University of Nevada, Reno

Evaluation of Smart Underground Mine Evacuation Efficiency through Virtual Reality Simulations

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Mining Engineering

by

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**Evaluation of Smart Underground Mine Evacuation
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Abstract

As mineral deposits gradually show lower grades and higher depths, the number of underground mining operations will have to grow in the future in order to sustain the populations thriving need for mineral resources. Underground mine operations are inherently dangerous. Hazards such as fires, explosions and caving of the rock are rare, but once they occur a speedy and safe egress of the mine workers is critical to their survival. Underground mine tunnel systems can extend to several hundred miles, with some employees working in the most remote developments. Static evacuation routes marked by exit signs or directional lines along the tunnel wall, can be obstructed by obstacles such as rockfall or made hardly noticeable in low-visibility conditions caused by smoke or dust. A vast amount of research has investigated and developed real-time evacuation guidance systems for occupational buildings. Those smart systems take changing environmental conditions into account and adjust the evacuation guidance systems to indicate the shortest path to the egress while avoiding danger zones.

The goal of this study was to determine if such a smart evacuation guidance system is more efficient than conventional approaches that use exit signs and if this thesis proves true to further quantify the efficiency. The test environment of this study was chosen to be a Virtual Reality (VR) underground mine. Research suggests that VR simulations are a cost-efficient, resource-saving and safe alternative to real-life simulations while still providing valuable indications.

In total thirteen (13) volunteers participated in the study. They were asked to evacuate the VR underground mine, two times using the conventional and two times being guided by the smart evacuation system. The statistical analysis of the total evacuation time proved that there was a significant difference between the efficiency of conventional and smart evacuation guidance systems. The highest achieved reduction in total evacuation time using the smart method amounted to nearly 40%. 83.33% of the participants preferred the smart evacuation guidance system over the conventional guidance system. Moreover, 100% agreed that smart evacuation could enhance mine safety.

Acknowledgment

First of all I want to express my sincere gratitude to my advisor Javad Sattarvand, who has given me the great possibility to study at the University of Nevada, Reno and has therefore allowed me to live my own version of the American Dream that I had nurtured since my early childhood. Most importantly, though, his constant motivation and reassurance helped me overcome barriers that I had set myself. I cherish every word of wisdom that he has shared with me. Furthermore, I want to thank Frederick C. Harris Jr. for introducing me to the world of Virtual Reality in his experimental teaching style, which transformed frustrating programming sessions to enjoyable experiments. His small pieces of advice along the way always proofed to be very impactful. The weekly calls with Sebnem Duzgun from the Colorado School of Mines cannot be left unmentioned. With her background in Mining Engineering as well as Virtual Reality she provided me with some key information and insights that propelled my research and greatly facilitated me in piecing together the puzzle. I want to thank our Chair of the Department, Manoj Mohanty, who was always ready to sit down with me and lend a hand whenever I felt overwhelmed with the complex world of statistics.

My family, my friends and my fiancé Christopher Liddle did not only patiently tolerate my mood-swings during these daring times, but reminded me that there is more that defines me than my academic degrees. This is a piece of advice I want to pass on to my fellow graduate students. I am incredibly grateful for the people that are accompanying me on life’s journey.

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List of Abbreviations

Abbreviation	**Meaning**
AR	Augmented Reality
AU	Australia
BC	British Columbia
CA	Canada
CD	Conventional method, dark environment
CI	Conventional method, illuminated environment
CN	China
CO	Carbon monoxide
FOV	Field of View
GER	Germany
HMD	Head-mounted-Display
IoT	Internet of Things
M	Mean
MSHA	Mine Safety and Health Administration
N	Sample Size
NIOSH	National Institution for Occupational Safety and Health
NSW	New South Wales
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
SA	South-Africa
SCSR	Self-contained self-rescuer
SD	Smart method, dark environment
SEM	Standard Error of the Mean
SI	Smart method, illuminated environment
TSS	Telemagnetic Signaling Systems
UI	User Interface
UK	United Kingdom
USA	United States of America
VE	Virtual Environment
VR	Virtual Reality

1. Introduction

1.1 Underground Mining

In order to sustain modern and future technologies, mineral resources such as gold, silver, platinum and copper have to be extracted from ground. Mining these natural resources can either be done in surface operations or underground. The main production steps in mining are loosening the in-situ rock mass, loading and hauling the blasted ore to the crusher and enriching the ore in a processing plant. Underground mines consist of drift networks that are cut into the ore body. The world's largest underground mine El Teniente in Chile has a drift network that amounts to 1,900 miles (Jamasmie, 2015). Even though safety has priority in the mining industry some inherent dangers in mining operations cannot be avoided. When excavating rock open spaces are created and all the stresses and pressures of the surrounding rock have to adjust to the newly introduced situation. Even after stabilization measures using roof bolts some danger of caving or rockfall remain. Introducing equipment needed to execute all the production steps, also introduces the danger of fire and gases present in the mine can be lit through sparks or open flames. These events can trigger mine evacuations. During mine evacuations every minute can be critical for the survival of the miners. The most common options to evacuate to are the main access, such as a ramp or mine shaft or a refuge chamber, which gives temporary safety until a mine emergency rescue team arrives and safely escorts miners to the surface.

1.2 Smart Evacuation

When entering buildings one usually comes across emergency plans that are hanging on the wall. They show the evacuation route for emergencies and the location of fire extinguishers. Through risk-assessments the evacuation routes are determined and subsequently marked throughout the building with exit signs. Those predetermined routes are static and cannot take changing conditions, such as a fire in the main hallway, into account. Therefore, a considerable amount of research has been conducted on smart evacuation guidance systems such as in Bernardes *et al.*, (2015); Ronchi *et al.*, (2015); Cosma, Ronchi and Nilsson,(2016); Arias *et al.*, (2019) and more. Such systems use the Internet of Things (IoT) to localize the danger, track the environmental conditions and compute an optimal evacuation route based on the present conditions for the evacuation guidance systems. Most papers on this issue propose either smart exit signs which can change the direction indicator or mobile phone applications that give every person an individualized route. For the latter the localization and tracking of each occupant has to be accomplished. Ideally, the smart evacuation guidance system guides the evacuee on the shortest and safest path out of the building or similar structure, even when the initial route gets obstructed.

1.3 Virtual Reality

Virtual Reality (VR) is an emerging technology that enables immersion into a three-dimensional, simulated environment. Older VR technologies lacked affordability, display resolution, frame rates and comfortable designs and therefore, VR was often overlooked by industries as well as gamers. Current VR technologies have evolved to cheaper, lighter systems that can offer a feeling of full immersion in the VR world. (Leonida, 2016) Most often VR utilizes a head-mounted display that has two separate displays for each eye and gives the user up to 200° field of vision (Jay). With the use of controllers the user can interact with and move within the virtual environment. The real-time positions and orientations of the HMD and controllers are tracked and translated into the VR world. Therefore, turning the head will make the view in the VR world turn the same direction as well. VR is primarily used for entertainment, but has also widely found acceptance as education, training and simulation tool.

1.4 Purpose

The overall purpose of this study is to investigate if a novel evacuation guidance approach could be saving crucial time during underground mine evacuations. Current evacuation guidance systems in use are not state-of-the-art and can face major limitations in low-visibility conditions or changing environmental conditions.

1.5 Problem Statement

New evacuation technologies could prevent entrapment and essentially save miners’ life. Current standard to mark evacuation routes are exit signs. These are also the only evacuation route marking required by law for underground non-coal mines (MSHA, *30 CFR § 57.11051 - Escape Routes*, 1985). Additionally, a mining company can choose to install lifelines, which give tactile directional cues to the nearest exit. Both of these approaches are static, which means they cannot adapt to changing conditions, as for example the obstruction of the original evacuation path. Fortunately, much can be done to prevent emergency evacuations by adapting safe and preventive practices. However, the probability of an emergency can never be eliminated. Once an emergency like a fire, an explosion or caving occurs, a fast and safe egress from the mine is crucial to saving mine worker’s lives. Other industries have already developed real-time, personalized evacuation guidance systems. Safety in mining could immensely benefit from such an approach, in order to avoid loss of orientation or inhibit adverse influence of bias on the decision-making process. Furthermore, the visibility of exit route signs can be considerably decreased in low-visibility conditions (Martell et al., 2019). Therefore, this thesis compares the efficiency of a real-time, individualized evacuation guidance system with a static guidance system to investigate the potential of such a smart evacuation system in mining.

1.6 Experiments

The simulations were conducted in a VR underground mine. For this study a virtual environment was chosen for the simulations as to save time, resources and keep the test participants out of the inherently dangerous environment present in underground mines. For the simulations a resemblance of an actual gold underground mine was created. Volunteers that participated in the study conducted two evacuations while using the conventional method that consisted of exit signs and two evacuations with a smart evacuation wayfinder. During the evacuation simulations the participants encounter an obstacle and have to redirect to an alternative exit. The metrics recorded were the total time it took the participant to evacuate as well as the time to react to the obstacle and change direction. Additionally, a pre- and post-survey collected the information about prior experiences with VR and underground mines as well as personal preferences and the experience with the VR during the simulation. A statistical analysis was conducted to determine if the smart evacuation method is more efficient than the conventional approach and if so how much time could be saved by implementing a smart guidance system.

1.7 Thesis Structure

Chapter 2 gives an overview over past and recent mine disasters as well as statistics pertaining fatalities in the different mining sectors. Furthermore, all federal mining regulations that are of special interest for the matter of this study are explained and subsequently compared to international federal mine regulations. Chapter 3 is devoted to all technologies revolving around real-time tracking of a person’s location and evacuation guidance systems. The chapter starts out with the current means used in the mining industry and is followed by novel, state-of-the-art evacuation guidance approaches from within the mining industry as well as other sectors. In Chapter 4 a brief overlook is given on how a person navigates through the world and especially how their navigation skills and decision-making process are influenced by existent danger. Chapter 5 addresses the potential use of VR as a training and simulation tool and especially seconds the integration of VR in mine safety by listing the research done in this field. The experiment is described in Chapter 6. It contains the hypothesis of the study, the experimental design as well as a closer description of the virtual mine environment and its functionalities. Chapter 7 examines the quantitative data obtained in the simulations and analyzes those to find statistically significant differences between the datasets. One section is dedicated to the qualitative data collected through the post-survey and used to further understand the aptitude of the smart evacuation technique as well as identify problems with the VR design. Chapter 8 concludes the study by summarizing the studies’ results and giving them more meaning by looking at the bigger picture of obtained data and collected opinions. The last section gives recommendations on how future research pertaining this topic should be conducted in order to obtain further data.

2. Legislation History and Current State

2.1 Historic Drivers of Mine Evacuation Legislation

A big driver of mine legislation have been and remain to be mine disasters. One of the most fatal disasters in US history took place in in an underground silver-operation: the Sunshine mine disaster in 1972. Major mine accidents that occurred in early 2006, moved the Mine Safety and Health Administration (MSHA) to bring an emergency temporary standard in effect just a few months after the incidents happened (Department of Labor and MSHA, 2006). This extraordinary measure was preceded by the Sago Mine explosion, resulting in 12 fatalities, and a conveyor belt fire at the Aracoma Alma Mine No.1 (both mines in West Virginia) with an additional 2 deceased miners. In accordance with section 101(b) in the Federal Mine Safety and Health Act of 1977, also known as `Mine Act', the Title 30 U.S. Code 811 revised and amended articles 48, 50 and 75 of the Mine Act. This standard put new regulations regarding accident notifications, the use and storage of as well as training on self-contained self-rescuers (SCSR'S), evacuation drills and evacuation auxiliaries like lifelines in place. After a public rehearsal of this temporary emergency standard the "Mine Improvement and New Emergency Response Act of 2006" (short: Miner Act) legislation was put in place in order to amend the Mine Safety and Health Act of 1977. (109th Congress, 2006)

Sunshine Mine Disaster: On May 2^{nd}, 1972 smoke was detected in one of the main drifts in the Sunshine Mine, Kellogg, Idaho. Within a short-time frame the volume of smoke as well as carbon monoxide engulfed the large parts of the mine. As a result 91 miners died of suffocation from carbon monoxide and smoke. Only 80 miners were able to evacuate in time, before the shaft hoistmen were overcome by carbon monoxide. An alternate escape to hoists was not described in the evacuation plan. One of the major reasons the disaster happened was that "The emergency escapeway system [...] was not adequate for rapid evacuation." (Jarrett, Levi and Look, 1972). On the escapeway many ladderways were included. In good conditions it would have taken 3-4 hours for a miner to evacuate from the lower levels. Secondary escape routes were inadequately marked. Among the listed reasons was also: "The company had not conducted evacuation drills." (Jarrett, Levi and Look, 1972)

Aracoma Alma Mine Disaster: The hazard faced in the Aracoma Alma Mine on January 19, 2006 was a conveyor belt that had caught fire. The root causes for the Aracoma Alma Mine disaster were among others: insufficient training of the dispatcher, poor or non-existing marking of personnel doors along the escapeway, missing CO alarm units and poor examination of the hazards by the miners, evacuation drills were not conducted in an adequate manner as well as many failures in testing and maintaining the functionality and cleanliness of fire suppression and operational equipment. Moreover, the investigators stated that the mine managements' initiation and conduction of the evacuation was too late. At the time of the fire occurrence 29 miners were underground of whom 12 worked in the affected section. Two of these lost their crew during evacuation at a time where visibility as very low and their deceased bodies were found 2 days later by the mine rescue team. (Murray et al., 2007)

The total number of fatalities in coal and metal/nonmetal mines – including underground as well as surface operations – was overall comparable between the years 1990-2018. Figure 1 shows that in some years the difference was exceptionally high, as in those years major mine disasters occurred such as the Aracoma Alma and Sago Mine Disaster in 2006 and the Upper Big Branch Mine Disaster in 2010 with 29 fatalities (Page et al., 2010). Figure 1 b) shows the progression of the number of employees in both branches in that same time period. The number of employees in the metal/nonmetal mine branch was and continues to be significantly higher.

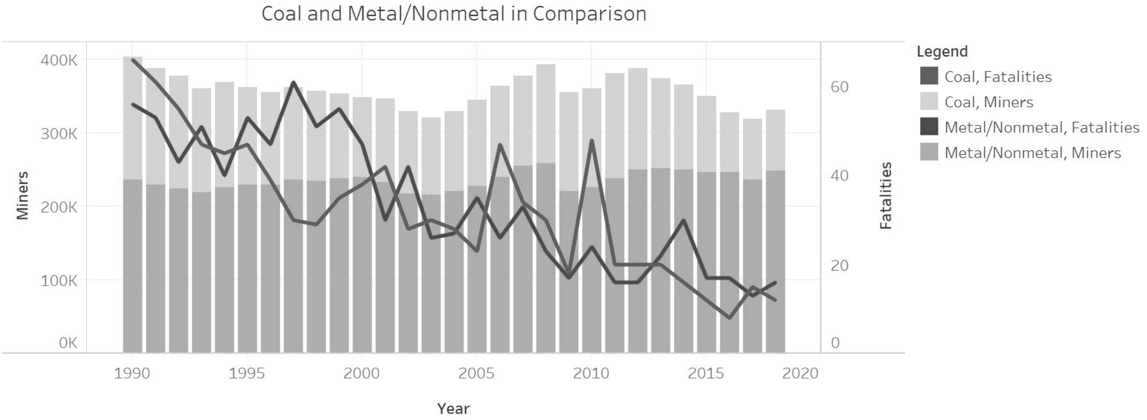

Figure 1: Mine fatalities (lines) and number of mine workers (bars) between 1990-2008 according to MSHA's fatality statistics (MSHA, *Metal/NonMetal Mining Fatality Statistics: 1900-2018*; *Coal Mining Fatality Statistics: 1900-2018*)

Taking into account that the number of workers in the nonmetal/metal mine industry is generally higher, the sole number of fatalities represents an insufficient measure of grave danger. Therefore, the actual percentage of fatalities that occurred per mine worker in each branch was derived and is visualized in Figure 2.

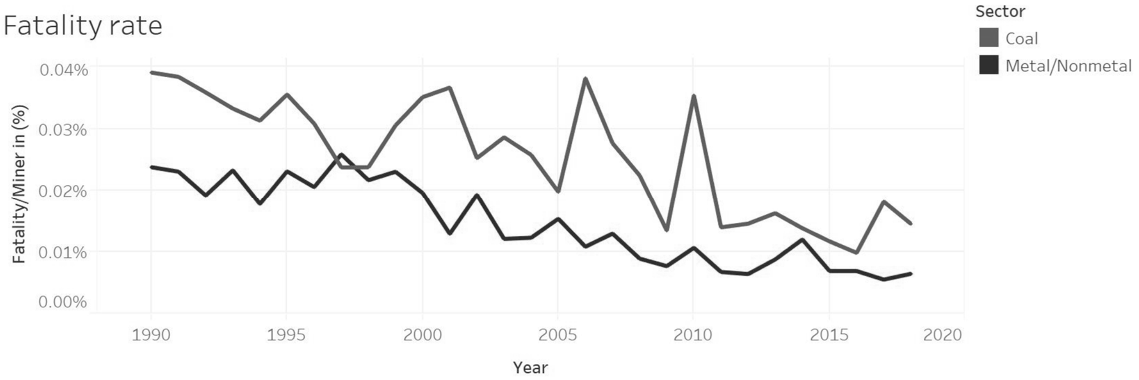

Figure 2: Percentage of fatal accidents per miner in each branch from 1990-2018 according to MSHA's fatality statistics (MSHA, *Coal Mining Fatality Statistics: 1900-2018*; *Metal/NonMetal Mining Fatality Statistics: 1900-2018*)

The data from MSHA's fatality statistics show that the percentage of fatalities per miner is higher in coal mining than in metal/nonmetal mining. Focusing on metal/nonmetal mines only, there is a significant difference in the fatality rate between employees in surface and underground mines as visualized in Figure 3.

