper drawings, a transparent plastic cover was prepared, on which was printed each type of shape followed by multiple amount of points on them, used as a reference to check if drawings

went through them or not. These covers then were put onto the actual paper drawing results and points were calculated. Only the points that touched the drawing made by participant were counted. If drawn shape (grey) and red figure had some white space in-between, the point was counted as a miss. Below you can see all 3 covers for each drawing figure. Line cover included 52 points, circle – 112 points and sinus – 81 points.

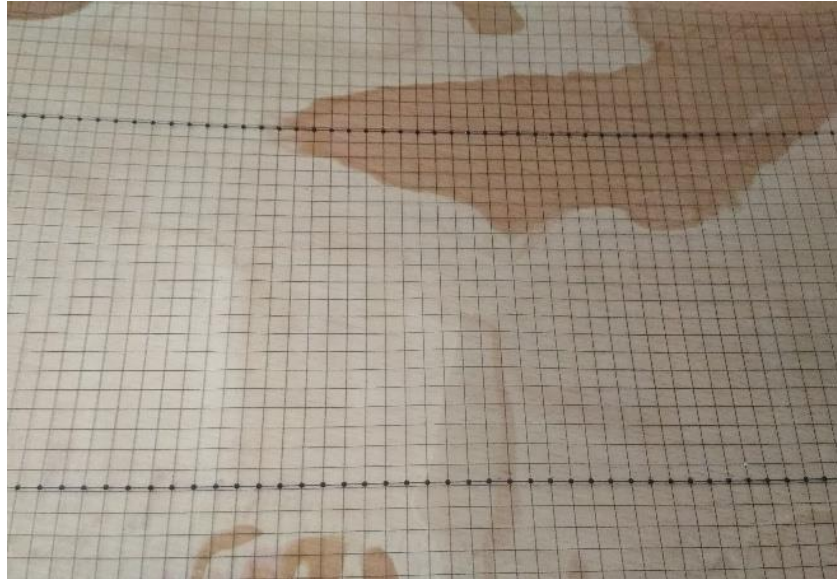


Fig. 54 Transparent foil for line points calculations (paper exp.)

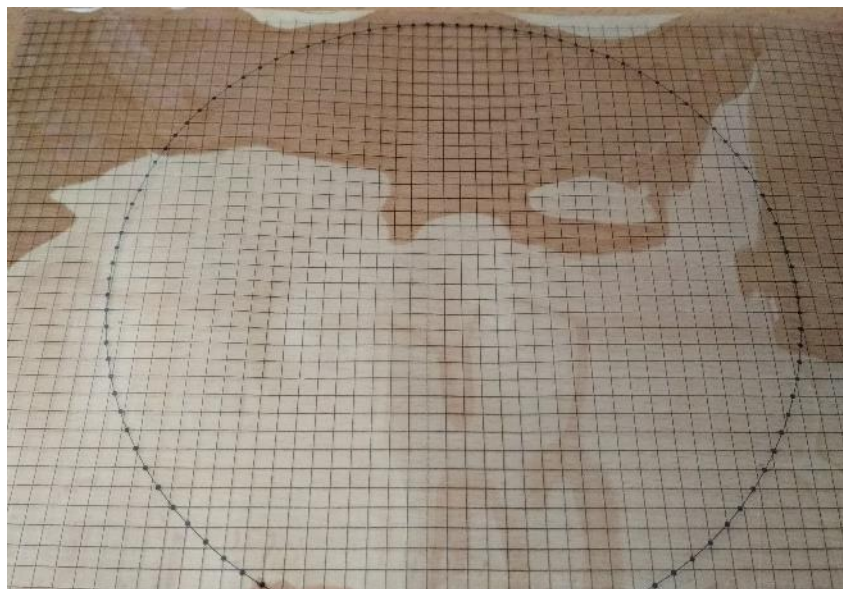


Fig. 55 Transparent foil for circle points calculations (paper exp.)

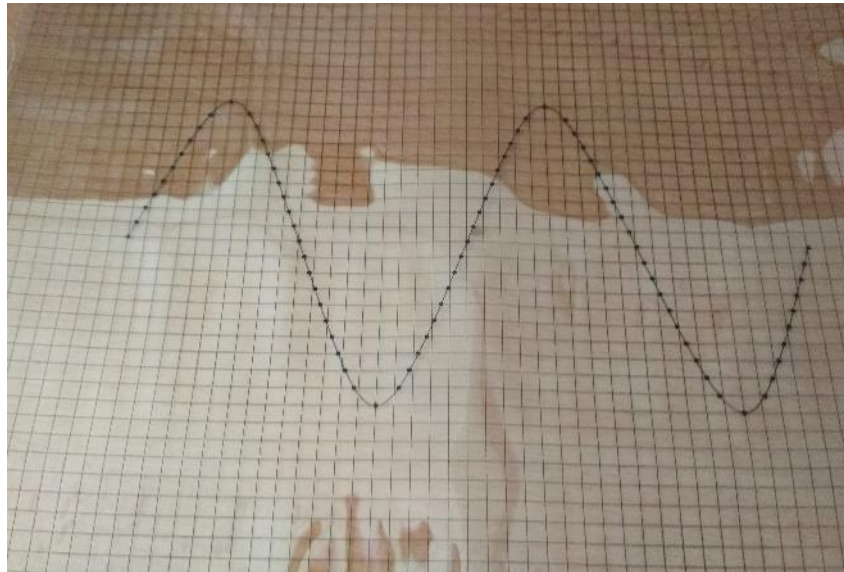


Fig. 56 Transparent foild for sinus points calculations (paper exp.)

11.6 Real world experiment results

Once all the points were calculated, they were converted into percentages. The higher the percentage, the higher the precision, meaning the more points were intersecting the drawn shapes done by participants (grey color).

Below you will see 6 images for each type of simulation. Both, precision and time data are in one chart, showing the trends between all participants for two sessions. The trends were found the same way as with VR data. All participant data (precision, time) were averaged out for each session and then put into a chart, to analyze a common trend.

The first type is OHL – one hand line test. Although, participants had VR sessions in a similar fashion, as we can see, results on paper indicate a slightly positive change in time required to draw a shape, but a negative effect for precision. Time to finish the drawing on the first session was ~6 seconds, and ~5 seconds on the second session. Precision of drawings on the first session was ~70%, and on the second session ~60%.

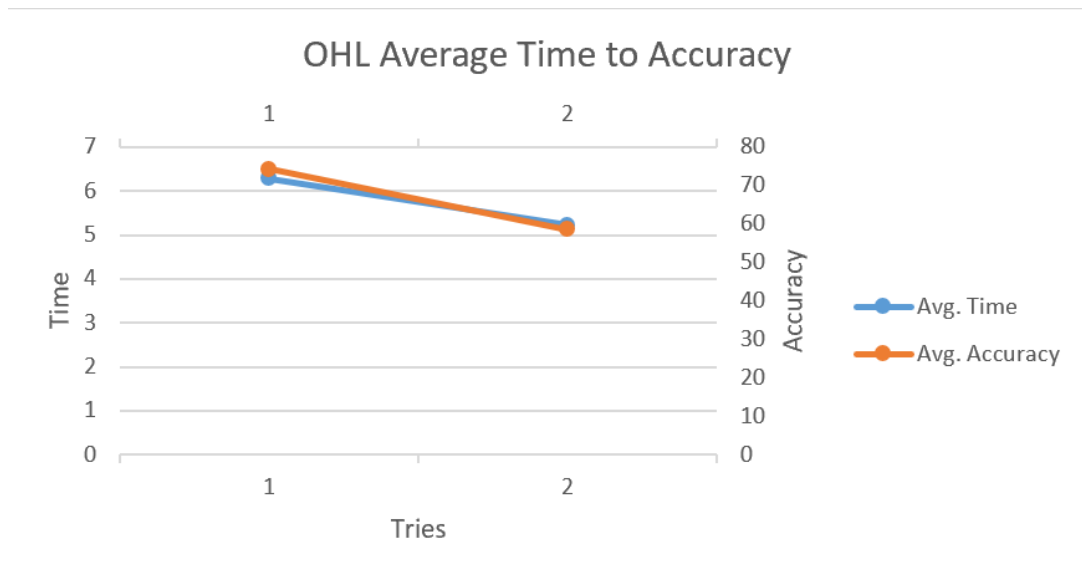


Fig. 57 OHL Avg. time to accuracy trend

The second type is OHC – one hand circle test. As we can see, results on paper indicate a slightly positive change in time required to draw a shape, but a sharp negative effect for precision. Time to finish the drawing on the first session was ~16 seconds, and ~14 seconds on the second session. Precision of drawings on the first session was ~65%, and on the second session ~ 56%.

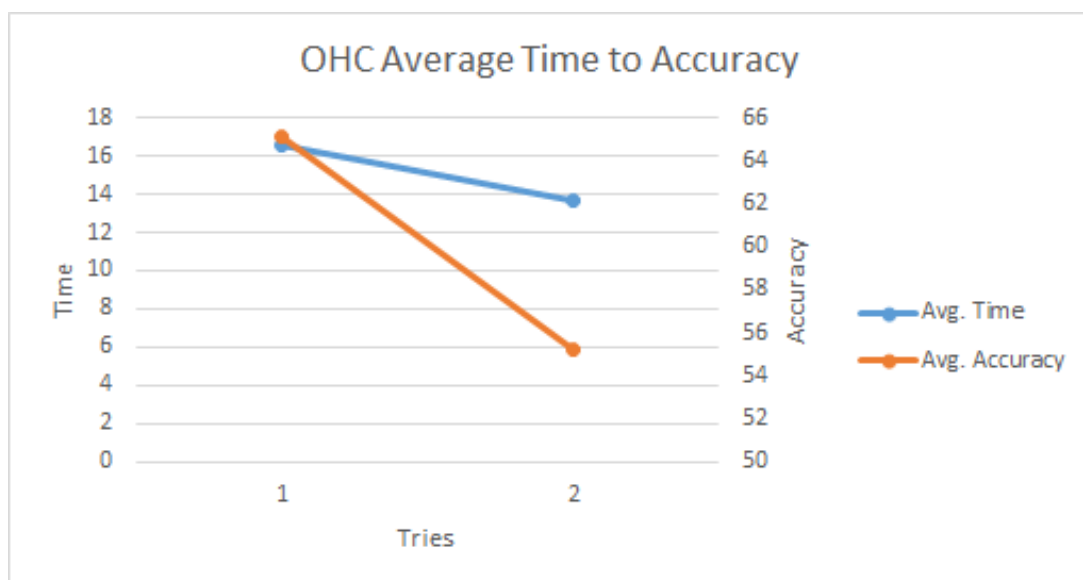


Fig. 58 OHC Avg. time to accuracy trend

The third type is OHS – one hand sine test. As we can see, results on paper indicate a slightly positive change in time required to draw a shape, but a sharp negative effect for precision. Time to finish the drawing on the first session was ~13 seconds, and ~11 seconds on the

second session. Precision of drawings on the first session was ~70%, and on the second session ~ 58%.