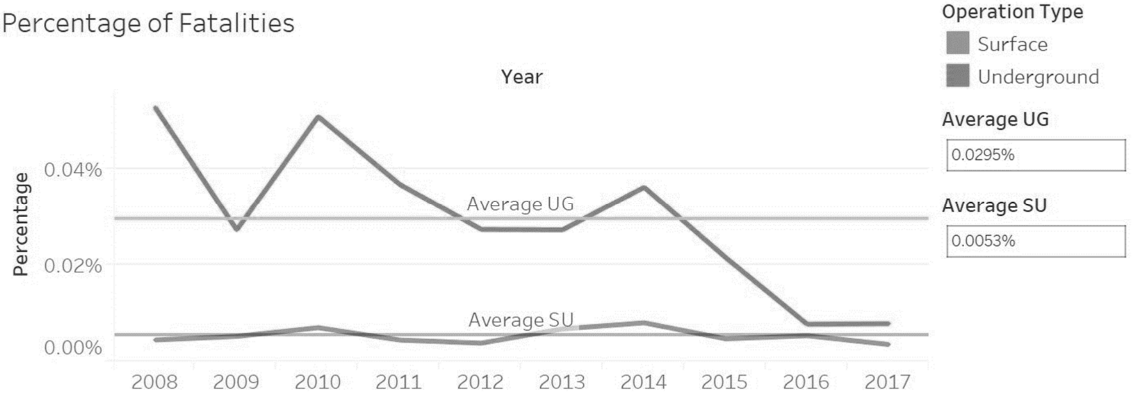

Figure 3: Percentage of fatal accidents per miner in surface and underground operations from 2008-2017 (NIOSH, , 2017; MSHA, *Fatality Reports*)

From the data obtained and visualized in Figure 3 a fatality per employee percentage of 0.0053% in surface operations and 0.0295% in underground mines can be derived. This makes the fatality rate in underground mines nearly six times as high as on surface. Some of the most fatal threats in metal/nonmetal underground mines from year 2008-2018 are ranked by number of fatalities in the following list:

- Equipment related (17 fatalities)
- Caving or rock fall (17 fatalities)
- Fire/Explosion (4 fatalities)
- Falling, Slipping, Tripping and Entrapment (4 fatalities)
- Electrical (2 fatalities)

A more detailed list on death causes in metal/nonmetal mines between years 2008 to 2018 can be found in Appendix A. Some of these incidents require an evacuation of the mine, depending on their nature and size. Between years 1991-2000 there were 61 fires recorded in metal/nonmetal underground mines. Compared to the 76 fire occurrences in that same time span in underground coal mines, the danger of fire does not seem to be significantly different in both sectors. 46% of the metal/nonmetal mine fires were caused by mobile equipment, 16% through cutting and welding and 10% can be assigned to electrical initiation. A more detailed breakdown of fire causes and a comparison to coal mines can be found in Appendix B. (Conti, 2005)

Fires, explosions, flooding as well as major rock fall or caving incidents can initiate a mine evacuation to remove miners from dangerous areas. In order to be effective, the evacuation should follow an emergency response plan, that all miners should be familiar with as well as with the evacuation routes and procedures. More recent cases where metal/nonmetal underground mines had to be evacuated are for example:

Table 1: More recent cases of mine evacuations (Elko Daily, 2018; Kidwell et al., 2012; Chomicz, 2012; Pallardy, 2010)

Year	Mine	Operating Company	Cause
2010	San Jose Mine, Chile	Codelco	Caving and collapse
2012	Pogo Mine, AL, USA	Sumimoto Metal Mining – Pogo	Equipment fire
2012	Exodus Mine, NV, USA	Newmont USA Limited	Person fell into stope
2018	Turquoise Ridge, NV, USA	Barrick	Equipment fire

During the mine disaster at the San Jose 33 miners got trapped for 69 days (Pallardy, 2010), which caused worldwide media attention. Some of the other evacuations can only be found in local newspaper articles. While fatalities resemble the biggest loss in mine disasters, traumas should not be left unmentioned as they can lead some survivors to self-destructive behavior, which can in worst case end in suicide (two recorded cases of suicide of survivors of the Sago disaster occurred within six months after the incident)(Alexander et al., 2010). Clearly, this data supports that mine legislature is not only a matter of the past, but has to be evaluated, not only following major mine disasters but also on a regular basis. The current mine safety legislature in the US as well as other countries with a significant contribution to the global minerals market are presented in the next chapter.

2.2 Legislation

2.2.1 Mine Evacuation Legislation in the USA

The Sunshine and Aracoma Alma mine disaster described in Chapter 2.1 have shown the importance of well-planned and trained mine evacuations. To ensure a quick and safe egress of all mine workers, the components of emergency response and evacuation procedures and training are enforced and regulated under the Title 30 of the Code of Federal Regulations (CFR), Mineral Resources, Chapter I. Rules in this chapter are established by MSHA (US). They are divided in coal and metal/nonmetal mines and further broken down into underground and surface mine operations.

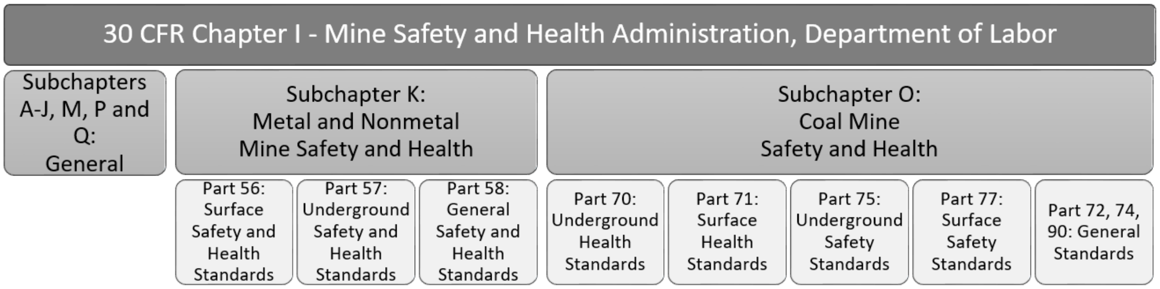

Figure 4: Schematic architecture of the Title 30 of the CFR

The following will look at regulations that only concern the metal/nonmetal underground mines. The official regulations that address safety and emergency training as well as emergency and evacuations plan can be found in Appendix C. A few summarizing highlights that are of specific interest for the research conducted in this thesis will be given in the following list:

- All persons going underground must receive theoretical annual emergency training as well as SCSR instructions. (MSHA, 2019 a)
- All persons working underground have to be instructed in escape and evacuation plans and procedures as well as fire warning signals once in every 12 months. They shall be instructed if the evacuation procedure of their working area changes. (MSHA, *30 CFR § 57.4363 - Underground Evacuation Instruction.*, 1985)
- Underground evacuation drills will be held every six months for each shift in order to assess their ability to reach the surface. (MSHA, *30 CFR § 57.4361 - Underground Evacuation Drills.*, 1985)
- An escape and evacuation plan showing the evacuation routes, means and direction of airflow as well as including the assigned responsibilities of key personnel in emergency events has to be developed. This plan has to be updated as necessary and posted in locations where they are easily accessible for all surface and underground personnel. (MSHA, 1995)

Since mine evacuations are very rare and occur mostly suddenly, it is even more important to have all employees well trained for the unlikely case of evacuation.

2.2.2 Mine Evacuation Legislation Internationally

Looking at the fundamentals of the regulation of mine emergency planning, evacuation preparedness and training, there are some significant differences among major mining countries. A summation of the legislative requirements is given in Table 2.

Table 2: Mine evacuation legislature in major mining countries in comparison

Country	**AU (NSW only)**	**CA (BC only)**	**CN**	**GER**	**SA**	**UK**	**USA**
Authority in Charge	NSW Department of Trade and Investment, Regional Infra-structure and Services	Ministry of Energy, Mines and Petroleum Resources	Several councils[1]	Bergamt	Mining Occupa-tional Health Advisory Committee	Health and Safety Commission	Mine Safety and Health Admin-istration
Name of Legislation, Year of Effect (Amend-ments not considered)	Mining Act, 1992; Work Health and Safety (Mines) Act, 2013	Mines Act, 1996; Health, Safety and Reclamation Code for Mines in British Columbia, 2008	Law of the People's Republic of China on Safety in Mines, 1993	Federal Mining Act (Bundes-berggesetz), 1982	Mine Health and Safety Act, 1996	Escape and Rescue from Mines Regulations, 1995	Mine Safety and Health Act of 1977; Mine Improvement and New Emergency Response Act of 2006
Emergency Plan	Required	Required	Only emergency exits required[2]	Required	Required	Required	Required
Emergency Plan Updates	Continuous, at least every 12 months	Continuous	Not specified	Continuous	Continuous	Continuous	Every 6 months
Evacuation Training	Instruction about emergency	Required[3] at least every	Safety education	Only theoretical	Instruction about emergency	Instruction about emergency	Required at least every 6 months

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[1] Competent departments of labour administration of the people's governments at or above the county level (Standing Committee of the Seventh National People's Congress, 1992)

[2] Article 10: "Each underground mine must have at least two walkable safety outlets and the direct horizontal distance between such outlets must comply with the safety rules and technological standards for mining industry." (Standing Committee of the Seventh National People's Congress, 1992)

[3] 3.13.2 A test of the warning system required under section 3.13.2 that does not involve evacuation of key process personnel shall be carried out at least once every 12 months on a production shift, and the manager

	procedures only	12 months	and training	training required	procedures only[4]	procedures only[5]	
SCSR Training	Required[6]	Required prior start of first work day	Not explicitly SCSR training	Required	Required	Required prior start of first work day	Required at least every 12 months
Reasons for Evacuation Initiation	Personal judgment and emergency plan	Not specified	Not specified	Not specified	Not specified	Occurrence of an emergency	Not specified

The US regulations differentiate between coal and metal/nonmetal underground mines more than any other country. While coal mines have to conduct practical evacuation drills and SCSR training every quarter of the year, underground metal/nonmetal mine regulations are less strict and frequent. Drills are to be conducted once every 6 months. The use of SCSRs has to be taught to new personnel before entering the mine and every 12 months after that. Evacuation training in metal/nonmetal underground mines is required every 6 months and has to be instructed in "Mine Emergency Training" taught by MSHA personnel or certified persons once a year. Another regulation demanding regular evacuation drills is the "Health, Safety and Reclamation Code for Mines in British Columbia". However, the related rule concentrates more on testing the warning system and is less clear about the personnel that has to evacuate the mine upon testing: "3.13.2 A test of the warning system […] that does not involve evacuation of key process personnel […] and the manager shall ensure that key process personnel unable to evacuate are knowledgeable with the warning system, and the evacuation procedure." (Ministry of Energy Mines and Petroleum Resources - Mining and Minerals Division, 2008). By stating that key personnel should not have to evacuate during tests, the rule indicates that other personnel should evacuate. Australia has the most intense SCSR training provisions of the compared legislations. At least every 6 months Australian mine workers have to don and practice the change-over of all types of SCSR present at the mine site and have to practice the use of and thus actually

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shall ensure that key process personnel unable to evacuate are knowledgeable with the warning system, and the evacuation procedure. (Ministry of Energy Mines and Petroleum Resources - Mining and Minerals Division, 2008);

[4] emergency procedures properly trained prior first time working, intervals determined by manager (consulted by health and safety committee), prior significant changes of procedures, mine layouts, employee's occupation or work etc. (Parliament of the Republic of South Africa, 1996)

[5] held at regular intervals, trained in use of equipment and actions to be taken in emergency, written instructions and information (Health and Safety Commission, 1995)

[6] prior start of work, every 6 months after that donning & change-over of each SCSR type present in a simulated environment, oxygen-generating SCSR prior start of work and every 3 years after that (NSW Government, 2015)

breathing through an oxygen-generating SCSRs before their first day at work in the mine and after that every 3 years. China is the only of the compared countries, where the use of SCSR training is not explicitly demanded by law. In general, the least specific regulation was found to be the Chinese law on safety in mines. Since these regulations do not differentiate mines by commodity or location, they apply to all mine operations in China. In comparison with the other countries' law one can find loopholes, which potentially can results in adapting unsafe mining practices. Among the mine industry the lack of safety regulations in Chinese mines is well known. A manifold of incidents in the past have occurred and still second this impression. Especially the coal mines have given rise to the number of fatal accidents, which amounted to about 20,000 victims from 2005 to 2009 according to Wang, Huang and Yang (2010). The "Law of the People's Republic of China on Safety in Mines" does not mention that an emergency plan has to be prepared, updated or given consent to by the responsible authority. It is, however, required to develop and mark two safety outlets that are walkable. According to this regulation these outlets have to comply to the "[…] safety rules and technological standards for mining industry." - (Standing Committee of the Seventh National People's Congress, 1992). The safety rules of this legislation itself do not further specify these emergency outlets. The "technological standards" are neither outlined nor referenced. Although, the evolution of the miners rights in the US is unneglectable, a NIOSH-funded report on escape strategies for underground coal mine still concluded that: "[…] research on current mining practices and the results of changes brought about by enactment of the 2006 MINER Act are lacking." (Alexander et al., 2010) Additionally, they found that compared to non-mining industries as well as mining practices in other countries: "[…] the US Research or technology transfer into the overall U.S. mine emergency response system has been found to be lacking […]."

3. Means of Evacuation

3.1 Conventional Evacuation Technologies

It is required by federal regulations that certain products, such as equipment, instruments and materials, have to be approved by MSHA before they are allowed to be used in underground coal mines and gassy underground metal mines. An approval is issued once the product successfully passes standard test procedures and fulfills MSHA's performance and design criteria's and are published on listings that can be accessed through e.g. MSHA's website.

The most common way to mark the evacuation route in underground mines is by the use of reflective signs, symbols and maps. The regulation pertaining to the placement of these signs and markings are given CRF 30 §57.11051, in which it is stated that: "Escape routes shall be- [...] (b) Marked with conspicuous and easily read direction signs that clearly indicate the ways of escape."(MSHA, *30 CFR § 57.11051 - Escape Routes*, 1985) Since a mine is an ever-developing and changing network of drifts, standardized distances for the placement of these direction signs can be hard to realize. However, the lack of specifics also leaves room for the implementation design and also effectiveness. Some mines place the signs at the rib of one intersecting mine drift, which might not always be visible instantly to miners coming from different directions. Others choose to hang two-sided signs from the back, so it can be seen from at least two directions. Another way to mark escape routes is the use of strobe lights, but according to 30 CFR 75.1714-4(e) these strobe lights can only be used additionally to reflective signs as strobe lights may malfunction (NIOSH, 2007). In contrary the placement of exit signs in highway tunnels is regulated by a law put in place by the National Fire Protection Association (NFPA). According to NFPA 502, section 7.15 reflective or lighted directional signs have to be installed at least every 25 m (82 ft.) along the side wall and indicating the direction to the two nearest exits. Furthermore, the NFPA 502 and NFPA 101 give specific regulations on the luminance level as well as font size of EXIT signs. (NFPA®, 2011; Higgins et al., 2015)

Figure 5: Left: Example of escape route sign at Turquoise Ridge mine (Featherston, 2018)*, Left: general example of signs hanging from the back* (HIE signs, 2019)

Brenkley, Bennett and Jones (1999) have criticized the sole use of reflective signs and symbols. According to them the disadvantages lie in the maintenance of the signs, such as cleaning and updating, the little attention paid to them by mine workers and the limited visibility in adverse conditions. Gouws and Philips (1995), as well as Weyman and Thyer (1997) have identified two major trends in the development of better orientation and guidance systems that have tried to fill in the conventional method of using reflective signs only: one is the use of passive lifelines (Gouws and Phillips, 1995), the other is the use of active electronic audio-visual guidance systems (Thyer and Weyman, 1997). Guidance and orientation systems should decrease evacuation time, be visible in very adverse conditions, provide unambiguous and if possibly a combination of visual, audible and tactile clues, pose low costs and maintenance, allow for flexibility to accommodate frequent changes in the mine's layout, be fail proof and not reliant on background lighting (Brenkley et al., 1999).

Lifelines, as illustrated in Figure 6, provide a tactile feedback to direct the evacuee into the direction of a refuge chamber, main access or SCSR refill stations. These tactile feedbacks are given by cones that are attached to the fireproof cord of the lifeline at least every 100 ft. and whose tapered side points opposite to the direction of the egress route (NIOSH, 2007). Reflective material has to be attached to the cord every 25 ft. Other attachments such as spirals, diamond shaped cones or spheres give different cues on where the lifelines directs the evacuee. A spiral coil indicates that the line leads to a refuge chamber, and four cones placed back-to-back and therefore resembling two diamond-shapes indicate an upcoming SCSR cache. A sphere or ball let the miner know that they are approaching a personnel door. A cone followed immediately by a second one points toward an upcoming branch line. The installation of lifelines is mandatory in anthracite, bituminous and lignite underground mines. For metal/nonmetal underground mines the installation remains optional. (MSHA, 1996) The major disadvantage of lifelines is their low visibility in smoky conditions, especially when miners find themselves disoriented after the occurrence of a mine emergency (Martell et al., 2019).

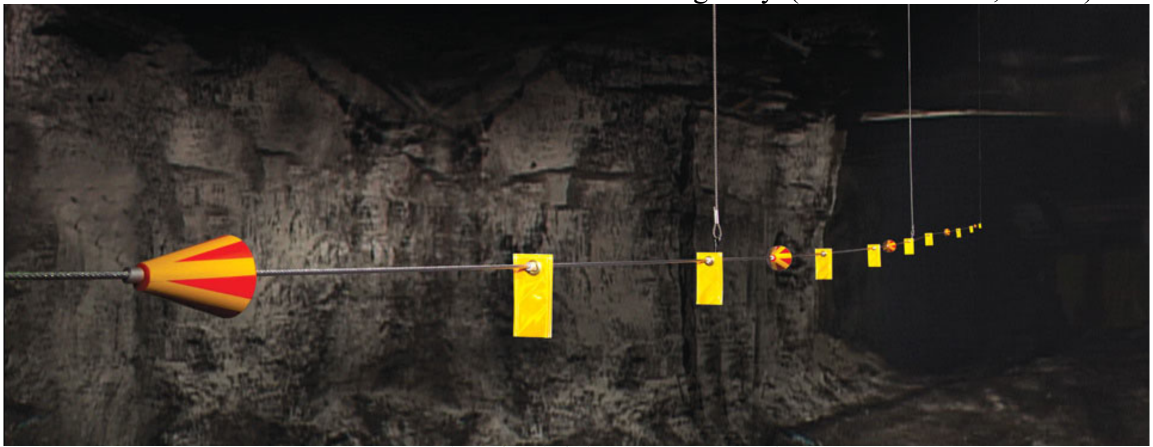


Figure 6: Example of a lifeline (CAB Products, 2019)

Compared to the other passive self-escape aids the lifeline is the most effective one once it could be located by the evacuee (compare Table 3).

Table 3: Passive and active evacuation guidance systems as described by (Martell et al., 2019)

Level	**Name**	**Functionality**	**Usefulness**
Passive	Signage	Visible cues	Useful in high-visibility conditions
	Markers	Visible cues	Useful in high-visibility conditions
	Lifelines	Tactical and visible cues on a cord	Most effective passive self-escape aid in low-visibility
Active	Mainsfail Operated Evacuation System	Series of sound- and light-emitting units	Proved very critical in zero-visibility conditions
	IMC's Egress Beacon System	Series of sound- and light-emitting LEDs	Decreased evacuation time
	Miniguide Ultrasonic Mobility Aid	Handheld device that detects objects with ultrasonic sound, gives tactile and audible cues	Helped avoiding tripping hazards, did not decrease evacuation time

In order to make this critical step of locating the lifeline easier, Martell et al. (2019) have proposed using a fibre optic as lifeline cord that will emit light. Their studies showed that green-lighted fibre lifelines has a higher visibility and would improve self-escape. Also they have concluded that the lighted lifelines were more easily located once the cap lamp was turned off. (Martell et al., 2019) The MOSES system utilizes a series of small light- and sound emitting units in cyclic routines to indicate the direction to a safe area for the mine personnel. The cycle time can be adjusted, but generally starts at the current mine workings and progresses to the safe area. Units are placed every 50 m. This system is mainly used in South African coal mines. It is activated by the environment-sensing sensors or manually. (Dhar, 2000; Bancroft, 1998) Brenkley et al. (1999) have identified the spacing of these units to be problematic in low-visibility conditions, where the use of MOSES still resulted in an egress duration three times longer than in a high-visibility environment. In order to address this problem the UK-based IMC Group has developed a guidance system using audio signals additionally to visible cues in conjunction with the UK Health and Safety Executive and Mines Rescue Service in 1998. The proposed beacons feature a green LED on one and red LED lights on the other side as shown in Figure 7. The beacons are then bolted to the wall in such a way, that when the miner walks towards a safe area, he is seeing the green lights, whereas if he walks away from it he will see the red lights. These evacuation directions are determined by the mine's risk assessment.