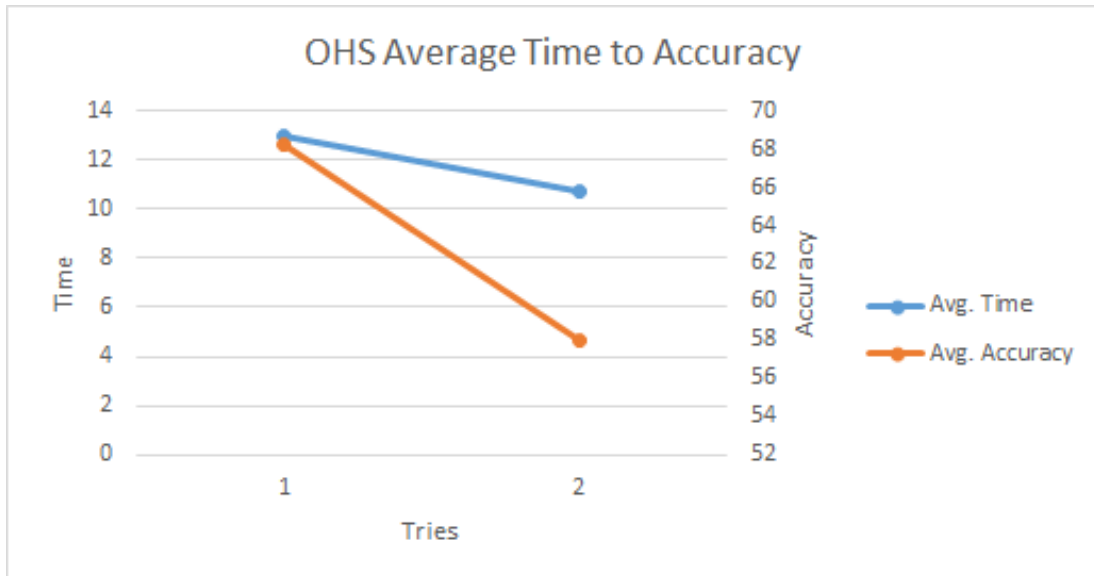


Fig. 59 OHS Avg. time to accuracy trend

The fourth type is BHL – both hand line test. As we can see, results on paper indicate a slightly positive change in time required to draw a shape, and sharper negative effect for precision. Time to finish the drawing on the first session was ~6 seconds, and ~4 seconds on the second session. Precision of drawings on the first session was ~70%, and on the second session ~ 48%.

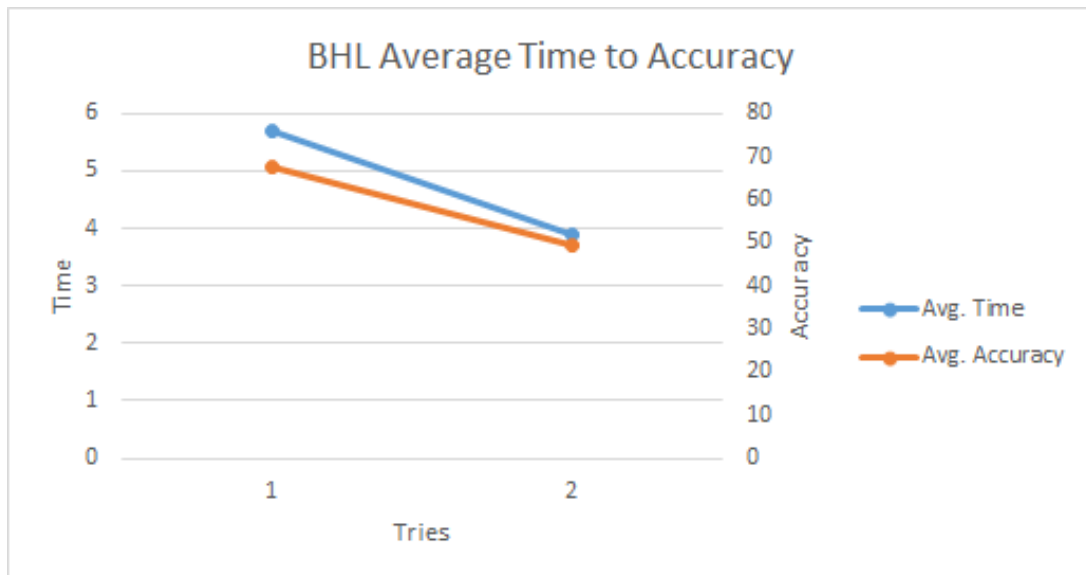


Fig. 60 BHL Avg. time to accuracy trend

The fifth type is BHC – both hand circle test. As we can see, results on paper indicate a slightly positive change in time required to draw a shape, and slightly negative effect for precision.

Time to finish the drawing on the first session was ~16 seconds, and ~12 seconds on the second session. Precision of drawings on the first session was ~50%, and on the second session ~ 45%.

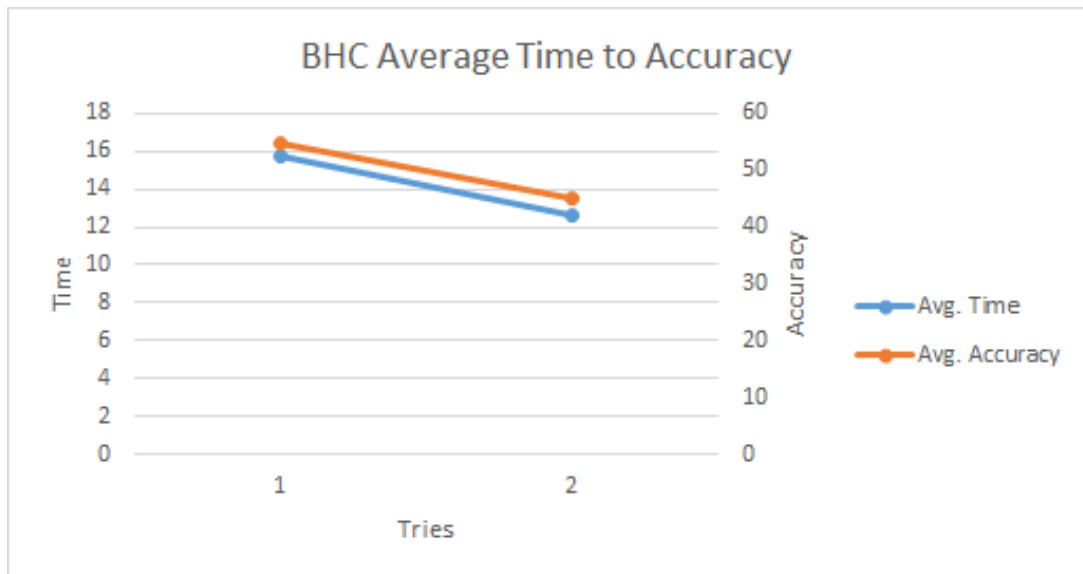


Fig. 61 BHC Avg. time to accuracy trend

The sixth type is BHS – both hand sine wave test. As we can see, results on paper indicate a slightly positive change in time required to draw a shape, and a sharper negative effect for precision. Time to finish the drawing on the first session was ~14 seconds, and ~10 seconds on the second session. Precision of drawings on the first session was ~63%, and dropped on the second session to ~ 53%.

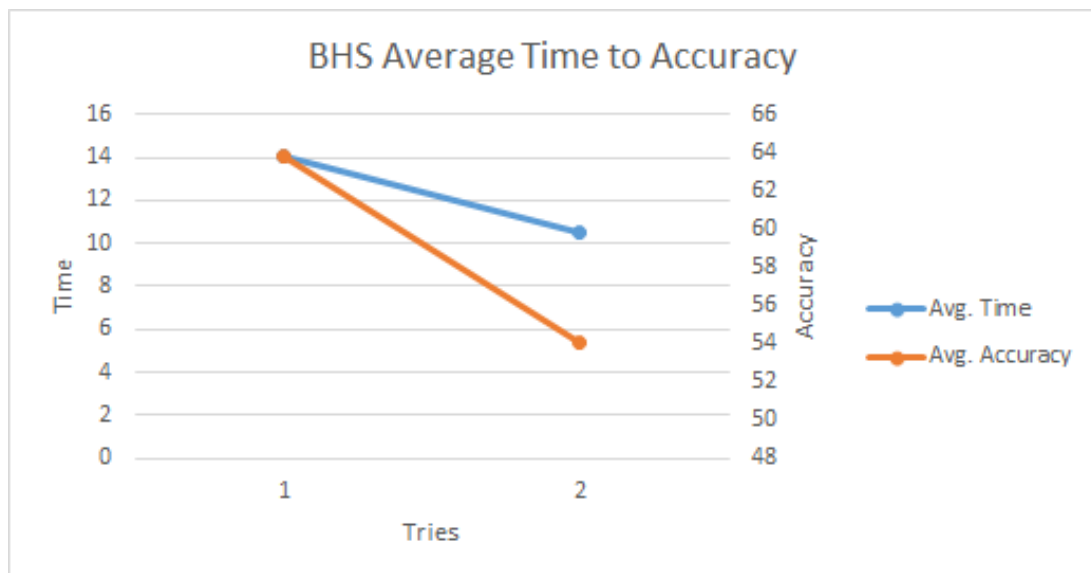


Fig. 62 BHS Avg. time to accuracy trend

12 In-depth statistical evaluation

For the statistical evaluation, the MATLAB R2017a software was used. The main goal was decided if there is difference between first a last try (VR and Paper), it means if participants have improved after the process of training in VR or not. All statistical methods that were used have been already mentioned in chapter 6 Used scientific methods. Results of analysis are in chapters VR Experiment and Paper Experiment.

12.1 Methodology of statistical evaluation

Statistical hypothesis testing was used for statistical processing of experimental data. **A statistical hypothesis** is a statement that relates to an unknown property or parameters of the probability distribution of a random variable. In statistical testing, we always have two types of hypotheses:

- **Null hypothesis** H_0 means hypothesis, the validity of which we verify using a test.
- **Alternative hypothesis** H_A means hypothesis that denies the validity of the null hypothesis.

To test the null hypothesis, we must always choose a significance level α . It means probability of rejection of a true null hypothesis (so-called type I error, more [x]). We always demand this probability small, so we choose it according to the habits $\alpha = 0.05$. The decision to reject / not-reject the null hypothesis is made using the p-value of test. We reject the null hypothesis if p-value of test is less than level of significance. More about hypothesis testing can be found here [309].

Statistical tests are used to verify the validity of the null hypothesis. There are parametric and nonparametric tests. Parametric are those for which we must know the distribution of data, they usually assume a normal distribution. Nonparametric do not require this assumption. Three tests were used in this work:

1. Jarque-Bera test
2. Paired-sample *t*-test
3. Wilcoxon signed ranked test

A detailed description of the tests and their use is given in the following subchapters.

12.1.1 Jarque-Bera test

First, the data obtained were tested for normality by the Jarque-Bera [310] test in order to decide whether we should use parametric or non-parametric statistical tests. Parametric tests can only be used for data with normal distribution, non-parametric tests are used for data with different distributions [311].

The Jarque-Bera test tested the null hypothesis that the measured data follow the normal distribution against the alternative hypothesis that the measured data do not follow the normal distribution.

If the p-value is greater than the significance level $\alpha = 0.05$, we do not reject the null hypothesis of data normality and we can use parametric test (Paired-sample t-test). Otherwise, we reject the null hypothesis of data normality and we have to use non-parametric test (Wilcoxon signed rank test).

12.1.2 Paired-sample t-test

This paired-sample t-test [312] is parametric and can only be used for data that comes from a normal distribution.

We test null hypothesis that the distribution of the observed variable (time/ distances/ accuracy) is identical in both groups (first a last try) and have the same mean (expected value) against the alternative hypothesis that the distribution of the observed variables is not identical in both groups and have the different mean.