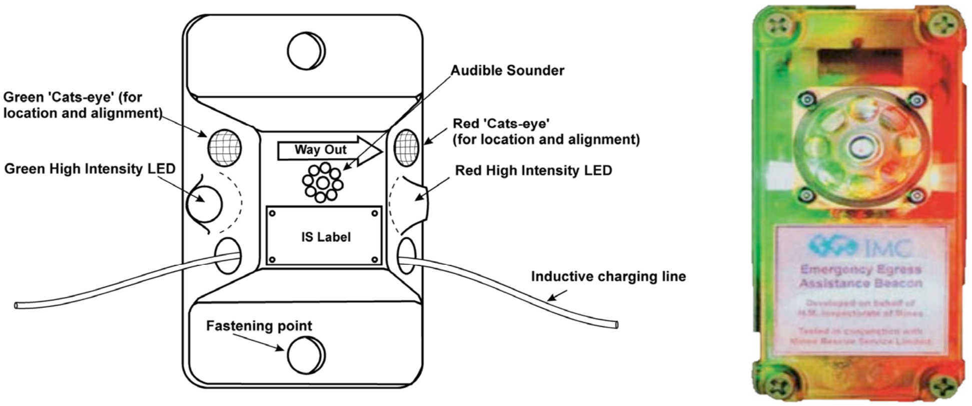


Figure 7: Emergency Egress Assistance Beacon, left: schematic view (Brenkley et al., 1999)*; right: actual design* (Health and Safety Executive, 2001)

In order to bridge the distance between the beacons and therefore visible cues, they have added sound sources that will emit a pulsing sound to indicate the location of the next beacon. The beacons have internal rechargeable battery cells and are connected to a charging line. Any interruption of the power supply of the charging line will result in activation of the beacon (Brenkley et al., 1999; Health and Safety Executive, 2001). Brenkley et al. (1999) also claim to have developed beacons: "[...] which incorporate programmable direction assignment, using low frequency inductive signaling techniques. This permits the direction of evacuation/direction to the refuge to be periodically reassigned to match changes in local requirements." Upon further research no implementation of the system in an actual mine could be found nor the approval by MSHA. The Miniguide Ultrasonic Mobility Aid as mentioned in Table 3 has not proven to reduce egress time and will therefore not be discussed in more detail.

NIOSH research indicated that the knowledge about the use of evacuation means such as SCSRs or communication tools seemed to be deficient once the miners had to utilize those. For example in the Sago mine disaster several miners reported that their SCSRs didn't work properly. However, after the incident those SCSR units were examined and found to be fully functional but not having been used to their capacity. NIOSH therefore suggest, that training miners on how to use evacuation devices is crucial to rapid and safe egress. Miners that have survived mine disasters reported that sometimes evacuees would take out the mouthpiece of the SCSR to be able to communicate verbally. This exposes the miner to high risks as toxic gases might be inhaled. Moreover, they reported about confusion on what to report to whom. NIOSH noted that non-verbal communication means should be implemented as supportive measurement and in long-term wireless communication systems developed and deployed. (Alexander et al., 2010)

The most common options to seek safety during evacuation are: main access ways (shafts or ramps), refuge chambers (Figure 8) or barricades. If the miner decides to stay in the refuge chamber or erect a barricade, they have to wait for the Mine Emergency Rescue Team (MERT) to come and guide them safely out of the mine. In general, it is inherently safer to seek egress through the main access ways as the time spent in hazardous conditions in the underground mine is reduced. However, in the actual case of emergency it might be safer to seek a refuge chamber, if for example the shaft is too far away to reach in a considerable time. A risk assessment of each mine site can determine in which cases refuge chambers should be preferred over other egress options. (Alexander et al., 2010)

Figure 8: Refuge Chamber, front side with door opened (MineARC Systems, 2019 b)

3.1.1 Existing Communication and Tracking Systems

In the past underground mines primarily used audible or visual alarms, wireless pager phones, underground telephones and messengers as well as stench gas, which they would introduce through the ventilation system, to warn miners of emergencies as mine fires. However, those systems often bring the disadvantage of being unreliable as well as slow. A full coverage of those alarm systems signal in an underground mine is not guaranteed as well. In evacuation situations every minute is valuable and could make a difference in the success of bringing the miners fast and sound to the surface. Early research into wireless systems was started by NIOSH in 1990 and focused on a wireless ultra-low-frequency electromagnetic alarm system. The tests were run at their experimental mine site, the Lake Lynn Laboratory in Pennsylvania. A receiving and transmitting antenna ring with a 15-50 m diameter in the underground workings in addition to a smaller 2 m diameter antenna ring above ground were installed for a cost of about $20,000. Simple messages were successfully sent from a computer on the surface to small receivers attached to the headlamp of the underground workers. These received signals initiated the flickering of the headlamp and were displayed on a small LCD display in form of short messages. The receivers were designed to be wearable by each individual underground worker and be integrated with the headlamp assembly. At the time of the publication of the paper, one limestone and four metal mines had successfully installed and tested the TSS alarm system. Among other suggestions on the broad application possibilities of the low-frequency system, the authors suggested that the flickering of strobe lights could indicate the evacuation route and beacons could transmit the location of underground miners. (Conti and Yewen, 1997)

Special conditions have to be taken into account when designing tracking systems for use in underground mines. Conditions can be very harsh and in general wireless systems should be preferred over wired systems as roof falls, equipment or other incidents could damage the communication lines, which would render the rest of the communication system useless. Repairing fibre optics or leaky feeder coax cables can be time consuming as qualified personnel has to be brought in. Mended cables often show lower performance as well. Wireless mesh networks in contrary still function when one node, which functions as a wireless router, gets damaged or stops working, as signals will simply be rerouted to other nodes. The nodes can communicate with each other. At least one node that acts as a bridge between the mesh network and another bigger network such as the Internet, has to be in a fixed position. Typically these nodes are placed throughout the mines, covering drifts and corners. However, they can also be attached to equipment to track its movement. Moreover, they can be wired to sensors and process and transmit their data. Every miner can be equipped with a tracking badge, which will be recognized by the nodes as he passes by and gives real-time information about the miner's location. The downside of the protocols sent by mesh networks is that they can't penetrate earth really well, which in case a drift collapses could heavily impact the mesh networks effectiveness. That's where a TSS system as proposed by MSHA outperforms the mesh network. (Strickland, 2008; Carrier, 2018) Some mine operations additionally have not yet implemented networks because of financial or geographical barriers and can therefore not yet make use of the IoT. (MineARC Systems, 2019 a)

3.1.2 Conventional Evacuation Simulation

Evacuation simulations can be utilized to analyze the average evacuation time, evacuee's behavior, identify bottlenecks and optimize evacuation routes based on the findings. Cellular Automaton is a discrete modelling method that has been widely used in a variety of scientific fields, e.g. chemistry, biochemistry, economy, physics and more. With the help of cellular automaton complex, real world phenomenon like basic processes in the nature can be simulated by simple programs. These programs consist of cells, which are arranged in a lattice and represent a defined room/environment. The state of each cell depends on the current state of its neighboring cells, the geometry and given boundary conditions.

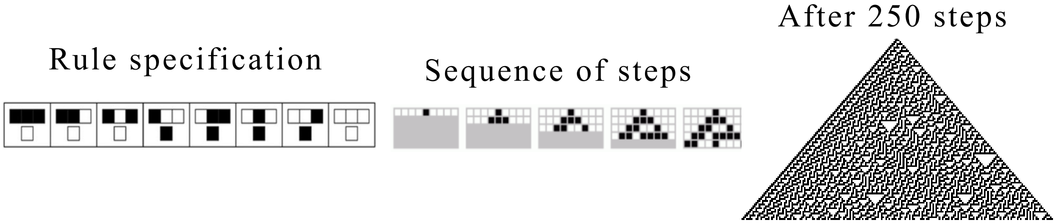


Figure 9: Cellular Automata rule number 30 and its evolution (Wolfram, 2002)

Different rules applied to this program will yield different behaviors of the cells and therefore different patterns. The neighboring cells can occur in eight different states. This leads to a total of 256 unique rules, some of which are shown in Figure 9. Patterns can look structured, nested or completely random. Some will repeat their patterns after a distinct number of steps. (Wolfram, 2002) This modelling method has been applied to evacuation simulations in order to evaluate the time pedestrians would need to egress different environment configurations and experimental conditions. In these scenarios the number and location of evacuation exits and obstacles, as well as the number of pedestrians to evacuate varied (Tissera et al., 2007). Extended studies examine among others the evacuation behavior, when a few cells in the environment are defined as 'fire', or when pedestrians show different levels of 'panic' (Zheng et al., 2011).

Fuzzy algorithms can be applied to real world problems, which are algorithmically not solvable, too computational heavy to be solved or too complex (Zadeh, 1965; Fu et al., 2016). 'Fuzzy sets' are objects within the observed phenomenon, which are not assigned a precise Boolean value (true, false), but are defined through a 'grade of membership' within the function:

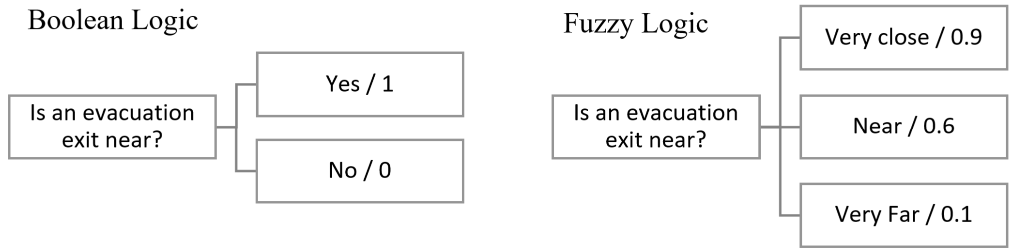


Figure 10: Underlying design of Boolean and fuzzy algorithms

Zhu, Liu and Tang (2008) have proven that fuzzy logic can be used to simulate pedestrians’ behavior during an evacuation and can therefore, be used to evaluate static evacuation routes. In Fu et al. (2016), the fuzzy logic and Boolean logic of cellular automata were combined to obtain a behavioral model of evacuees.

3.2 State-of-the-Art

(Alexander et al., 2010): “The mining industry is lagging behind the rest of the U.S. emergency response community in the incorporation of behavioral research into pre-event, event, and post event interventions.”

3.2.1 Smart Evacuation Technologies

Smart evacuation system usually refer to real-time evacuation guidance systems that are adaptable to changing conditions such as location and spreading of fire and resulting safest and fastest exit routes. Some of them utilize the IoT to not only locate the origin of danger but also track the occupant’s position. A few of these implemented and tested systems are presented in subchapter 3.2.2 and 3.2.3. For now the components of these evacuation systems will be discussed.

Smart Evacuation without individualized guidance can be achieved by installing exit signs that can change the direction indicator based on the current emergency situation. This can be realized by detecting the location of fire via sensors (e.g. thermometers and smoke detectors), computing the safest and shortest route for the occupants on the separate floors and send this information to the intelligent exit signs. The direction can be changed by e.g. using LED lights as shown exemplarily in Figure 11.

Figure 11: Schematic design of a smart exit sign with LED's that can give directional cues

If the evacuation guidance system is supposed to give individual routes to the evacuee, the evacuees' position has to be determined and tracked. In order to track people in real-time a network of sensors and transmitter and/or transceivers is needed. These components can communicate wirelessly. Some of the technologies used to determine localization of people indoors are: (Lujak et al., 2017)

- Wi-Fi: the received signal strength between the occupants' phone and several access points (refer to Figure 12 a) gives an indication (RSSI) of the occupant's position using trilateration, the accuracy is low
- Beacons: beacons use low energy Bluetooth and send out their specific ID in a customizable frequency, this ID can be received and processed by smartphones, due to the low cost a dense network of beacons (as can be seen in Figure 12 b) can be installed, which yields a high accuracy
- RFID: Radio Frequency Identification utilizes a RFID readers, which are distributed throughout the building, and RFID tags, which are worn by the occupants (see Figure 12 c). Similar to Wi-Fi technology mentioned above, the position is calculated using triangulation. A dense network of readers is costly. This usually results in a low accuracy. It might be complicated to equip every occupant with a RFID tag as well.

Figure 12: a) SENTINEL™ wireless station for underground by IWT®; b) components of a Beacon by Estimote Inc. and c) a RFID reader and tag (IWT, 2019; Robu, 2019; Warren, 2019; Zoon, 2019)

Company Vandrico has developed a smartwatch called “MineSafe” (see Figure 13) to enable a simple two-way communication in underground mine emergencies in collaboration with SAP’s Co-Innovation Lab and Illumiti. The smartwatch utilizes Wi-Fi as well as signals from sensors to be able to:

- Track workers location
- Identify and predict potential hazards and alert miners about dangerous conditions
- Receive real-time incident reports
- Give automated safety guidance in emergencies
- Enable real-time two-way communication

Lorraine Howell, the vice president of R&D at Illumiti further explains that: ”Localised evacuation messages can also be sent based on the worker location in the mine.” (Illumiti and Vandrico, 2019; Shemer, 2019) That the trend of wearing technologies like smartwatches will also diffuse into the mining industry and contribute to an improvement in safety is likely, however what’s holding the implementation back are the cumbersome designs and concerns about the access to the collected data. (MineARC Systems, 2019 a)

Figure 13: Smartwatch “MineSafe” (Shemer, 2019)

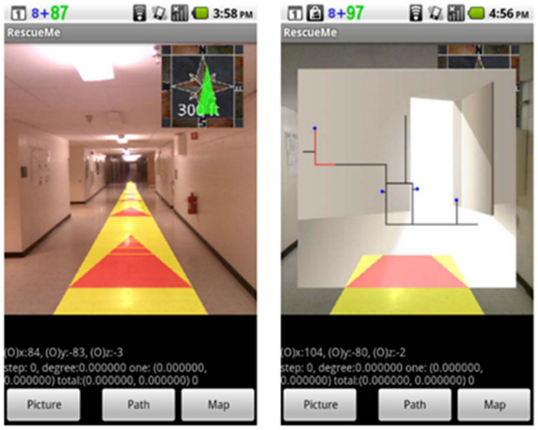
3.2.2 Real-Time Evacuation in Other Industries

Many different real-time evacuation systems have been proposed for the evacuation of smaller or larger, public or business buildings. Most of them make use of the Internet of Things (IoT) and utilize a number of sensors, smart evacuation indicator boards or even the occupant’s smart phone as localization and emergency guidance system. One example for such a smartphone application developed by Ahn and Han (2011) is shown in Figure 14. It is also worth noting, that most authors proposed to employ wireless communication between the single evacuation system components. A few of those proposed systems are presented in Table 4.

Table 4: Real-time evacuation systems found in literature. Features that were not clearly specified are put in quotation marks.

Author	Locating fire	Tracking people	Shortest route algorithm	Guidance system
Chen (2009)	Thermometers, “position sensors” and cameras	N/A	Fuzzy algorithm, accounting for angle and	Smart boards (LEDs) that function as exit route

			distance between danger and exit	signs and can change direction indicator
Inoue et al. (2009)	Thermometers, hygrometers, cameras, microphones	Beacons, positioning processing is performed on mobile phone	“Route search algorithms”	Beacons send instructions to phone, shows floor map and position, at intersections etc. a picture of that exact area pops up with directional cues
Lujak et al. (2017)	Smoke and temperature sensors	iBeacons	Distributed optimization algorithm	Evacuation app, additionally smart LED boards
Majumder et al. (2017)	Retrofitted fire detectors with microprocessors and wireless transceivers	N/A, occupant confirms position in phone app	Customized algorithm using map and fire situation and path-planning strategies	Link will be sent to persons mobile phone, once they confirm their location the app shows best route in real-time
Ahn and Han (2011)	Not specified	Using mobile phone camera and external image labelling services to identify room and floor numbers etc.	Algorithm based on pedometry-based localization, person’s stride distance and speed collected through app, map layout	Evacuation app shows pictures of current area overlaid with guiding arrows, can work without Wi-Fi as well (see Figure 14)



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(O)x:84, (O)y:-83, (O)z:-3
step: 0, degree:0.000000 one: (0.000000,
0.000000) total:(0.000000, 0.000000) 0
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```
(O)x:104, (O)y:-80, (O)z:-2
step: 0, degree:0.000000 one: (0.000000,
0.000000) total:(0.000000, 0.000000) 0
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(a) Viewing 3D map (b) Viewing 2D map

Figure 14: “RescueMe” mobile phone AR system as proposed by Ahn and Han (2011)

3.2.3 Real-Time Evacuation in Underground Mining

Jalali and Noroozi (2009) proposed two algorithms to calculate the shortest path out of an underground mine and have electronic boards underground, which will indicate the safest evacuation route with an arrow sign. The developed algorithm is based on the Floyd-Warshall and predecessor π algorithm. Jalali and Noroozi (2009) do not further elaborate what components are used for the necessary network to localize and direct miners. For underground mine localization and tracking of personnel, Wang et al. (2010) suggest to equip every worker with a node, from which the received signal strength indicator (RSSI) can be read and used for real-time localization of the worker. The hardware includes the node, fixed stations, which are either powered by the underground electric wires in the drifts or batteries in case of electricity loss, and a base with Ethernet or an optical port. Additionally, a software is needed that brings all the received signals together and applies algorithm to localize the worker. The proposed software is divided into a node application layer, a server layer and information publisher layer. As the author indicated the RSSI-localization on its own is not reliable and accurate enough. Therefore, a robust fault-tolerant localization and the Monte Carlo based localization algorithms were tied into the localization-algorithm to improve accuracy. This whole system, consisting of numerous nodes was deployed in the XinYuan Mine (owned by XinAn Coal Mine) and in the experimental building of the National High Performance Computing Center (NHPCC) at the University of Science and Technology of China (USTC). The results indicated a timing delay of received signals of less than 10 s and 5 m accuracy. (Wang et al., 2010) Rehman et al. (2019) have proposed an emergency evacuation guidance system for underground mines, which makes use of existing miner tracking systems, sensor networks and communication systems. The sensors role is to detect changing conditions that could indicate a danger. According to Rehman et al.: “Modern miner tracking systems use triangulation from various communication nodes or radio frequency identification (RFID) to estimate the miners’ location at any time.”

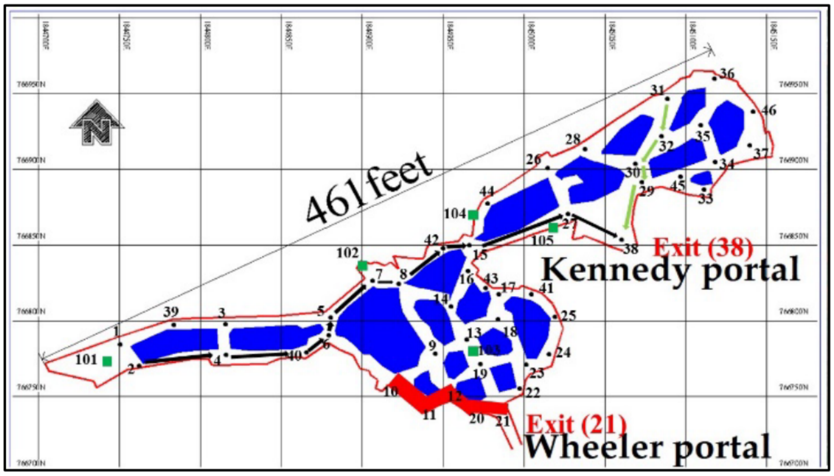

Figure 15: Shortest path calculation of one miner starting at node 2 (black arrows) and a second miner starting at node 31 (green arrows) to Exit (38), when the primary Exit (21) would be blocked by a roof fall (Rehman et al. (2019))

A network of nodes will be deployed at major intersections in the underground mine, which are the foundation for the optimum path computation and will send the directions to the nearest exit to the individual in case of emergency. Mainly, the paper focuses on adapting the Dijkstra’s algorithm to this specific case as well as evaluating the developed algorithm through simulation experiments at the Missouri University of Science & Technology Experimental Mine. Variables considered in the algorithm are: distance between nodes, ease of travel and risk factors. As opposed to Jalali and Noroozi (2009), Rehman et al. (2019) in addition define refuge chambers as emergency exits, but with a lower preference, whereas exits as shafts or ramps are the primary, preferred escape points. The experiments showed that the algorithm gave the desired outcome and was able to find the optimum evacuation path. It is proposed that the miner's transponders can be used for the localization of miners as well as provide evacuation directions to miners. (Rehman et al., 2019) Barker-Read and Li (1989) have established a computer program that considers the miners' tolerance to toxic gases, heat or oxygen depletion additionally to the distance to the evacuation exit for the calculation of optimal escape routes through a "double-sweep" algorithm.

4. Human Factor

As to understand how a person can benefit from a wayfinding system during evacuation, the following subchapters will roughly explain the decision-making process while navigating, including external cues as well as cognitive bias.

4.1 Cognitive Navigation

Two types of cues are processed by the human brain to make decisions about orientation and navigation and can be categorized under:

1. Idiothetic Cues, that are vestibular (inner ear), proprioceptive (sense of self-movement and position of body) and also perceived through motor efference (counting steps) for path integration, uses subcortical areas
2. Allothetic cues, that are visual, auditory, tactile for processing landmark information, uses higher level cognitive processes including contextual spatial memory

The path to a distinctive goal is computed through the combination of spatial orientation and navigational knowledge. Path integration is the sense of walked distance and relative orientation to the external environment as reference frame. In case the remembered landmarks and the path integration do not match the computed route has to be adjusted. Either by averaging those two factors or one of them will take the dominance. Active movement is important for spatial navigation, as without movement no idiothetic cues can be collected and processed. In their absence navigation will be solely based on landmark recognition. (Taube et al., 2013)

4.2 Behavioral Response to Emergency Evacuations

Literature of the past 30 years has suggested that evacuees' decision-making specifically in fire evacuation events was mainly influenced by panic, which could lead to self-destructive responses. However, more recent literature acknowledges that the evacuees' response is closer to normal behavior patterns and a result of adaptive and cooperative decision-making and takes into account the information presented to them (Lindell and Perry, 2004; Alexander et al., 2010; Kinsey et al., 2019) Based on a manifold of disaster research literature Lindell and Perry (2004) have developed the Protective Action Decision Model (PADM), which conceptualizes "typical" human behavior in case of emergency as well as the adaptation of behavior following changes in the environmental conditions (as seen in Figure 16). The predecisional process describes all factors that lead an individual to initiate the evaluation of a threat and following procedures. Once the individual identifies a threat, protective measures are evaluated and realized. This decision process can constantly be affected by the information accessible and/or obtained throughout. Lindell et al. state that the decision stages in the PADM are followed sequentially, however, individuals might skip several stages, for example if they feel that the order to evacuate or the information is credible or unambiguous.

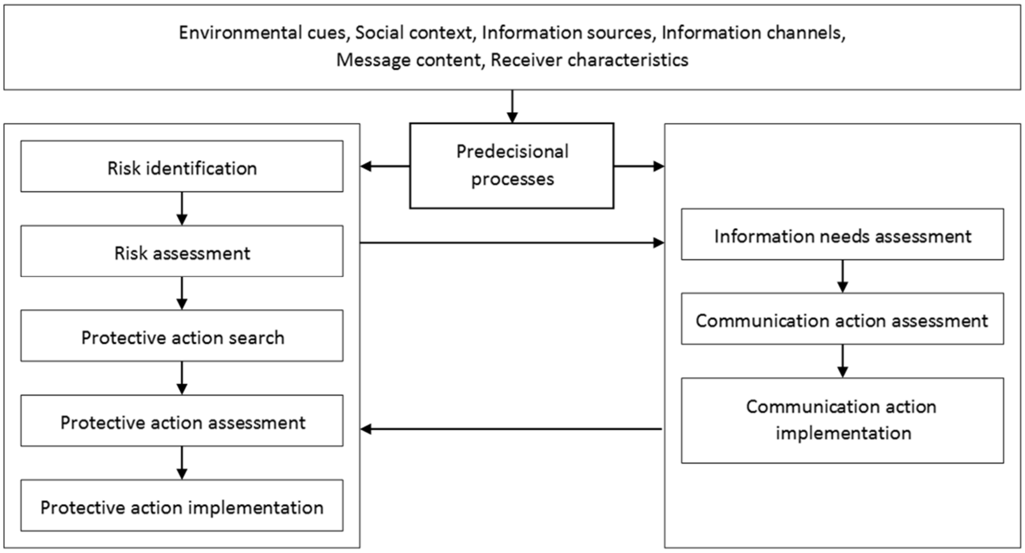

Figure 16: Simplified PADM model according to (Lindell and Perry, 2004)

A common response to danger alerts and evacuation instructions is disbelief or gullibility and is extensively described by Kuligowski (2011) for evacuees of the 9/11 incident in 2008 (Kuligowski, 2011). This response can be linked to cognitive bias (in this case the "optimism bias"), which makes an individual believe that their personal chance of facing a risk is lower than that of other persons (Kinsey et al., 2019). Kinsey *et al.* (2019) argument that a variety of cognitive biases are essential factors in decision-making during fire evacuations and that their consideration in past fire simulations and evacuation behavior predictions and design have been heavily underestimated. Instead, it has either been ignored that evacuees make their own local decisions or their ability to make decisions was outright disregarded. Kinsey et al. (2019) describe two cognitive processes that lead to decision-making: an automatic system and a reflective system. The automatic system does not require any work memory and judges situations based on identified contextual patterns that can be recognized through past experiences or acquired knowledge. It is an unconscious process that acts quicker than the reflective system and focuses more on the situational context than on information. The reflective system is a conscious process that requires work memory in order to evaluate and respond to unfamiliar situations that need assessment by the individual. While the reflective system has partially been considered in evacuation simulations, the automatic system has mostly been disregarded. Especially, in situations where time is limited or a high precision of the outcome is not required, the automatic system with its underlying heuristics is more likely to contribute to the decision-making process. However, these condition also increase the likeliness and influence of cognitive biases. Cognitive biases interfere with the decision-making process by shifting focus on potentially less relevant or irrelevant information and/or inappropriately processing information. The occurrence and effect of cognitive bias depends on situational aspects, such as mood and context. Another example other than the before mentioned 'optimism bias', is the 'bandwagon bias', which describes the tendency of individuals: "[...] to do (or believe) things because many other people do (or believe) the same”, which has also been proven by Kinateder *et al.* (2014) and Kinateder and Warren (2016). These cognitive biases obviously can lead to poor decision making in fire evacuation, such as longer egress time, wrong path-finding, ignoring of danger etc. In high risk situations such as fire evacuations, the result of cognitive bias in decision-making can have a more negative impact on the outcome than in everyday decisions e.g. picking a meal at a restaurant. Even though, the impact of cognitive biases on decision making in fire evacuations has not yet been quantified, Kinsey et al.(2019) suggests that these biases play a significant role and should be considered in evacuation simulations. With those findings, Kinsey et al. (2019) have expanded the PADM model with the aspects of decision-making, heuristics and cognitive biases and tailored it to decision-making in fire evacuation events. NIOSH has also weighed in on how important it is to consider decision-making processes prevention, and mitigation of mine disasters (Alexander et al., 2010).

5. Virtual Reality as Training and Evaluation Tool

Virtual environments have gained attractiveness for conducting simulations and trainings. Some reasons are that some real world environments are inaccessible, pose inherent risks or conducting of simulations and/or training in such is very expensive. (Aizhu et al., 2008; Alexander et al., 2010)

5.1 Introduction to Virtual Reality

Virtual Reality places the user in a three-dimensional virtual environment, which the user perceives through an egocentric view or “first-person” view. The difference to 2D desktop games and partially to CAVEs, is that moving and rotating the head will turn the view ‘in-game’ accordingly as in real life. Crouching will end in adjusted eye-height and some set-ups allow physical movement to be translated into movement in the game. Also, the ability of using grab, pinch and push actions with VR controllers that are closer to hand interaction in real life, give the possibility to interact more realistically with the virtual environment (VE). Therefore, the idea to use VR for training purposes, such as behavior in certain situations or use of tools and equipment, has been tested in a vast amount of papers. Research has indicated that material taught in immersive VR will be kept faster and longer in mind (Grabowski and Jankowski, 2015; Zhang, 2017; Tichon and Burgess-Limerick, 2011) than with less immersive methods.

Table 5: Training methods categorized by levels of engagement (Burke et al., 2006)

Engagement	Examples of training methods
Low	Presentations, lectures, pamphlets, videos, written materials
Moderate	Feedback to learning results, computer-based instructions
High	Hands-on-training, behavioral simulation, active participation

5.2 Applications in Mining

Alexander et al. (2010) have noted that the majority of health and safety training in the mining industry are conducted in a low engagement manner, mostly using oral and/or multimedia presentation and written materials (refer to Table 5). They suggest and strongly support to use high-engagement training in which the miner is actively participating in hands-on-training and engaging in discussions with an expert/instructor and other trainees in order to improve the trainees’ decision-making and problem solving in critical situations. Costs related to real-life trainings can be a constrictive factor when it comes to the frequency of training and quality of training. In order to test if VR can be a low-cost and safe alternative to real-environment evacuation training, Aizhu et al. (2008) created a VR emergency evacuation simulation for larger buildings, in which fire spreads based on numerical models. They then investigated if this tool helps to identify the most effective evacuation methods. Their motivation of this research was that real-life evacuation training and drills can be too costly, have limited repetitiveness and carry an inherent danger. Also mathematical models, such as Cellular Automaton or fuzzy logic (refer to

Chapter 3.1.2), to predict human behavior in a case of fire are too simplified and disregard how small details can affect a persons' decision making during evacuation. Aizhu et al. conclude that the evaluation of emergency evacuation procedures can be conducted inexpensively and safely in the VR simulation. (Aizhu, Chi and Yuan, 2008) Squelch (2001) furthermore mentions specific benefits of VR mine safety training as e.g. train employees to use equipment even if the equipment is unavailable or inaccessible as well as preventing costly mistakes and down-time. The cost factor was also identified by the United States Government Accountability Office's (GAO) paper on deficiencies in underground coal mine safety: "Although mine operators recognized the importance of simulated emergency training, many mines faced challenges conducting such training due to their limited access to special facilities and the high cost of such training." (GAO, 2007) In a response Alexander et al. have suggested that every centralized mine rescue training facility should provide hands-on evacuation drills as well as virtual-reality theaters, as they have been proven to be a valuable addition to the conventional training. According to Alexander et al. four mine rescue stations in New South Wales, Australia, have already implemented such virtual reality theaters. Alexander *et al.* (2010) therefore draw the conclusion that: "Virtual reality appears to be a very promising technology for improving the realism of MER [Mine Emergency Response] training."

Figure 17: VR set-up for the mine evacuation simulation at LMR 155, UNR

The idea of employing virtual reality in order to conduct and evaluate evacuation training has already been picked up by NIOSH in 2009 and they have developed a computer application, which simulates a mine evacuation. Trainees conduct this virtual training on a computer screen and are assigned to a virtual avatar with the mission to evacuate a mine. This can be played in multiplayer mode, where other trainees join the same scenario through other computers (Orr et al., 2009). Squelch (2001) has developed a VR safety and hazard training on a desktop and using joysticks, which was well received by the target group. Since then Stothard, Mitra and Kovalev (2008) as well as Tichon and Burgess-

Limerick (2011) have backed up this finding by concluding that VR can be an effective tool for such trainings in the mining industry. Kizil and Joy (2003) furthermore, identify simulations and education as another application field of VR in mining. Isleyen's and Duzgun's (2019) roof fall hazard assessment and risk mitigation VR application teaches safety around identifying potential risks, mitigating those and enhances decision-making process involved in ensuring safe operations. Foster and Burton (2004) identified remote operation of equipment using VR as a mean to increase operator's ergonomics and reduce human error by overcoming the limited Field-of-view (FOV), poor control design etc. of equipment. Most of these applications were designed for underground mines, but since hazards are not unique to underground operations, Lucas, Thabet and Worlikar (2007) have proposed to investigate the benefits of a VR conveyor belt safety training for surface mining operations. From all the before mentioned VR applications in mining, it can be anticipated that VR will find its way into everyday training, simulations and education in the mining industry.

VR has also been successfully used to test the evacuation behavior in emergencies (Ronchi et al., 2015; Kinateder et al., 2014; Kinateder and Warren, 2016) in other industries such as highway construction, and wayfinding systems (Ronchi et al., 2015; Cosma et al., 2016; Arias et al., 2019) in highway tunnels.

5.3 Navigation in VR

According to Witmer et al. training of route knowledge in VR can almost be as effective as in real world environments. However, when Witmer et al. tested the use of VR against real world environments in learning route knowledge, the VR users had experienced motion sickness and were unfamiliar with the stereoscopic display, which might have negatively affected their route learning process. (Witmer et al., 1996) Burigat and Chittaro define two types of navigation in VR. VR Navigation in HMD's can either be done passively by showing videos, pictures or a pre-recorded run-through of certain routes or actively by having them walk that predetermined environment or route in the VE. In active VR navigation different forms of control such as joystick, keyboard etc. are possible to move in the VE. (Burigat and Chittaro, 2016) Taube, Valerio and Yoder (2013) however, questioned the comparability of navigation in the real-world, on a 2D desktop and HMD, if the person's motion is constrained. In studies where the subjects' navigation abilities were tested after showing them a specific route in HMD or on a computer desktop, did not result in any significant differences. In both cases the subjects were deprived of idiothetic cues as they did not physically walk to acquire any sense of location and orientation. Interestingly, subjects performed the same when these cues are missing even if the level of immersion they were exposed to differed strongly from videos to HMD to actual being driven along the route in the real world. (Ruddle et al., 1997; Waller et al., 2003) According to Tauber, Valeria and Yoder the subjects used only allothetic cues, thus landmarks, to walk the predefined route. In these cases VR does not proof to have an advantage when it comes to spatial knowledge acquisition. Other studies that compared spatial knowledge acquisition from looking at maps, walking the route in real-world and navigating the route in VR showed a higher error for the group using VR. However, points are made that the learning and testing conditions might have posed some disadvantages for VE users due to a lack of visual clues of depth and missing information from the outside of the building, which subjects in the real-world navigation were able to use as recognizable landmarks. (Richardson et al., 1999) Chance *et al.* examined the ability of subjects to indicate directions to target objects after those subjects have travelled a maze beforehand in an HMD. One group had to walk to traverse through the maze, the other group had a joystick to navigate, while they themselves sat in a chair. The study found, that the error of pointing in the direction of the target object was much lower when subjects had used the walking method rather than the joystick method. Also they reported less incidents of motion sickness. Therefore, they concluded that vestibular and proprioceptive information significantly improves egocentric spatial orientation. (Chance et al., 1998) If there are no idiothetic clues provided in VR, the placement of allothetic clues can benefit the route knowledge acquisition as proven by (Jansen-Osmann and Fuchs, 2006; Sharma et al., 2017; Mallot et al., 1998)

6. Experiment

6.1 Hypotheses

The goal of this is experiment is to assess the efficiency of two different evacuation methods in underground mines. One method is a conventional approach (later indicated by capital letter “C”), where the user has to find the egress by following egress route signs and using information available on maps placed in the virtual underground mine. The other method is a smart evacuation method (later indicated by capital letter “S”), where the user will be guided by a wayfinder to the nearest egress. The wayfinder floats in front of the user at all times and is always in the FOV of the HMD.

The anticipated benefits of a smart evacuation method in comparison to conventional methods and the corresponding hypotheses of this research are:

- Smart evacuation is faster
- Smart evacuation leads to quicker decisions
- Smart evacuation promotes confidence in decision-making

6.2 Experimental Design

Any study conducted at a University that involves human subjects requires the prior approval of the universities’ Institutional Review Board (IRB). In order to be granted the approval the IRB board needs to receive an application package that includes the description, purpose, all forms used during the experiment as well as certificates that show that the principal investigator and the experimenter have received training in human research. Only if the study is in accordance with the Code of Federal Regulations on the Protection of Human Subjects (45 CFR 46.104) the study will be approved. Only after receiving the approval can the study legally be conducted. This studies’ IRB approval can be found in Appendix D.

6.2.1 Participants

The participants (also referred to as users) volunteered to run the simulations and were either recruited students (either undergraduate or graduate) or post-docs at the Mackay School of Earth Sciences and Engineering at the University of Nevada. They were approached via email (see Appendix E).

6.2.2 Environment

All simulations described in the following chapters were run in a VR world. As the literature review suggested, virtual environments can be cost- and time efficient tools to produce valid test results that are representative to real-world test results. Therefore, a virtual underground mine was created, which resembles the Turquoise Ridge mine, located north of Winnemucca, Nevada and is currently owned and operated by Nevada Gold Mines LLC. The topmost four levels of the mine (Lvl. 900, 1250, 1550 and 1715) were reconstructed as can be seen in Figure 18. Computation and labor time and effort did not justify a true-to-scale and detailed design of the mine. Therefore, the reconstruction is conceptual.