We reject the null hypothesis if p-value of test is less than the significance level $\alpha = 0,05$ and it means that there is a statistically significant difference between the first and last try. If we do not reject the null hypothesis, there is no statistically significant difference.

12.1.3 Wilcoxon signed rank test

If data does not come from a normal distribution, we use in next step parametric Wilcoxon test for two paired samples [313]. It is non-parametric equivalent of paired-sample t-test. We test the null hypothesis data in both groups (first a last try) are samples from continuous distributions with equal medians, against the alternative that they are not.

The method of evaluation and conclusions are the same as for paired-sample t-test.

12.2 VR experiment

Here these two hypotheses are verified:

H1: Distance reducing trend (increasing drawing accuracy) for VR testing is to be expected;

H2: Time reducing trend (increasing drawing speed) for VR testing is to be expected;

There was tested statistically significant difference between first and seventh (last) try. First, normality test was realised. In Table 1 and 2 we can see p-values of test for both observed variable (distances and time) and for all 6 versions of experiment.

VR Distances	One Hand Line		One Hand Circle		One Hand SineWave		Both Hands Line		Both Hands Circle		Both Hands SineWave	
	1	7	1	7	1	7	1	7	1	7	1	7
p-value	0,001	0,500	0,035	0,500	0,246	0,416	0,390	0,500	0,056	0,024	0,234	0,391

Table 1 VR Distances – Jarque-Bera test

VR Time	One Hand Line		One Hand Circle		One Hand SineWave		Both Hands Line		Both Hands Circle		Both Hands SineWave	
	1	7	1	7	1	7	1	7	1	7	1	7
p-value	0,002	0,041	0,500	0,018	0,500	0,323	0,500	0,369	0,173	0,255	0,153	0,051

Table 2 VR Time – Jarque-Bera test

As can be seen, the p-value was in some cases lower than the significance level $\alpha = 0,05$ it means that not all data sets come from a normal distribution. Therefore, non-parametric Wilcoxon signed rank test was used. It was tested if there is a significance difference between first and last try of VR Experiment for all variants (one hand/ both hands, Line/ Circle/ Sinus wave).

In Table 3 we can see the results for the variable Distances. For all variants the p-value is lower than the significance level $\alpha = 0,05$. It means that we reject the null hypothesis and there is a statistically significant difference between the first and last try. We know from the figures 43–48 that the average values of the variable Distances decreased. This test confirmed this change at the significance level $\alpha = 0,05$ and it means that drawing accuracy was increased and hypothesis H1 is confirmed.

VR Distances	One Hand Line	One Hand Circle	One Hand SineWave	Both Hands Line	Both Hands Circle	Both Hands SineWave
p-value	0,002	0,001	0,004	0,006	0,002	0,001

Table 3 VR Distances Wilcoxon signed rank test

Table 4 shows the results for variable Time. Again, in all cases the p-value is lower than the significance level $\alpha = 0,05$. It means that we reject the null hypothesis and there is a statistically significant difference between the first and last try. As we know from figures 43–48, this difference is that the time in the last try is lower than in the first. This confirms hypothesis H2 about expected time reducing trend (increasing drawing speed) for VR testing.

VR Time	One Hand Line	One Hand Circle	One Hand SineWave	Both Hands Line	Both Hands Circle	Both Hands SineWave
p-value	0,030	0,023	0,024	0,026	0,006	0,026

Table 4 VR Time – Wilcoxon signed rank test

12.3 Real world experiment

Here these two hypotheses are verified:

H1: Accuracy increasing trend for RW tests (on paper) is to be expected;

H2: Time reducing trend (increasing drawing speed) for RW tests (on paper) is to be expected;

As in the case of the VR experiment, it was tested difference between first and last (second) try. First, normality test was realized. The results of the normality test can be seen in the tables 5 and 6 for all versions of experiment.

In case of variable Accuracy, see Table 5, the p-value was in some cases lower than the significance level $\alpha = 0,05$ it means that not all data sets come from a normal distribution. Therefore, non-parametric Wilcoxon signed rank test was used.

Paper Accuracy	One Hand Line		One Hand Circle		One Hand SineWave		Both Hands Line		Both Hands Circle		Both Hands SineWave	
	1	2	1	2	1	2	1	2	1	2	1	2
p-value	0,043	0,500	0,016	0,435	0,488	0,162	0,035	0,500	0,135	0,500	0,371	0,185

Table 5 Paper Accuracy – Jarque-Bera test

In case of variable Time, see Table 6, all p-values are greater than the significance level $\alpha = 0.05$, we do not reject the null hypothesis of data normality and we can use paired-sample t-test.

Paper Time	One Hand Line		One Hand Circle		One Hand SineWave		Both Hands Line		Both Hands Circle		Both Hands SineWave	
	1	2	1	2	1	2	1	2	1	2	1	2
p-value	0,089	0,086	0,471	0,144	0,500	0,209	0,052	0,224	0,358	0,118	0,206	0,143

Table 6 Paper Time – Jarque-Bera test

In Table 7 we can see the results for the variable Accuracy. The p-value is lower than the significance level $\alpha = 0.05$ in case of one hand: line and circle and both hands line. This means that in these cases there is a statistically significant difference between first and second try. As we know from figures 57, 58 and 60, this difference lies in the reduction in accuracy. This is the opposite of what we assumed. In the other versions of experiment, we did not reject the null hypothesis, so there is no statistically significant difference between the first and second try. This means that accuracy has not decreased significantly in these cases, but it also has not improved. Hypothesis H1 was therefore not confirmed.