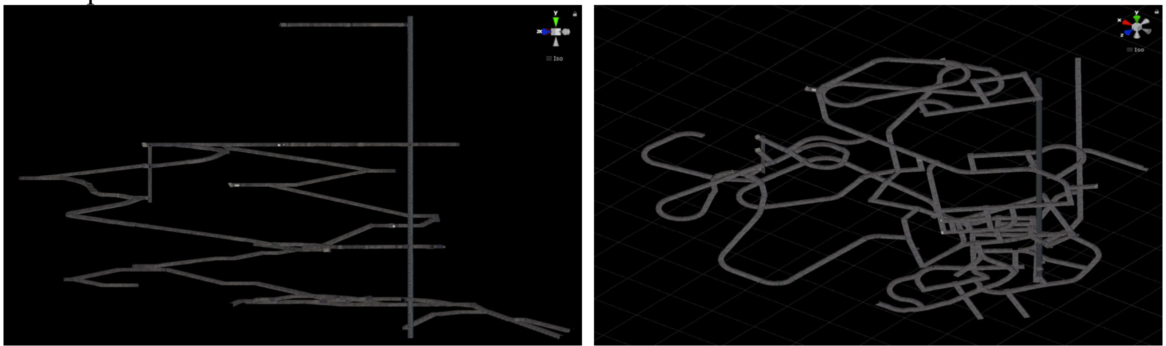

Figure 18: VR mine drift network a) side-view; b) tilted view

The most important features of the mine layout for this simulation is the location of evacuation infrastructure such as refugee chambers and shafts as well as egress route signs and maps. These infrastructures were placed in consultation with a former employee from the Turquoise Ridge mine. This procedure ensured that the simulations using the conventional method are matching the actual conditions in the mine. Consequently, possible bias by the experimenter are eliminated, which – since the placement of the exit route signs were identified to be very critical to the outcome – could otherwise lead to beneficial or adverse conditions for either method. The layout of the two different evacuation wayfinding systems are depicted in Figure 19.

Figure 19: a) Conventional method: Example of egress route sign placed on a drift wall; b) Smart method: smart wayfinder floating in front of user and turning its tip toward the nearest exit;

6.2.3 Experimental Design, Procedure and Evacuation Scenarios

In order to assess the efficiency of each evacuation method a within-subject design was chosen for the experiments. First, all volunteering participants were thoroughly instructed on the nature and the procedure of the experiment (see Appendix F and Appendix G). Their gaming experience and familiarity with underground mines was obtained through a pre-survey (see Appendix H). In order to eliminate a learning curve when participants are transitioned from the conventional to the smart method, an introductory level was set up. In this introductory level they were able to experience and get used to the HMD, locomotion, haptics, controls used in the simulation and the VR environment until they claimed to feel "comfortable" using those. This measure also decreases the differences in gaming experience, as less experienced participants have the ability to learn. This experimental design, was also based on the general assumption that almost all participants have not used VR before.

Once the introductory level was finished, the participants started the mine evacuation simulations. In each simulation the user will be directed through signs only (conventional) or a wayfinder (smart) to a first evacuation target. However as soon as they reach the first target, they will be redirected to a second evacuation target as the first one will prove to be unusable in the course of the simulation. Between the point of time where the user reaches the first target and will be told via the interface to redirect and the time it takes them to proceed their egress to another exit, the time will be measured and serves as the variable "reaction time". This reaction time will help to assess how fast decisions can be made with either method to change the course. Upon start of each simulation a timer will run, which will record the variable "total time", to evaluate how long it took the user from the starting point to reaching the final (second) target. An example of these recordings can be found in Appendix I. The simulations will be held in following order:

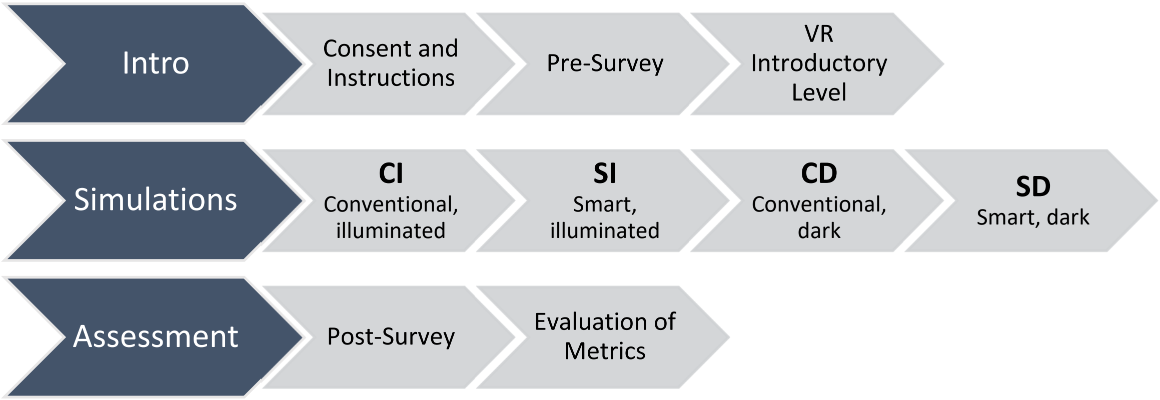

Figure 20: Sequence of stages of the experimental design and codes for the different simulations (starting from the top and going left-to-right)

The illuminated simulations (indicated by capital letter “I”), take place on the same mine level (see Figure 21), as well as both simulations in dark conditions (indicated by capital letter “D”), (see Figure 22). The difference between the illuminated and dark conditions, is that the FOV of the user is considerably smaller in the dark conditions. In addition, they can’t see down the drift/path as much as in the illuminated simulations. Same levels were chosen in order to ensure that the same complexity was met in the conventional as well as smart method. The complexity is defined as: number of possible directions taken along the shortest route and number of intersections. In order to ensure that the participants did not simply remember the evacuation route from the first simulation and therefore finish the second one faster based on their recollection of the route, both evacuation routes in the conventional and smart method were different. However, to make them comparable, all metrics such as distance to final target, number of curves, number of obstacles, obstacle occurrence time and distance of obstacles were the same. Please refer to Figure 21 and Figure 22 to see the comparability of both levels and evacuation routes from a birds-eye-view. The experiment was concluded with a post-survey that assessed the sense of presence according to the Presence-Questionnaire by Witmer, the preference regarding evacuation methods and if the user thinks that smart evacuation is a better approach than the conventional method (the full post-survey can be found in Appendix J).

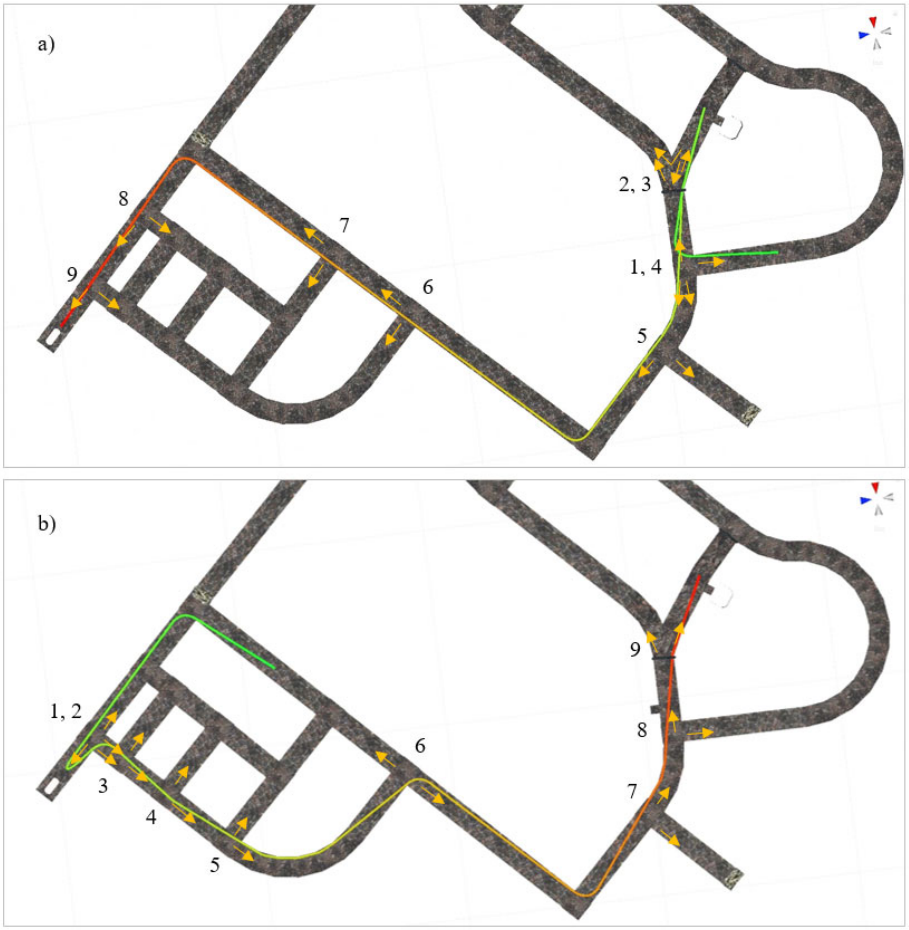

Figure 21: The shortest path from starting point (green) to final target (red) is indicated by the colored line. Decision points are marked in this graphic with yellow arrows and amount to 18 each for a) the conventional simulation route (CI) and b) the smart simulation route (SI). Intersections are numbered chronically and amount to 9 each. Both routes are illuminated.

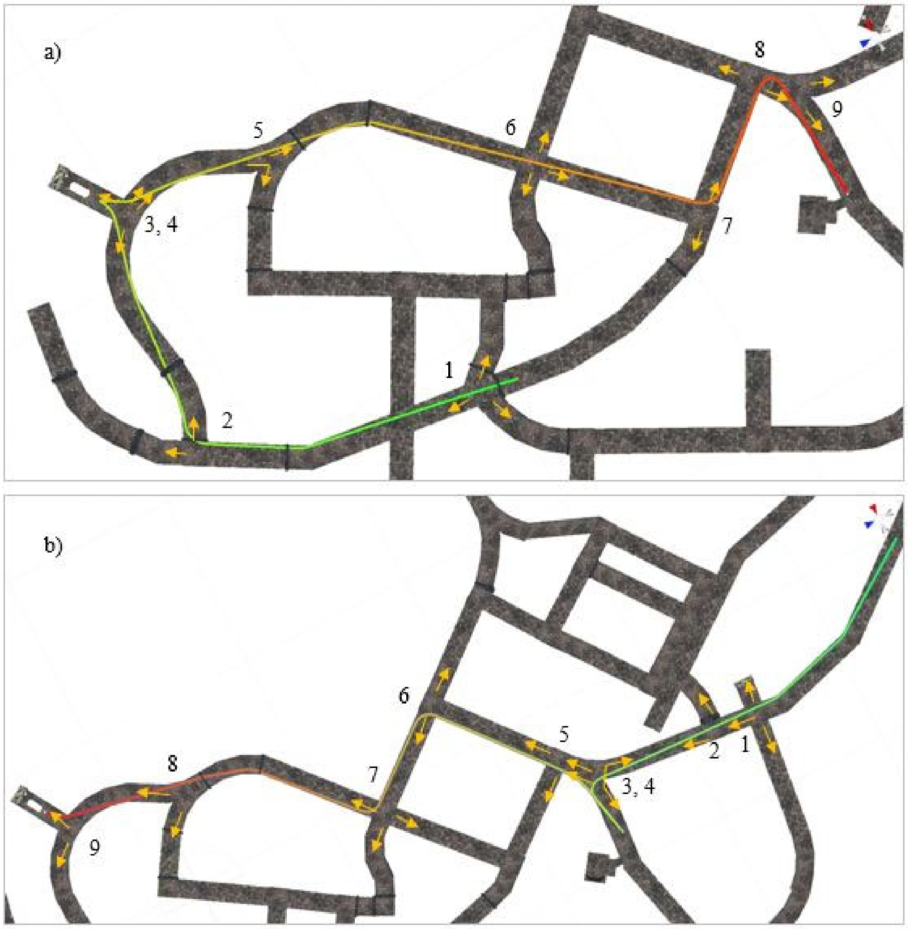

Figure 22: The shortest path from starting point (green) to final target (red) is indicated by the colored line. Decision points are marked in this graphic with yellow arrows and amount to 20 each for a) the conventional simulation route (CD) and b) the smart simulation route (SD). Intersections are numbered chronically and amount to 9 each. Both routes are not illuminated.

6.3 The Virtual Simulation Environment

6.3.1 Functionalities

In order to create and program these simulations, which can be seen as "serious" games, the Unity 2018.3.2f1 game-engine was used. It is an open-source software that specializes in developing games on a variety of the most modern platforms, such as Windows, Android, iOS, PlayStation etc. The company itself claims that 60% of all existing VR and AR contents were created using the Unity game engine (Unity Technologies, 2019). Unity has some pre-made drag and drop features with which very basic games can be created. Any more complex game requires scripting in the programming language C#. The Turquoise Ridge mine design was exported from the mine planning software Vulcan by Maptek™, and imported to Unity, which showed the layout as simple strings. These strings were used to assemble a variety of tunnel/drift sections in order to create a walkable VR mine environment. The head-mounted goggles used to render the VE were the HTC Vive HMD. The HTC Vive goggles' position and rotation and thus the movement of the user's head in real-time, is tracked through two sensors that constantly send out infrared light and get recognized by the HMD's and controllers' photoreceptors (refer to Figure 23). The SteamVR application has to be run in the background as it is an interface that enables communication between the VR hardware and software. The user can move in this VE by walking on the Virtuix Omni treadmill as can be seen in Figure 23. Once the user has put on the Omni shoe-slipovers with attached tracking sensors, he can step into the Omni treadmill and start walking. Through the concave design of the Omni base and the low-friction slip-overs the feet of the user will glide back to the center after every stride. He can therefore walk in place and is moving more naturally than other convenient VR locomotion mechanisms, such as teleportation or flying. We chose to utilize a treadmill such as the Virtuix Omni to help participants navigate the VE by collecting idiothetic cues as described in Chapter 4.1.

Figure 23: HTC Vive HMD (middle), controllers (bottom left and right) and lighthouse sensors (top left and right). (HTC Corporation, 2019)*, Omnidirectional treadmill "Omni"* (Virtuix, 2019

6.3.2 Implementation

A texture was applied to the drifts as to mimic the actual look of mine drifts. Ends of open drifts were closed off with rock piles, which prevents the user from leaving the mine. In the VE the user is subject to physics and therefore will be kept on the ground through the force of gravity as he moves through the drift system. Colliders are applied to all visible entities to avoid the user from walking through objects and walls. Drifts were illuminated by inserting models of light bars and adding a light source to them. Lights, however were only added to simulations with illuminated conditions, thus CI and SI. In all simulations the user is equipped with a virtual headlamp, that moves and rotates with the head and therefore with view of the user as well. In those simulations in dark conditions (CD and SD), this headlamp is the only light source, through which the FOV is largely decreased. A user interface (later referred to as UI) was created, that always stays in a predefined position in the user's FOV. The UI is used to transmit information to the user in game, such as the time of playing and instructions. In simulation SD the UI did not show up for the first obstacle and the final target. Therefore, the assistant chose to directly tell the instructions to the participants once they had crossed the trigger for the UI. An audio listener was added to the player object, so that sounds played through an audio source can be heard on the user's headphone. To mimic the mine environment even further a ventilation noise is played upon start of the game. Smoke sources are also equipped with an audio source. However, once the simulations were approved and the first test persons started, the audio did not work and was therefore omitted for all following participants as well. The waypointer utilizes Unity's NavMesh feature. NavMesh calculates and bakes walkable paths in the current game level based on the objects mesh renderers and terrains (in this case the floor of the drift). This results in a navigation mesh consisting of walkable surfaces. During the process of baking the NavMesh the maximum angle of walkable slopes and step heights can be determined. Once a NavMesh is baked a NavMesh Agent can be added, which is a pre-made asset available in Unity.

Figure 24: Example of the NavMesh in Lvl. 1715 indicated by the blue color

If the NavMesh Agent is given a specific target, the AI agent will utilize an A*-algorithm to compute the shortest path and then starts moving towards the target following that shortest path. The agent cannot pass through walls. The forward direction of the agent always points towards the next step within shortest path. The waypointer in the smart method simulations SI and SD is such an AI agent. In order to make the direction it points to more easily visible, a three-dimensional arrow object was created in the modelling software Blender and exported to Unity in a .fbx-format. The target it points to in the simulation are controlled through a script. In order to prevent the waypointer from moving towards the target while the user is standing still, the waypointer was parented to the player's camera object in the object hierarchy in Unity. Therefore, the waypointer will move with the rotation and movement of the camera and thus the user's head. It stays in the user's FOV while still pointing towards the target.

6.3.3 Documentation

The simulation will start once the examiner pushes the "Start Recording"-button in Unity's plug-in recorder, which will then record the in-game view of the user. The examiner can end the simulation any time by deactivating the play-button in Unity's window. Upon end of the game, the recording will stop and the video saved on the local drive. One script was developed to take a screenshot of the mine level from above every 5 seconds. On this screenshot one can see the current player's position as well as the trail of the path he has taken so far. The trail is color-coded, so that the more recent walked parts of the trail are red and the former ones are colored green (as can be seen in Figure 21). Thus, the recorded video as well as the screenshots can be used to analyze, where the player had struggles to find the right path. The trail itself is only rendered in this screenshot and cannot be seen by the user in the game itself. The smoke, created through the ParticleSystem asset in Unity, is rendered only in-game but not in the screenshot to ensure full visibility of the trail evolution.

FIND A REFUGE CHAMBER
TO EVACUATE!

Figure 25: Example of the UI upon start of the game

Four text-files have been created for the different simulation conditions in which the date and start time, the reaction time as well as total duration of the simulation will be stored. The reaction time starts once the user walks through an invisible trigger on his way to the first target. When the trigger is activated a UI will pop up for 5 seconds that looks comparable to the one in Figure 25 and will tell the user:” The shaft is out of order! Find a refuge chamber!” or “The refuge chamber is full! Find the shaft!” depending on the simulation condition. The reaction time stops, once the user walks through a second trigger indicating that he has made a decision to proceed in another direction. These reaction triggers are all placed apart in the same distance in each simulation condition. The last trigger is activated upon reaching the final target and will automatically read the time from starting the simulation to activating the final trigger and store it in the text-file as well. Additionally, in a separate text-file the information about the Omni’s count of steps and hip-ring angle will be recorded in an interval of 2 seconds. The changes in those values can then be shown in a graph over time and be used to compare how much the user had to change direction or turned around to assess other route options in each simulation condition.

7. Results & Analysis

7.1 Sample Description

In total 13 participants voluntarily conducted the simulations. Four people reported to play games several times a month. Two had experienced VR for about 10 times, two for 3 times, four for two times and four for one time. Only two people claimed to never have experienced VR. Nine participants reported that they had been in an underground mine before. As this study is not interested in performance or behavior difference between men, women and LGBTQ+, the gender was excluded from the pre-survey.

Three people did not proceed with the simulations in dark conditions, as they had encountered fatigue or motion sickness in the simulations before to a degree where they did not feel comfortable. One person did not successfully finish the conventional, dark simulation as the person simply got lost in the mine for over 10 minutes and asked to stop.

The major hypotheses of this research is that the smart evacuation method is more efficient, thus brings evacuees faster to the safe area, than the conventional evacuation method. Furthermore, if this proves to be true the efficiency should be determined quantitatively. Moreover, it is predicted that evacuees' decision-making process will be accelerated when using the smart evacuation method. Another assumption is that smart evacuation will promote confidence in decision-making, thus decreasing confusion and errors along the evacuation path.

7.2 Quantitative Results

Quantitative data was collected by scripts in the simulation environment and stored in .txt-files. Variables of interest were the total evacuation time (also referred to as total time) and the time to react to obstacles within the simulation (referred to as reaction time). Total evacuation times obtained through the simulations are shown in Table 6. None of the data showed outliers. All results were statistically compared against a significance level of $\alpha = 0.05$. The total time it took each participant to evacuate in each simulation was taken as a measure of efficiency.

Table 6: Total times (s)

ID	CI	SI	CD	SD
0	252	217	196	180
1	256	225	188	229
2	394	151	-	-
3	521	191	-	-
4	390	183	-	-
5	440	237	192	160
6	462	281	304	239
7	278	278	312	263
8	298	190	226	128
9	289	124	161	129
10	301	161	209	142
11	211	175	-	-
12	178	164	200	182

In Figure 26 the average evacuation time of all simulations CI (N=13, M=328.46, SEM=27), SI (N=13, M=198.23, SEM=13.41), CD (N=9, M=220.89, SEM=17.45) and SD (N=9, M=183.56, SEM=16.59) are put in comparison. As can be seen in Figure 26 the average time to evacuate using smart evacuation (SI, SD) was in all cases lower than the time needed when using the conventional method (CI, CD). However, it is notable that the participants in average finished the simulation in CD and SD sooner than in the CI and SI. Noteworthy is the performance difference between CI and CD. Even though the participants' FOV was limited in CD they outperformed the average time compared to the one in CI by 32.75%.

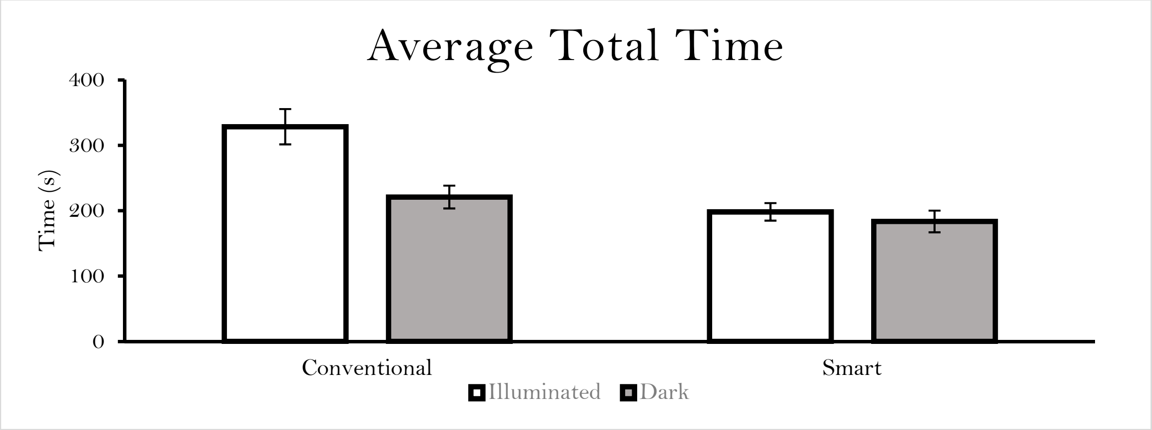

Figure 26: Average time needed to finish each simulation and range of error

The standard deviation σ is a measure on the variability within the collected data and thus on how far the collected data spreads around the data's mean. A low variability implies that the data is more or less gathered around the mean, whereas a high variability implies that the data can spread further away from the mean. The variability for the collected data in all four simulations is visualized in Figure 27. For CI the standard deviation (σ=103.58) is strikingly higher than for SI (σ=47.41), CD (σ=52.36) and SD (σ=49.76).This information makes it evident that the total times in CD were partially far spread around/from the mean, with a maximum time of 521 s and a minimum time of 178 s. Even though the value of 521 in dataset CI looks like it could be an outlier, a closer look at the acceptable data range that is defined by two standard deviations from the mean and results in (121.30, 535.62) confirms that all data in CI is within range. The time it took to evacuate in CD is not as consistent as in all other simulations SI, CD and SD. The difference between the standard deviation of SI, CD and SD is not considerably high.

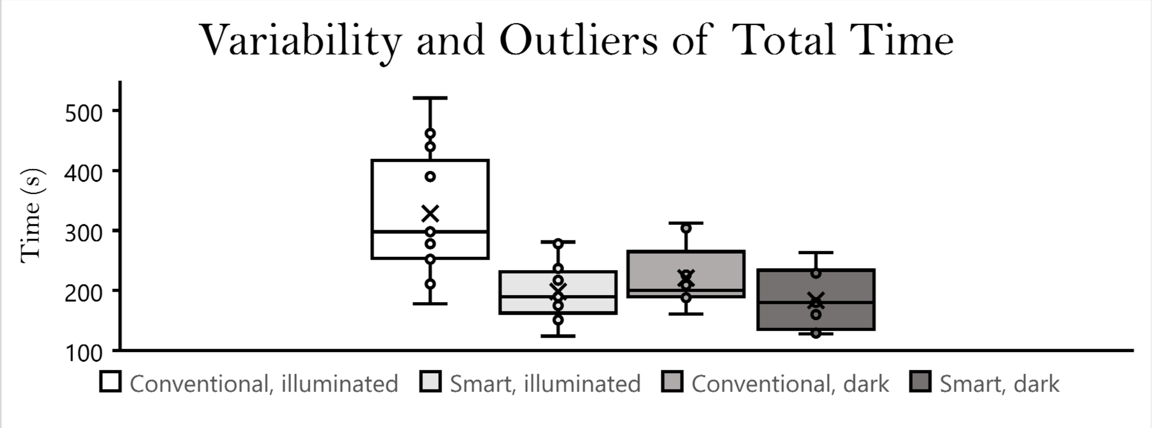

Figure 27: The variability (σ) (box), collected data points (dots) and maximum and minimum values (whiskers) as well as the mean (M) (line) of the total times collected for each simulation

In order to confirm that the data sets were normally distributed, the skewness and kurtosis factor as well as a Shapiro-Wilk test were run. These test were run for the datasets that resulted out of the subtraction of two simulations, thus the time difference d (e.g. CI - SI), as these differences are used in the following matched pair t-test as well (refer to Appendix K). The skewness for CI-SI was 0.36, for CD-SD -0.59, for CD-CI 0.45 and for SI-SD 0.14. The acceptable range for skewness is (-1, 1). The kurtosis value for CI-SI was -0.76, for CD-SD 1.25, for CD-CI 0.40 and for SI-SD -1.05. The acceptable range for the kurtosis factor is (-2, 2). In order to conclude if the difference between the simulations was significant a matched pair t-Test was conducted, comparing each method to one another and are given in Table 7. As to ensure that the statistical calculations conducted in Excel deliver the right results, a manual calculation was done for CI-SI (see Appendix L) as well and the results were found to be matching.

Table 7: Statistical significance of difference between the total times of the methods as well as the achieved reduction in total time

Time Difference (d) (M_1>M_2)			**Average time reduction**	**p-Value**	**Significance**
CI	-	**SI**	-39.65%	0.000554	significant
CD	-	**SD**	-16.90%	0.021974	significant
CI	-	**CD**	-32.75%	0.018969	significant

SI	-	**SD**	-7.4%	0.037993	significant

The null hypothesis, which says that the difference between the datasets is zero, was rejected in all above cases, as the observed t-values were bigger than the critical t-values taken from the t-tables. The full table with statistics results can be found in Appendix M. To further test if the difference was statistically significant the p-Values were determined. Each probability value (p-Value) that is lower than the beforehand defined significance level α = 0.05, indicates that there is a significant difference between the data sets of the compared simulations. In all cases there was a significant difference in total time. Smart evacuation was in all cases significantly faster than conventional evacuation. The simulations in the dark environment were significantly faster than in the illuminated environment. The biggest average time reduction can be observed between CI and SI with a percentage of -39.65%. The corresponding p-Value of 0.000554 is very low. Another considerable difference can be observed between CI and CD where time was reduced by 32.75%, thus evacuees were faster in the dark environment. The p-Value here is 0.018969. Between CD and SD a p-Value of 0.015036 indicates a significant difference, meaning that the simulations in SD went considerably faster and reduced the average total time by 16.90%. When comparing SI against SD the p-Value of 0.037993 on the verge of being statistically significant. A time reduction of 7.4% was obtained.

One example that visually shows the data obtained by CI versus SI and CD versus SD is given in the scatter plot in Figure 28. The trend line through the single data points indicates, that the time taken in CI is not significantly related to the time taken in SI. That means, that whereas the time in CI might increase or decrease significantly, the total times obtained in SI stay relatively the same. The formula matching the linear trendline is: $y = 0.1137x + 160.9$, which shows that the slope is relatively flat. For CD vs SD the trendline's equation is $y = 0.667x + 36.223$, which is a steeper slope but still indicates that as the x-value (the time take in CI) increases the y-value (the time taken in SI) increases only by two-thirds.

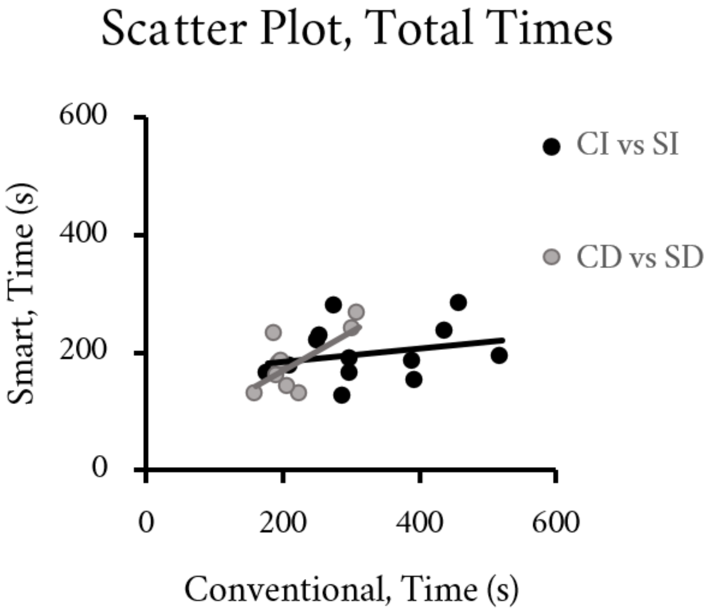

Figure 28: Scatter plot with single data points of total time and regression lines of the data

The same statistical analysis was conducted for the reaction time. The reaction time describes the time between the evacuee running into an obstacle and leaving the area after having made a decision. The reaction times were automatically collected through a script that was activated by invisible triggers within the game to ensure consistency. The collected reaction times can be seen in Table 8.

Table 8: Reaction times (s)

ID	CI	SI	CD	SD
0	30	20	17	12
1	28	12	7	6
2	9	13	-	-
3	9	21	-	-
4	36	12	-	-
5	14	15	23	15
6	37	12	8	6
7	20	12	26	17
8	9	20	9	8
9	20	11	13	12
10	14	12	5	21
11	16	8	-	-
12	24	22	33	30

The trend of average reaction times (compare Figure 29) looks similar as the trend observed with average total time with CI (N=13, M=20.46, SEM=2.63), SI (N=13, M=14.62, SEM=1.21), CD (N=9. M=15.67, SEM=3.07) and SD (N=9, M=14.11, SEM=2.45).

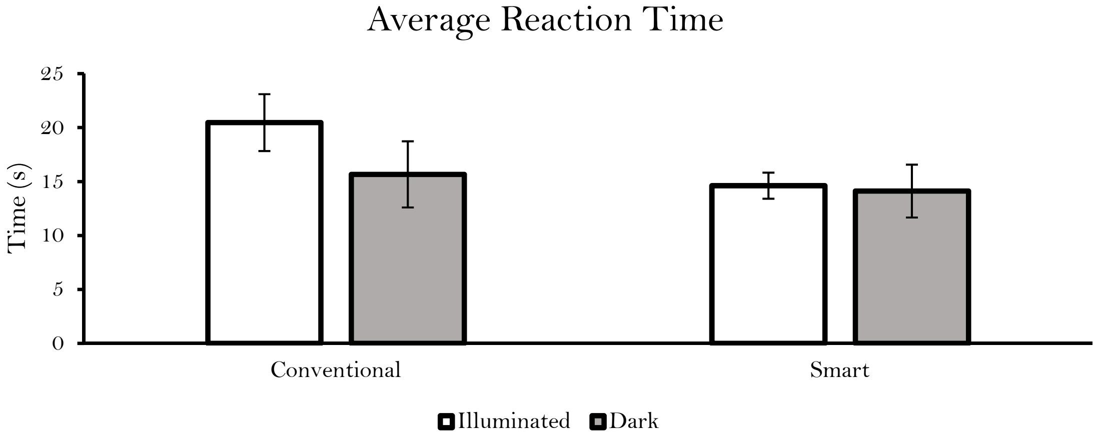

Figure 29: Average reaction time for each simulation and range of error

Again in both smart evacuations SI and SD the average time was lower than in the conventional simulations CI and CD, with CD being strikingly higher. Compared to the variability of the total times, the variability of the reaction times were in both conventional simulations CI (σ=9.5) and CD (σ=9.2) comparable and higher than in both smart simulations SI (σ=4.36) and SD (σ=7.36). The data collected in CI and CD are therefore less consistent than in SI and SD, while SI is showing the most consistent data.

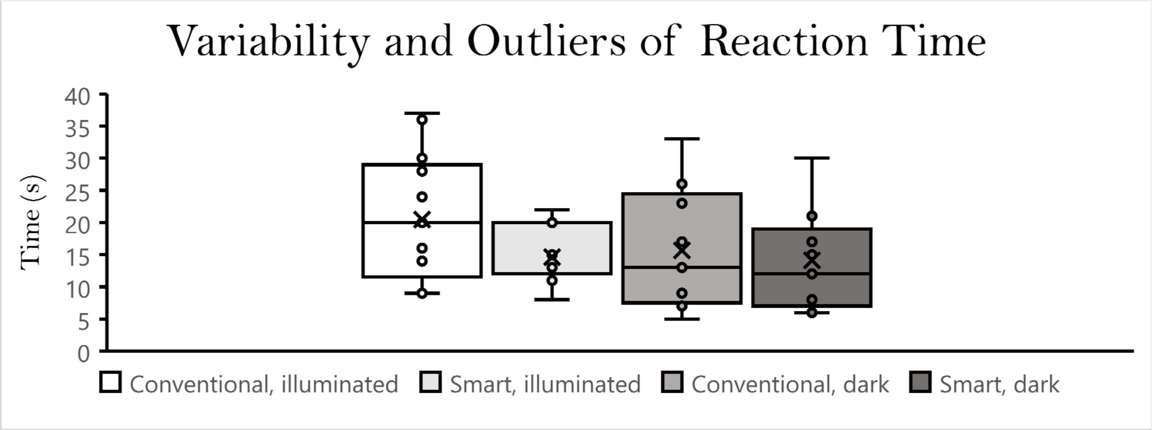

Figure 30: The variability (σ) (box), collected data points (dots) and maximum and minimum values (whiskers) as well as the mean (M) (line) of the reaction times collected for each simulation

Before conducting the statistical analysis of significance, normality tests were conducted (refer to Appendix N). All datasets passed, except for CD-SD, where a skewness of -1.97 and a kurtosis factor of 5.129 were obtained and thus were considerably out of the acceptable range. However, the same dataset CD-SD has an outlier with the value of (-16). When the outlier was eliminated the skewness was 0.89 and the kurtosis value -0.95 and could therefore be still be considered normally distributed. A normal matched pair t-test as was applied to CD-SD without the outlier and a nonparametric sign test to the same dataset including the outlier. The overall results of the matched pair t-test for each dataset are shown in Appendix O, whereas the result of the Sign-Test can be seen Appendix P. In the case of CD-SD a statistical significance was found using both statistical methods. For the matched pair t-test a p-Value of 0.013613 was obtained and with the Sign-Test a p-Value of 0.017578. Both methods therefore attest a significant difference in reaction time between Conventional, dark and Smart, dark. All other datasets were normally distributed and the matched pair t-test could not prove any significant difference between those datasets, which are listed in Table 9. The scatter plot and regressions lines of the reaction times data did not reveal any noteworthy information or relationship between the datasets.

*Table 9: Statistical significance of difference between the reaction times as well as the reduction in time achi*eved, *results obtained through nonparametric sign-test with outlier included

Time Difference (d) (M_1>M_2)			**Average Time reduction**	**p-Value**	**Significance**
CI	-	SI	-28.57%	0.090777	not significant
CD	-	SD	-22.06	0.013613	significant
***CD**	-	SD	-9.93%	0.017578	significant
CI	-	CD	-23.43%	0.465899	not significant
SI	-	SD	-3.45%	0.679870	not significant

The biggest reaction time reduction was observed between CI and SI with a percentage of 28.57%, where the p-Value is 0.090777. Even though, the p-Value for CI-CD is relatively high with 0.465899, the reaction times showed an average reduction of -23.43%. However, since the difference is not statistically different as in CI-SI and in SI-SD no strong conclusion can be made about the efficiency of the smart evacuation over the conventional evacuation method. Additionally, the author wants to point out that the data sets especially for CD-SD, CI-CD and SI-SD had only nine samples and therefore the analysis of these datasets can be less powerful than with larger datasets.

7.3 Qualitative Results

In order to get more data about the participants' behavior and preferences qualitative data was collected such as data given by use of the Omni Virtuix and the pre- and post-surveys. Furthermore, the path taken by the users was examined especially when there were conspicuous times collected. The screenshots with the taken path in each simulation as well as the videos of the users FOV, helped interpreting their decision-making process. One thing that became evident, is that most participants seemed to forget that they were equipped with the smart wayfinder that would show them the shortest path after running into the first obstacle. Hence, many would examine the mine map to try to find the shortest way instead of simply following the wayfinder. This might be due to the design of the waypointer, which vanished into the wall when participants stood close to the drift's wall and would examine the map, and therefore for that time they were not reminded of the wayfinder's presence. That could have contributed to the outcome that there was no statistically significant difference between the reaction times while using the conventional or the smart method.