Paper Accuracy	One Hand Line	One Hand Circle	One Hand SineWave	Both Hands Line	Both Hands Circle	Both Hands SineWave
p-value	0,011	0,034	0,083	0,020	0,063	0,095

Table 7 Paper Accuracy – Wilcoxon signed rank test

Table 8 shows the results (p-values) of paired-sample t-test for variable Time. Based on the results, we can say that there is significant difference between try 1 and 2 in case of one hand: circle, sinus wave and both hands: line, circle and sinus wave at the significance level $\alpha = 0,05$ %. There is not significant difference between first and second try in case of experiment

with one hand – line at the significance level $\alpha = 0.05 \%$ (but there is at the level 0,1 %). As we know from figures 58–62, the trend of the variable Time was declining in all cases. It means, we confirm hypothesis H2 in all versions of experiment with the exception of one hand line at the significance level $\alpha = 0.05 \%$. However, even in this case, it can be seen from Figure 57 that some improvement has taken place, so we can confirm the hypothesis H2 for this version as well, but at the significance level of 0.1 (higher level of uncertainty).

Paper Time	One Hand Line	One Hand Circle	One Hand SineWave	Both Hands Line	Both Hands Circle	Both Hands SineWave
p-value	0,091	0,021	0,041	0,016	0,018	0,014

Table 8 Paper Time – Paired-sample t-test

12.4 Conclusion

Using the statistical hypothesis testing, 4 hypotheses were tested, which was set out in the chapter 6.3. Specifically, these were hypotheses:

VR experiment

H1: Distance reducing trend (increasing drawing accuracy) for VR testing is to be expected;

H2: Time reducing trend (increasing drawing speed) for VR testing is to be expected;

Results: In the case of the VR experiment, both hypotheses were confirmed. In the case of both monitored variables (distances, time), there were statistically significant changes (in terms of improvement).

Real world experiment

H1: Accuracy increasing trend for RW tests (on paper) is to be expected;

H2: Time reducing trend (increasing drawing speed) for RW tests (on paper) is to be expected;

Results: In the case of the paper experiment, there was confirm only hypothesis H2 about variable Time. In case of variable Accuracy, there was no change or change for the worse.

13 Hypothesis and data evaluation

13.1 VR experiment hypothesis

- H1: Distance reducing trend (increasing drawing accuracy) for VR testing is to be expected;

Result: As we can see from the charts for all types of simulations, the distance trends between drawn points (by participants) and shapes positioned on the table (green) were mostly decreasing throughout all the sessions. Although, accuracy values were dipping and rising at some point in each type of simulation, in the end, it still preserved the downtrend in distance between drawn points and shapes, which means increasing accuracy. This hypothesis can be proven as **true**.

- H2: Time reducing trend (increasing drawing speed) for VR testing is to be expected;

Result: As we can see from the charts for all types of simulations, the time trends to finish the drawings (yellow) were mostly decreasing throughout all the sessions. Compared to accuracy trends, time trends were mostly in continuous decline, meaning the drawing speeds were increasing. Thus, it can clearly be stated that this hypothesis can be proven **true** as well.

- H3: One handed test would be more accurate than two handed in VR;

Result: According to averaged values from the table below for precision throughout all sessions and comparing them between one handed mode vs two handed, numbers mostly indicate that one handed testing accuracy was slightly higher compared to two handed. Here a simple operation of reducing both hand tests average distance values from one hand tests average values from respective sessions is made. Negative difference indicates that time to draw in one hand tests was faster by difference amount compared to both hands' tests. A positive difference indicates the opposite. This hypothesis can be proven as **true**.

OHL vs BHL avg D diff							
OHL D	11.125	10.4375	7.0875	7.6875	7.13125	5.9625	4.9875
BHL D	10.40625	7.892857	7.45	8.2875	7.753333	6.946667	6.713333
Difference	0.71875	2.544643	-0.3625	-0.6	-0.62208	-0.98417	-1.72583
OHC vs BHC avg diff							
OHC D	12.16875	8.48125	6.75625	6.2375	6.45	6.75625	5.1375
OHC D	12.70625	10.55	9.6375	7.60625	7.54375	8.225	7.10625
Difference	-0.5375	-2.06875	-2.88125	-1.36875	-1.09375	-1.46875	-1.96875
OHS vs BHS avg D diff							
OHS D	7.45625	6.23125	5.09375	4.2875	4.7875	4.28125	4.41875
BHS D	8.975	7.94375	6.95625	6.61875	6.41875	5.94375	5.2375
Difference	-1.51875	-1.7125	-1.8625	-2.33125	-1.63125	-1.6625	-0.81875

Fig. 63 One hand vs both hands average distance difference calculation (7 sessions)

- H4: One handed test would be faster than two handed in VR.

Result: According to averaged values from the table below for time throughout all sessions and comparing them between one handed mode vs two handed, numbers indicate controversial data. Here a simple operation of reducing both hand average time values from one hand average time values from respective sessions is made. Positive difference values indicate that one handed test took more time to complete drawings (by difference amount) compared to both handed tests. Here, half of the difference values are negative, thus, this hypothesis cannot be proven, and it is **false**.

OHL vs BHL avg T diff							
OHL T	6.06875	5.4625	5.73125	5.025	4.73125	4.59375	3.7375
BHL T	5.2	4.6125	4.48125	4.4	4.1625	3.7875	3.6375
Difference	0.86875	0.85	1.25	0.625	0.56875	0.80625	0.1
OHC vs BHC avg T diff							
OHC T	12.34375	12.2	12.05	11.225	10.625	9.9875	8.775
BHC T	11.6625	11.1125	11.25625	10.6	10.16875	9.78125	9.0125
Difference	0.68125	1.0875	0.79375	0.625	0.45625	0.20625	-0.2375
OHS vs BHS avg T diff							
OHS T	11.025	10.53125	10	9.475	9.20625	8.725	8.18125
BHS T	10.9	10.7625	10.675	10.01875	9.61875	9.5125	8.9
Difference	0.125	-0.23125	-0.675	-0.54375	-0.4125	-0.7875	-0.71875

Fig. 64 One hand vs both hands average time difference calculation (7 sessions)

13.2 Real world experiment hypothesis

- H1: Accuracy increasing trend for RW tests (on paper) is to be expected;

Result: As we can see from the chart data, although having multiple sessions of doing similar activity in VR, accuracy trends for RW (paper) experiments were all decreasing in all types of simulations. This hypothesis couldn't be proven true, thus it's **false**.

- H2: Time reducing trend (increasing drawing speed) for RW tests (on paper) is to be expected;

Result: Compared to accuracy measurements for paper experiments that worsened on the second session, the time values actually improved by a small amount, which is sufficient to prove the hypothesis as **true**.

- H3: One handed test would be more accurate than two handed on paper;

Result: Below is the table with averaged values of distance (%) calculations for all types of experiment. Additionally, the difference is calculated by reducing values of both hand test average values from one hand average test values. Positive values indicate that one hand test

simulation was performed with higher accuracy, whereas negative value indicates the opposite. Here we can see that all the values are positive numbers, which means that all one-handed drawing tests were performed faster than two handed on both real (paper drawing) sessions.

OHL vs BHL avg D		
OHL D	74.21875	58.46875
BHL D	67.68125	49.4625
Difference	6.5375	9.00625
OHC vs BHC avg D		
OHC D	65.08125	55.20625
BHC D	54.5375	44.86875
Difference	10.54375	10.3375
OHS vs BHS avg D		
OHS D	68.2625	57.94375
BHS D	63.8375	54.08125
Difference	4.425	3.8625

Fig. 65 One hand tests vs both hand tests average distance difference

Thus, this hypothesis can be proven as **true**.

- H4: One handed test would be faster than two handed on paper.

Result: The table below shows averaged time values from both paper drawing sessions, which is the average time to draw the shape. Here, both hand test average values were reduced from one hand test average values to find the difference. Positive difference values indicate that one hand drawing test took longer to finish, which means for us that this hypothesis is proven as **false**, due to most of the numbers being of positive value. Simply put, both hand tests took less time to complete, compared to one hand tests.

OHL vs BHL avg T		
OHL T	6.2775	5.226875
BHL T	5.69875	3.879375
Difference	0.57875	1.3475
OHC vs BHC avg T		
OHC T	16.52	13.67375
BHC T	15.7025	12.62563
Difference	0.8175	1.048125
OHS vs BHS avg T		
OHS T	12.94	10.7375
BHS T	14.07875	10.46938
Difference	-1.13875	0.268125

Fig. 66 One hand tests vs both hand tests average time difference

14 Benefits of the dissertation

The content of this chapter is a summary of theoretical and practical benefits of the dissertation. Subsequently, recommendations for further research in the field of VR are given.

14.1 Practical benefits

It is important to note that the precision training simulation in this work carried a more general character. The basic shapes (line, circle, sine) that participants had to follow with their hands were chosen specifically so to eliminate any confusion. As almost all participants had no previous experience with VR, bringing more complexity to the test by using complex shapes would create unwanted difficulties. Thus, by using simple shapes, participants didn't have to spend a lot of time understanding what to do.

Although, such VR training that focuses on task precision and potentially speed of performance can be utilized in many different areas (ex. surgery), the main area of interest of this experiment was to prove usefulness of such training for industrial manufacturing specifically. Precision is a useful skill in many operations and as an example, industrial jobs such as metal working and wood working require high accuracy of motion and sometimes are very dangerous to perform. As robotics and machinery advance, more and more operations are becoming automatic, but still a lot of the operations are done manually by workers.

Manual dexterity is the ability to use your hands in a skillful, coordinated way to grasp and manipulate objects and demonstrate small, precise movements. As a lot of skill depends mostly on repeating the same task over and over again, VR can be considered a great tool to perform these tasks in any fashion and unlimited amounts.

Metal Working

When it comes to metal working, its operations include: Cutting, Folding, Welding, Machining, Punching, Shearing, Stamping, Casting.

Of those, the most interesting to us by the type of this work's training simulation are Cutting and Welding, as they resemble the process that participants had to perform the most.

Cutting is a collection of processes wherein material is brought to a specified geometry by removing excess material using various kinds of tooling to leave a finished part that meets specifications.

Welding is a fabrication process that joins materials, usually metals or thermoplastics, by using high heat to melt the parts together and allowing them to cool, causing fusion.

Both of these operations can be done manually by hand, are very risky and require a lot of precision. These jobs would definitely make use of VR training, but that would require a more specific type of simulation to be constructed for training those particular skills.

Wood Working

Wood working operations include: Sawing, Planing, Chipping, Shaping, Moulding, Hogging, Lathing and sanding.

Of those, the most resembling to current experiment is Sawing.

Sawing means to cut through wood or another material using a saw or other tool. It can be a hand tool or a power tool, and it usually has either a blade or a disk with a jagged cutting edge.

As with metal working, the process can be often risky and also requires high precision when performed manually. These areas of industry could greatly benefit when using VR to train their employees when it comes to precision training specifically.

14.2 Theoretical benefits

When it comes to similar studies on precision training resembling this experiment, a very common topic that comes out in Industrial VR training is Welding simulation. One of the most common injuries for welders is burns — specifically, burns from heat, sparks, fire, and also from the intense ultraviolet and infrared radiation that a welding arc produces.

Depending on where they work, many welders are also at risk for cuts, crushed fingers, electrical injuries, and chemical exposure. Chronic injuries from repetitive motions such as carpal tunnel and HAVS are common as well. The CDC has identified welding as a job at high risk for carpal tunnel syndrome. As a highly risky job that also requires high precision of motion, VR welding simulations became very popular trying to make training safer.