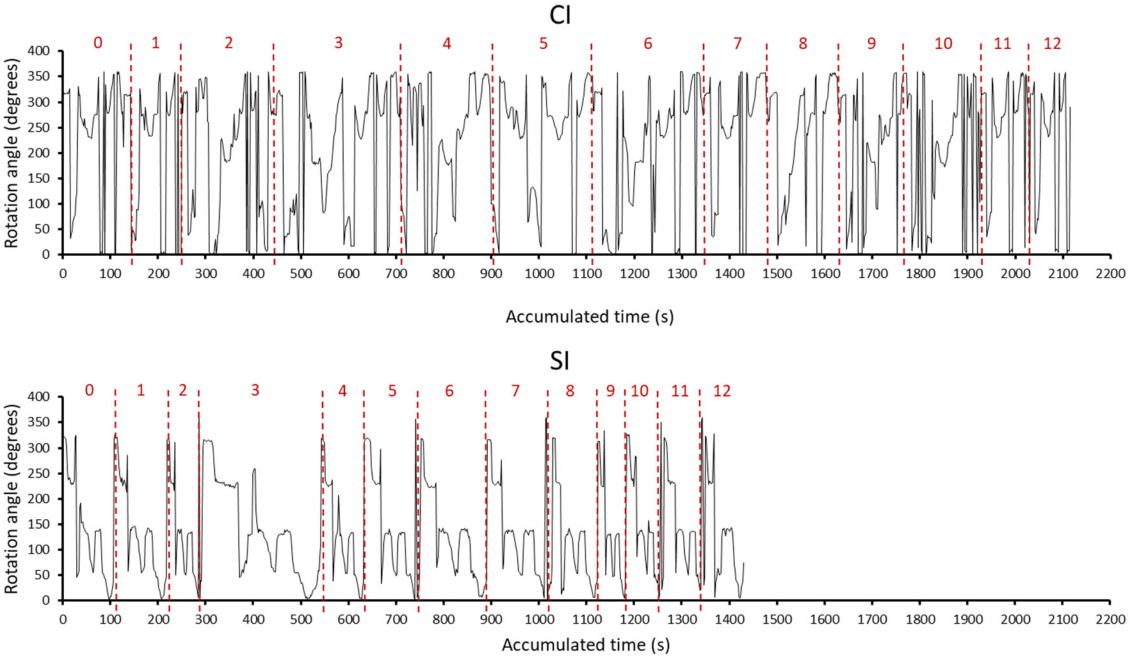

Figure 31: Angle of turning in the Omni during CI and SI, the turning sequence of each participant is indicated by the participants' number and the dotted, vertical lines

Figure 31 gives a solely visual representation on how often the participants were turning in the Omni for CI and SI, either changing their walking direction or turning to look around. Comparing the amount and even density of vertical lines in both graphs one might conclude that participants have turned around more while using the conventional evacuation method. This could indicate that some participants did not find the shortest route, had to redirect or ensure that they had chosen the right path, whereas in the smart evacuation method participants mostly followed the arrow. The homogeneity in reoccurring turning patterns for each participant in SI can be interpreted as lower level of confusion about where to go as most participants took similar turns at similar times. At this point the author wants to reinforce, that both levels had the same amount of 90° and 180° turns. Looking at the same graphs for CD and SD (compare Figure 33) no considerable difference can be visually noticed between the amount and sequence of turning using the conventional method or smart method. When examining the recorded videos and recorded path of the participants while using the conventional method in dark conditions, one can see that most participants chose a path that was slightly longer than the computed shortest path, but included less turns:

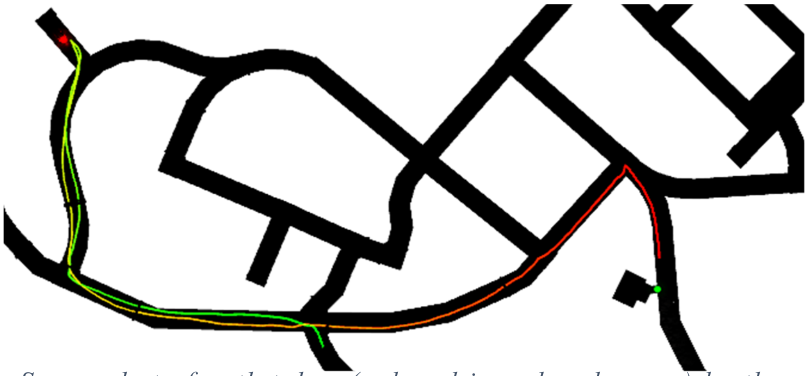

Figure 32: Screenshot of path taken (colored in red and green) by the participant

This might be due to the participants remembering a shaft-exit sign that they came across at the very beginning of the simulation, which might have led them to simply return that same route instead of taking another, shorter, but unknown route. Therefore, the assumption can be made that sign placement had an effect on the decision-making process of the participants during the simulation.

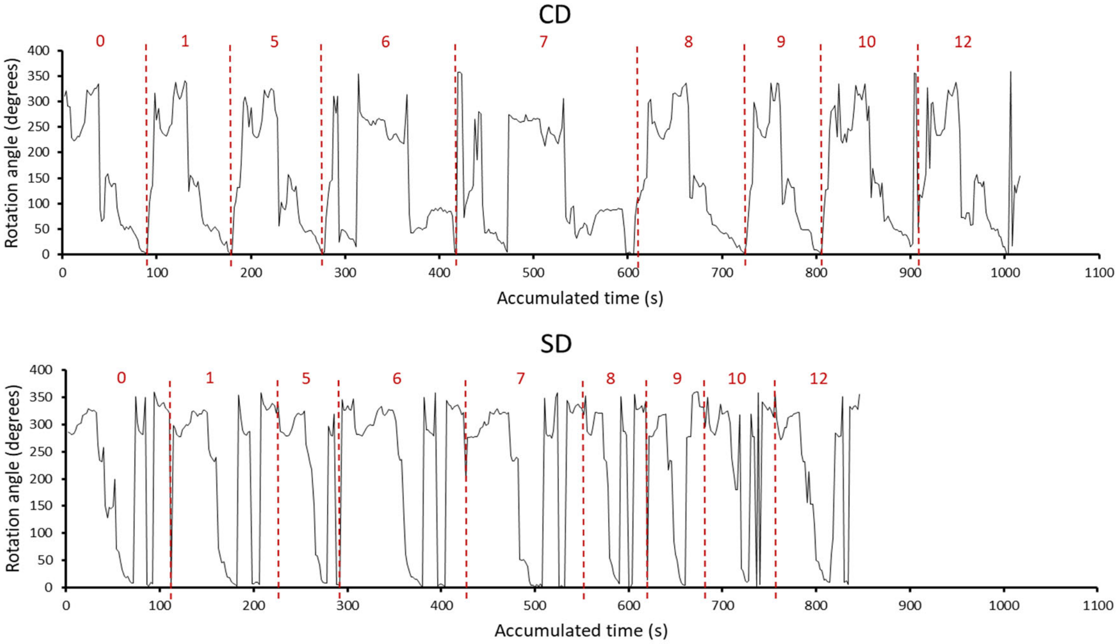

Figure 33: Angle of turning in the Omni during CD and SD, the turning sequence of each participant is indicated by the participants' number and the dotted, vertical lines

The post-survey gave qualitative information about the feeling of presence within the VE and the personal preferences of the participant. Furthermore, it was investigated if participants felt if the apparatus influenced their performance considerably. The average ranking for the presence questionnaire (PQ), which uses a Likert scale from 1-7, can be found in following table:

Table 10: Post-Survey Questionnare Results

No.	Question (equivalent answers for ranking 1 - 7)	Mean	StDev

1	How natural was the mechanism which controlled movement through the environment? (Extremely artificial – Very natural)	3.84	1.50
2	How inconsistent or disconnected was the information coming from your various senses? (Not at all – Completely)	3.38	1.92
3	How much did your experiences in the virtual world seem consistent with your real-world experiences? (Not consistent – Very consistent)	4.88	1.38
4	How completely were you able to actively survey or search the environment using vision? (Not at all – Completely)	6.40	0.64
7	To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session? (Not confused – Very confused)	1.79	0.92
8	How quickly did you adjust to the virtual environment experience? (Not at all – Less than 2 minutes)	6.38	0.96
9	How proficient in moving and interacting with the virtual environment did you feel at the end of the experience? (Not proficient – Very proficient)	5.57	1.61
10	How much did the visual display quality interfere or distract you from performing assigned tasks and required activities? (Not at all – Prevented task performance)	2.15	1.34
11	How much did the control devices interfere with the performance of assigned tasks or other activities? (Not at all – Prevented task performance)	2.68	1.64

Participants did not feel that the locomotion technique using the Virtuix Omni was either extremely artificial or felt very natural (Q1), the participants claimed that the Omni did not interfere heavily with the performance of the assigned task (Q11). At the end of the experiment the majority felt proficient or very proficient using the Omni Virtuix (Q9). Furthermore they reported that they got used to the VE fairly quickly approaching a time under 2 minutes (Q8). Participants felt that they were able to explore the whole environment using vision completely (Q4). There are no values given by the PQ that indicate the lack of presence or a lack of control over moving in the VE. Some of the questions (Q1, Q2, Q3) answers average score is around the median. In conclusion the tendency shows that the participants felt more immersed in the VE than they felt disconnected. Question 5 and 6 in the post-survey addressed the sounds in the simulation, however, since these did not function those questions were omitted.

83.33% of the participants claimed that they preferred the smart evacuation over the conventional method, with some stating that:

- [..] it’ll guide me to where I need to go without me worrying about not taking the right turn.
- [smart evacuation is] easier to follow, less thinking

In addition all, thus 100.00%, of the participants thought that smart evacuation can contribute to safety in mining, with statements given such as:

- Definitely much better [than signs] even if there were more signs.

- […] can definitely help me to consume lower amount of energy […].
- Yes, because it would help me safe time and get to safety faster.
- […] people will be calm.
- Yes, I do think it would contribute immensely.

Some remaining random comments on the simulation addressed that there should be more signs throughout the mine, with one person stating that he thinks the smart evacuation would still be "superior" to the conventional method. One person noted that it was very interesting and felt real, while one person stated that the "shaking of [the] virtual world", which can be assumed to refer to a low frame rate, caused motion sickness. All participants stated that the study increased their interest in virtual reality.

8. Conclusion and Future Research

8.1 Conclusion

This study proved that the evacuation times differ significantly for smart evacuation guidance and conventional evacuation guidance. The results verify that the smart evacuation method is faster and saved tremendous amounts of time of up to 40%. The hypotheses that smart evacuation is faster was proven to be true.

In contrary there was no statistically significant difference in the time it took the participants to react to changing conditions in the environment, which prompted them to change the course of their route. As the recorded videos show, most participants consulted the mine map rather than the smart wayfinder in these situations. From examining the recorded videos and screenshots it can be assumed that the decision-making process was facilitated by the smart wayfinder along the path but not when the path had to be changed completely. The second hypotheses stating that decision-making can be accelerated through smart evacuation could not be proven to be true through quantitative data, but the qualitative data indicates that this hypotheses cannot be fully rejected as well. The hypotheses needs further testing.

Furthermore, when taking the post-survey answers, the frequency of turning in the VR world, as well as video and screenshot footage into considerations, it becomes evident that the participants felt more confident in their decision-making process when they followed the smart wayfinder. They preferred the “easy” guidance and had to turn around less to evaluate which way would bring them to the safe area faster. Thus, the hypothesis that smart evacuation leads to more confident decision-making was proven to be true but cannot yet be quantified.

Even though, it was attempted to prevent a major learning effect throughout the simulation with the use of an introductory level a minor learning effect cannot be eliminated. Against the author’s expectation the participants did not perform worse, but in most cases even better in the dark simulation environment where their FOV was constrained to a small angle and their visibility range shortened. This might be caused by a slight learning curve in the course of the simulations, as participants have acclimatized to the use of the treadmill and the wayfinder.

In overall this study seconds the initial hypothesis stating that smart evacuation is more efficient than the conventional method and leads to more confident decision-making. The maximum time reduction achieved by using the smart evacuation instead of the conventional evacuation method amounts to up to 40%. In overall 83.33% of the participants preferred the smart evacuation method over the conventional evacuation method and 100% seconded that smart evacuation could be beneficial for miners’ safety during mine evacuations.

With these findings, the author proposes to further test how smart evacuation can shorten critical evacuation time while making the egress from a mine safer.

8.2 Future Research

As the results show, there is potential for using smart evacuation guidance systems for underground mines in order to reduce evacuation time. Therefore, further research on this topic should be conducted in order to complete this first fundamental study.

For future research it is recommended to recruit a bigger number of volunteers and conduct experiments based on a between-subjects design rather than a within-design. This prevents the occurrence of a learning effect which can influence the results negatively. Moreover, a between-subjects design reduces bias or possible disadvantages or advantages that can unintentionally occur due to different but random route assignment.

This study only looked at one isolated aspect of smart evacuation, which is the real-time guidance. However, this study did not investigate how smart evacuation can outperform conventional methods when registering hazardous conditions beforehand and guiding the evacuees on an optimal route from the very beginning. In this study the author did not want to give an inherent advantage to the smart evacuation method by leading the participant straight to the final target, instead of running into one obstacle first. When implemented in an actual mine, the smart guidance systems should detect the obstacle or hazard condition and compute the shortest and safest route based on this information. Another feature that should be implemented is an algorithm that takes the individual’s fitness into account. This could help to distribute miners among refuge chambers and shafts based in a way that for example less fit or older miners’ have to walk less and have a higher chance of reaching a safe area in time. Moreover, if this algorithm is fed with the maximum occupancy of the refuge chambers it could ensure that none of them gets overfilled.

In order to increase immersion and make the scenarios more realistic the mine drifts could be modelled using LIDAR data. This could help to identify main and side drifts, and give additional cues on where main infrastructures such as the shaft or ramp are located. More powerful results could be obtained, if miners could participate in a smart evacuation simulation that takes place in a VR model of the mine they currently work at. This could give further insight on how smart evacuation affects decision-making and possibly eliminates cognitive bias when the evacuee already knows the layout of the mine and locations of evacuation infrastructure.

As cognitive bias has a major effect on the decision-making processes it should be quantified in future research how the real-time, individual smart guidance system can reduce panic as well as bias during evacuation situations.

Once the efficacy, reliability and algorithm of the smart evacuation guidance system have been further proved and improved, a study on which device is best suited for the smart wayfinder such as a smartwatch or a mobile phone would have to be conducted.

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Appendices

Appendix A Employees and Fatalities in Mining

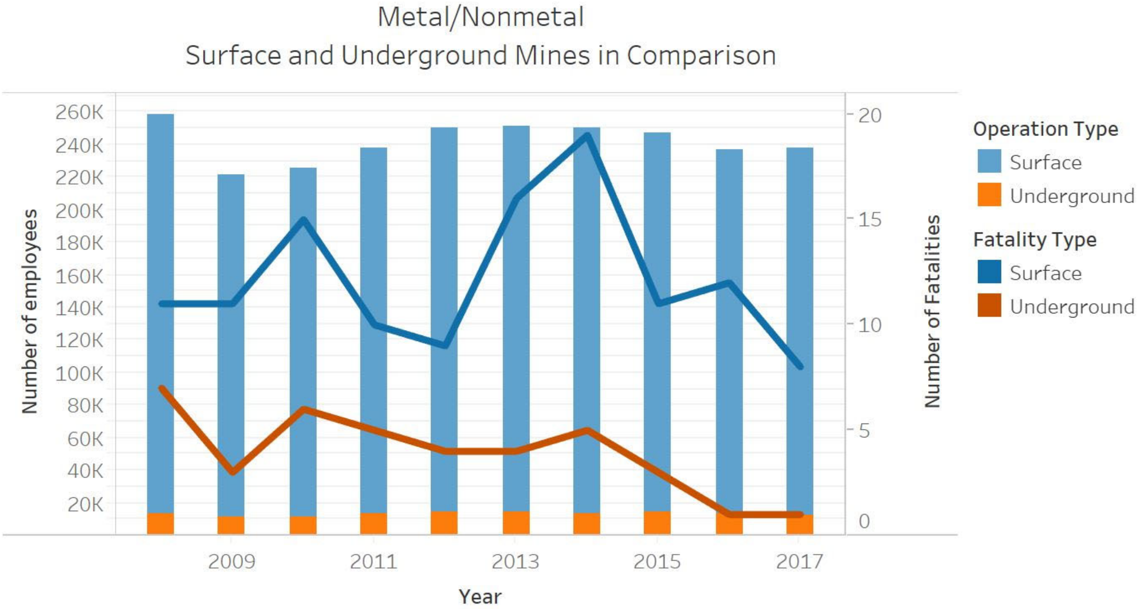


Figure 34: Difference in annual number of employees and fatalities in surface and underground operations from 2008-2017 (NIOSH, , 2017; MSHA, *Fatality Reports*)

Appendix B **Fatalities per Accident Category**

Table 11: Fatalities per accident category in metal/nonmetal mines between 2008-2017 according to MSHA's fatalities reports

Accident classification	Underground	Surface/ Surface of Underground
Drowning	0	1
Electrical	2	7
Explosives and Breaking Agents	3	3
Fall of Face, Rib, Side or Highwall	3	3
Fall of Roof or Back	10	0
Falling, Rolling, or Sliding Rock or Material of Any Kind	3	25
Hand Tools	0	1
Hoisting	2	0
Ignition or Explosion of Gas or Dust	0	1
Inundation	0	1
Machinery	4	27
Non-Powered Haulage	0	1
Other	0	3
Powered Haulage	10	44
Slip or Fall of Person	4	15
Striking or Bumping	0	1
Total	44	150

Appendix C US Mining Legislation

Table 12: US legislations addressing underground metal/nonmetal mine evacuation plans, procedures and training (MSHA, *30 CFR § 57.4361 - Underground Evacuation Drills.*, 1985, , 1995; *30 CFR § 57.4363 - Underground Evacuation Instruction.*, 1985, , 2008; *30 CFR § 57.11051 - Escape Routes*, 1985)

---

§ 57.11053 Escape and evacuation plans.

A specific escape and evacuation plan and revisions thereof suitable to the conditions and mining system of the mine and showing assigned responsibilities of all key personnel in the event of an emergency shall be developed by the operator and set out in written form. Within 45 calendar days after promulgation of this standard a copy of the plan and revisions thereof shall be available to the Secretary or his authorized representative. Also, copies of the plan and revisions thereof shall be posted at locations convenient to all persons on the surface and underground. Such a plan shall be updated as necessary and shall be reviewed jointly by the operator and the Secretary or his authorized representative at least once every six months from the date of the last review. The plan shall include:

(a) Mine maps or diagrams showing directions of principal air flow, location of escape routes and locations of existing telephones, primary fans, primary fan controls, fire doors, ventilation doors, and refuge chambers. Appropriate portions of such maps or diagrams shall be posted at all shaft stations and in underground shops, lunchrooms, and elsewhere in working areas where persons congregate;

(b) Procedures to show how the miners will be notified of emergency;

(c) An escape plan for each working area in the mine to include instructions showing how each working area should be evacuated. Each such plan shall be posted at appropriate shaft stations and elsewhere in working areas where persons congregate;

(d) A fire fighting plan;

(e) Surface procedure to follow in an emergency, including the notification of proper authorities, preparing rescue equipment, and other equipment which may be used in rescue and recovery operations; and

(f) A statement of the availability of emergency communication and transportation facilities, emergency power and ventilation and location of rescue personnel and equipment.

[50 FR 4082, Jan. 29, 1985, as amended at 60 FR 33722, June 29, 1995]

§ 57.18028 Mine emergency and self-rescuer training.

(a) On an annual basis, all persons who are required to go underground shall be instructed in the Mine Safety and Health Administration approved course contained in Bureau of Mines Instruction Guide 19, “Mine Emergency Training” (September 1972). The instruction shall be given by MSHA personnel or by persons who are certified by the District Manager of the area in which the mine is located.