While these Welding simulators measure test results/quality of the weld differently compared to this one, and also use real welding devices and stations with haptic feedback during the process, they cannot be exactly compared but there is a cross interest that can be considered equal for both areas. Most popular VR Welding tools on the current market are: VRTEX® 360 & 360+, Weld VR Simulator, Virtuweld VR welding simulator, guideWELD® VR welding simulator. Most of such tools require purchasing the whole system, including hardware station as well as software support for training.

Feedback from the process, such as haptic feedback is considered very important when dealing with such training. As the experiment in this study didn't use it, it could be interesting to perform similar experiment to gather similar data but this time with haptic feedback. That would allow direct comparison of with/without haptic feedback results of such experiments.

But when it comes to welding specifically, it is generally important to get the most realistic haptic feedback to allow a user understand the correct path of motion for highest precision.

A study [314] on Metal Active Gas Welding found that realism in an application plays a vital role in order of users to get immersed into the process to achieve highest results. It was found that overall, the biggest missing parts of such applications are lack of the sense of reality and lack of interactive step by step teaching aid. With these in mind, highest results can be achieved in welding training.

Another experiment [315] suggests that VR welding simulations are good not only for novice welders but also for experienced ones as well. As the results show some difference in quality between novice and experienced welders, data also suggests that even experienced welders can struggle with higher difficulty welds which can in turn allow them to train and become better at new levels.

One of the studies [316] proposed a cost-effective and environment-friendly method of training both novice and skilled welders using Phantom haptic device for user guidance during the process. This haptic guidance, which emulates the presence of a human tutor who feedbacks forces to a welder to show the proper force/position relation within predefined trajectories for attaining hand-mind-eye coordination skills in a virtual environment is supposedly helping increase the quality of weld process. As described above, interactive aid during the process can positively affect the results of the training.

There is a study [317] suggesting that human-robot collaboration can yield even better welding results in comparison to using separately either a human or a robot. Using human-robot collaboration allows combining the advantages of humans (adaptive intelligence) and robots (higher movement accuracy and physical limitation).

Finally, a research [318] on different types of welding difficulty tasks shows that the higher the difficulty of the welding task is, the less effective VR training becomes, thus requiring supplementation from real-world training instead. But for easy-medium type of training, VR is considered to be a great tool.

As the studies above suggest, using Virtual Welding training is very beneficial in many cases and although there is considerable difference between this work's experiment and the studies training, it could be argued that if some form haptic feedback (ex. controller vibration) could be brought into this work's testing, further deeper analysis and comparison could be made between welding training assessments and data gathered by this experiment of measuring precision of motion as the gap of difference would greatly decrease.

14.3 Final thoughts and recommendations for further research

Although in this experiment we can clearly see some benefits of VR training, overall benefits on real world scenarios proved to be questionable. As VR sessions mostly, improved starting from the first session continuing to the 7th session, where the trendline was very positive, the final result for paper experiment seems to be unaffected by VR training. But we have to remember that there are different training tasks and different simulations and because results for this test proved not so positive in the case of skill transfer, it cannot be completely concluded that using VR has no benefit for training in workplace.

There is plenty research trying to find out whether VR training skills can be transferred to RW applications, and in fact, there is no one specific answer, either only positive or negative on this subject. Some studies [319][320][321][322][323] suggest that VR should be used for training/maintenance and some [324][325][326][327] don't see any difference at all.

Although here, we mostly saw VR training benefits mainly in VR context, with further testing and improvements in experimental design, results could be different.

In this work, it was concluded that using Virtual Reality could be beneficial in some aspects and in order to maximize skill transfer, more work and thought process should be put into action.

Conclusion

The main point of this work was to find out the effects/benefits of using Virtual Reality for training purposes. Specifically the training was focused on hand movement precision improvements using specific type of VR simulation that would allow users/participants to perform similar movement tasks throughout a prolonged period of time (approx. One month). As VR is said to be a very effective technology to be used in this sphere, for this experiment, a VR simulation using Unity3D game engine was created. This engine proved itself to be very powerful and easy to use as it was already used for other types of simulations prior to this one.

The simulation for this work was in preparations for several months. In addition to VR tests, Real World experiments also took place. VR tests took place seven sessions where as RW tests only twice, on the start date and end date of the experiment. This was done to analyze the effects of training not only in VR itself but also transfer of skills to RW.

Once the experiment was done, the data were collected and counted. VR data was gathered right inside the Unity3D game engine during the test process itself. Than that data (json format) of precision were exported to Excel where in pre-prepared macro templates they were calculated. RW data, performing shape movements (line, circle, sinewave) was counted at the end of the experiment using specific to this works way of counting precision. At the end, as VR data, RW data was exported to Excel templates and using specific macros, the precision results were calculated and analysis was done.

The results suggest very positive outcome for VR training specifically. As the participants had to perform seven sessions, four tries of each type of simulation (6 overall, per one hand/two hands, line/circle/sinewave), in the end, the results improved drastically, they were actually improving from start to the end. It was pointed out that it might be possible that four training sessions for this type of training could be sufficient as after fourth attempt, although improvements exist, they are not that massive.

When it comes to RW tests, the results suggest that the transfer of skill from VR to RW was only partial. Only time value improved from the first try compared to the second one. It was suggested that there could be multiple reasons for this, such as participant forgetfulness, noninterest, tiredness etc. It is recommended to perform such an experiment with a much bigger pool of participants, in-depth questionnaires, and possibly perform RW tests more frequently in between the VR tests, to let the participants remember what they are training for. Additionally, it could also be a type of simulation that resulted in these outcomes. In order to be sure about some factors that could cause these non-beneficial effects, more research and experimentation should be performed on top of this work.

This work suggested using this type of training only in one way, using information from this work and performing similar research could eventually result in different outcomes, which then will be used to prove some other important points about using VR for training and its benefits. Future work should be targeted at delving into the factors described above more deeply, to prove, disprove, the given hypothesis.

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