(b) On an annual basis, all persons who go underground shall be instructed in the Mine Safety and Health Administration course contained in Bureau of Mines Instruction Guide 2, “MSA W-65 Self-Rescuer” (March 1972) or Bureau of Mines Instruction Guide 3, “Permissible Drager 810 Respirator for

Self-Rescue" (March 1972). The instruction shall be given by MSHA personnel or by persons who are certified by the District Manager of the area in which the mine is located: Provided, however, That if a Mine Safety and Health Administration instructor or a certified instructor is not immediately available such instruction of new employees in self-rescuers may be conducted by qualified company personnel who are not certified, but who have obtained provisional approval from the District Manager. Any person who has not had self-rescuer instruction within 12 months immediately preceding going underground shall be instructed in the use of self-rescuers before going underground.

(c) All instructional material, handouts, visual aids, and other such teaching accessories used by the operator in the courses prescribed in paragraphs (a) and (b) of this section shall be available for inspection by the Secretary or his authorized representative.

(d) Records of all instruction shall be kept at the mine site or nearest mine office at least 2 years from the date of instruction. Upon completion of such instruction, copies of the record shall be submitted to the District Manager.

(e) The Bureau of Mines instruction guides to which reference is made in items (a) and (b) of this standard are hereby incorporated by reference and made a part hereof. The incorporated instruction guides are available and shall be provided upon request made to any Metal and Nonmetal Mine Safety and Health district office.

[50 FR 4082, Jan. 29, 1985, as amended at 71 FR 16667, Apr. 3, 2006]

§ 57.4361 Underground evacuation drills.

(a) At least once every six months, mine evacuation drills shall be held to assess the ability of all persons underground to reach the surface or other designated points of safety within the time limits of the self-rescue devices that would be used during an actual emergency.

(b) The evacuation drills shall -

(1) Be held for each shift at some time other than a shift change and involve all persons underground;

(2) Involve activation of the fire alarm system; and

(3) Include evacuation of all persons from their work areas to the surface or to designated central evacuation points.

(c) At the completion of each drill, the mine operator shall certify the date and the time the evacuation began and ended. Certifications shall be retained for at least one year after each drill.

§ 57.4362 Underground rescue and firefighting operations.

Following evacuation of a mine in a fire emergency, only persons wearing and trained in the use of mine rescue apparatus shall participate in rescue and firefighting operations in advance of the fresh air base.

§ 57.4363 Underground evacuation instruction.

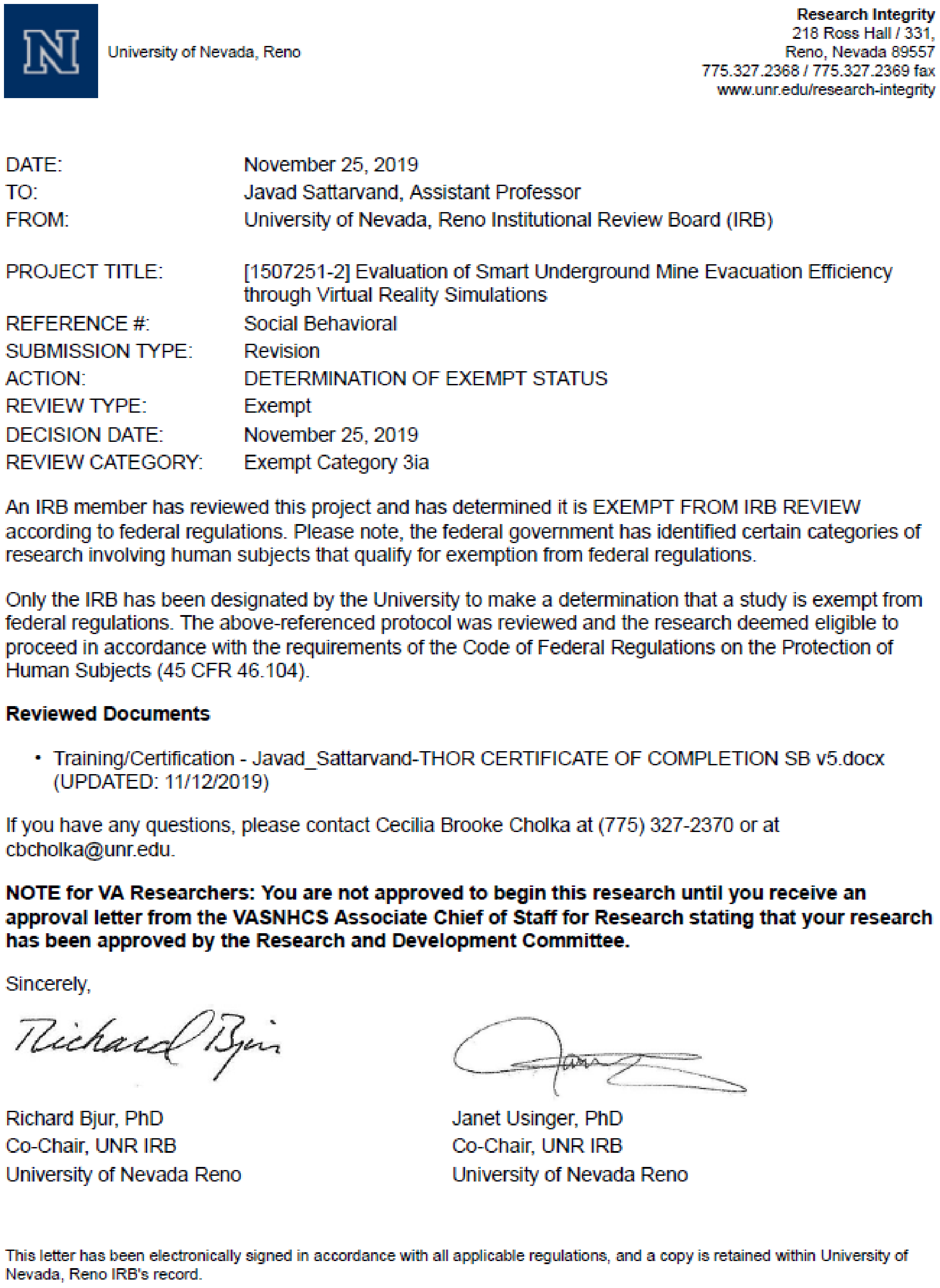
(a) At least once every twelve months, all persons who work underground shall be instructed in the escape and evacuation plans and procedures and fire warning signals in effect at the mine.

(b) Whenever a change is made in escape and evacuation plans and procedures for any area of the mine, all persons affected shall be instructed in the new plans or procedures.

(c) Whenever persons are assigned to work in areas other than their regularly assigned areas, they shall be instructed about the escapeway for that area at the time of such assignment. However, persons who normally work in more than one area of the mine shall be instructed at least once every twelve months about the location of escapeways for all areas of the mine in which they normally work or travel.

(d) At the completion of any instruction given under this standard, the mine operator shall certify the date that the instruction was given. Certifications shall be retained for at least one year.

Appendix D UNR IRB Approval



University of Nevada, Reno

Research Integrity
218 Ross Hall / 331,
Reno, Nevada 89557
775.327.2368 / 775.327.2369 fax
www.unr.edu/research-integrity

DATE:	November 25, 2019
TO:	Javad Sattarvand, Assistant Professor
FROM:	University of Nevada, Reno Institutional Review Board (IRB)
PROJECT TITLE:	[1507251-2] Evaluation of Smart Underground Mine Evacuation Efficiency through Virtual Reality Simulations
REFERENCE #:	Social Behavioral
SUBMISSION TYPE:	Revision
ACTION:	DETERMINATION OF EXEMPT STATUS
REVIEW TYPE:	Exempt
DECISION DATE:	November 25, 2019
REVIEW CATEGORY:	Exempt Category 3ia

An IRB member has reviewed this project and has determined it is EXEMPT FROM IRB REVIEW according to federal regulations. Please note, the federal government has identified certain categories of research involving human subjects that qualify for exemption from federal regulations.

Only the IRB has been designated by the University to make a determination that a study is exempt from federal regulations. The above-referenced protocol was reviewed and the research deemed eligible to proceed in accordance with the requirements of the Code of Federal Regulations on the Protection of Human Subjects (45 CFR 46.104).

Reviewed Documents

- Training/Certification - Javad_Sattarvand-THOR CERTIFICATE OF COMPLETION SB v5.docx (UPDATED: 11/12/2019)

If you have any questions, please contact Cecilia Brooke Cholka at (775) 327-2370 or at cbcholka@unr.edu.

NOTE for VA Researchers: You are not approved to begin this research until you receive an approval letter from the VASNHCS Associate Chief of Staff for Research stating that your research has been approved by the Research and Development Committee.

Sincerely,

Richard Bjur

Richard Bjur, PhD
Co-Chair, UNR IRB
University of Nevada Reno

Janet Usinger, PhD
Co-Chair, UNR IRB
University of Nevada Reno

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Nevada, Reno IRB's record.

Appendix E **UNR IRB Advertisement Email**

We need you!

You want to go on a treasure hunt in a virtual underground mine and contribute to mine safety research at the same time?

The purpose of this user study is to investigate different evacuation methods in underground mines and will take approx. 45 minutes.

All participants will be able to play with our newest addition to the lab: the Virtuix-Omni treadmill. Come and give it a try!

Schedule your appointment under:

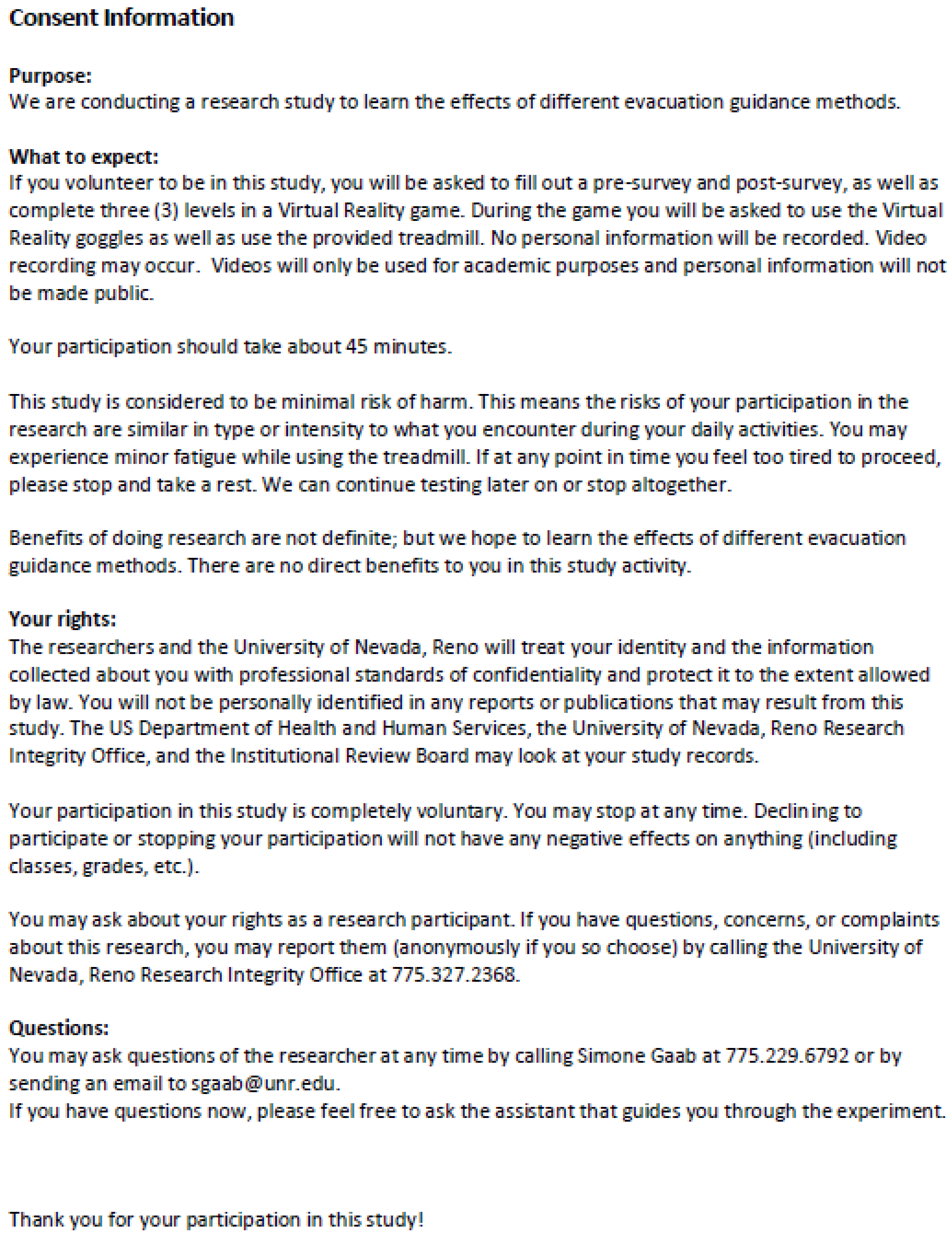
www.thislinkhastobecreated.com/

Or email Simone at:

sgaab@unr.edu

Hope to see you at LMR 155!

Appendix F UNR IRB Consent Information



Consent Information

Purpose:
We are conducting a research study to learn the effects of different evacuation guidance methods.

What to expect:
If you volunteer to be in this study, you will be asked to fill out a pre-survey and post-survey, as well as complete three (3) levels in a Virtual Reality game. During the game you will be asked to use the Virtual Reality goggles as well as use the provided treadmill. No personal information will be recorded. Video recording may occur. Videos will only be used for academic purposes and personal information will not be made public.

Your participation should take about 45 minutes.

This study is considered to be minimal risk of harm. This means the risks of your participation in the research are similar in type or intensity to what you encounter during your daily activities. You may experience minor fatigue while using the treadmill. If at any point in time you feel too tired to proceed, please stop and take a rest. We can continue testing later on or stop altogether.

Benefits of doing research are not definite; but we hope to learn the effects of different evacuation guidance methods. There are no direct benefits to you in this study activity.

Your rights:
The researchers and the University of Nevada, Reno will treat your identity and the information collected about you with professional standards of confidentiality and protect it to the extent allowed by law. You will not be personally identified in any reports or publications that may result from this study. The US Department of Health and Human Services, the University of Nevada, Reno Research Integrity Office, and the Institutional Review Board may look at your study records.

Your participation in this study is completely voluntary. You may stop at any time. Declining to participate or stopping your participation will not have any negative effects on anything (including classes, grades, etc.).

You may ask about your rights as a research participant. If you have questions, concerns, or complaints about this research, you may report them (anonymously if you so choose) by calling the University of Nevada, Reno Research Integrity Office at 775.327.2368.

Questions:
You may ask questions of the researcher at any time by calling Simone Gaab at 775.229.6792 or by sending an email to sgaab@unr.edu.
If you have questions now, please feel free to ask the assistant that guides you through the experiment.

Thank you for your participation in this study!

Appendix G Experiment Instructions

Instructions

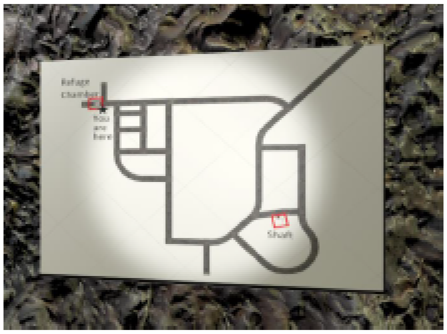
You will be placed in an underground mine.
Please, follow the instruction given on the starting screen:

During your evacuation you will come across two signs:

Brings you to the **shaft.**

Brings you to the **refuge chamber.**

At shafts and refuge chambers you will be able to see a map of the current mine level:



During evacuation follow the instructions on the screen. If you have forgotten the instructions **please ask your assistant to repeat** those.

Appendix H **UNR IRB Pre-Test Survey**

Pre-Test Survey

Participant ID:__________________

How often do you play video games?

[ ] every day
[ ] 2-3 times a week
[ ] once a week
[ ] once a month
[ ] less than once a month

Do you have any experience with virtual reality?

[ ] Yes, I have used virtual reality approximately ______ times.
[ ] No

Have you ever been in an underground mine?

[ ] Yes, for ________ hours/days/weeks/months
[ ] No

What interested you in participating in today's testing?

Appendix I **Example of Collected Raw Data**

```
0
The simulation started: 11/26/2019 10:23:22 AM
Reaction took:29.79989s
Time to reach target: 251.8315
The simulation ended:11/26/2019 10:28:38 AM
1
The simulation started: 11/26/2019 1:19:01 PM
Reaction took:27.69992s
Time to reach target: 256.0991
The simulation ended:11/26/2019 1:24:46 PM
2
The simulation started: 11/26/2019 2:23:14 PM
Reaction taking other way took:8.900005s
Time to reach target: 393.5322
The simulation ended:11/26/2019 2:32:16 PM
3
The simulation started: 11/26/2019 3:22:25 PM
Reaction taking other way took:8.566668s
Time to reach target: 520.6011
The simulation ended:11/26/2019 3:34:18 PM
4
The simulation started: 11/26/2019 4:12:47 PM
Reaction took:36.46645s
Time to reach target: 389.2999
The simulation ended:11/26/2019 4:21:35 PM
5
The simulation started: 11/26/2019 5:22:19 PM
Reaction took:14.03341s
Time to reach target: 440.2208
The simulation ended:11/26/2019 5:33:11 PM
6
The simulation started: 11/27/2019 9:11:17 AM
Reaction took:36.86645s
Time to reach target: 462.4153
The simulation ended:11/27/2019 9:22:14 AM
7
The simulation started: 11/27/2019 10:14:55 AM
Reaction took:20.40003s
Time to reach target: 277.5605
The simulation ended:11/27/2019 10:21:28 AM
8
The simulation started: 11/27/2019 11:31:31 AM
Reaction taking other way took:8.666669s
Time to reach target: 297.6889
The simulation ended:11/27/2019 11:38:26 AM
```

```
9
The simulation started: 11/27/2019 12:21:17 PM
Reaction took:20.00004s
Time to reach target: 288.5578
The simulation ended:11/27/2019 12:27:42 PM
10
The simulation started: 11/27/2019 2:11:21 PM
Reaction took:13.8334s
Time to reach target: 301.288
The simulation ended:11/27/2019 2:18:18 PM
11
The simulation started: 11/27/2019 3:17:56 PM
Reaction took:15.86677s
Time to reach target: 211.4229
The simulation ended:11/27/2019 3:22:54 PM
12
The simulation started: 11/30/2019 2:17:30 PM
Reaction took:23.53332s
Time to reach target: 178.1824
The simulation ended:11/30/2019 2:21:34 PM
```

Appendix J UNR IRB Post-Test Survey

Post-Test Survey

Participant ID:________________

Which evacuation method would you prefer and why?

Do you think smart evacuation can contribute to safety in mining? Please explain your thoughts.

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply:

1. How natural was the mechanism which controlled movement through the environment?

|_______|_______|_______|_______|_______|_______|_______|
EXTREMELY ARTIFICIAL BORDERLINE VERY NATURAL

2. How inconsistent or disconnected was the information coming from your various senses?

|_______|_______|_______|_______|_______|_______|_______|
NOT AT ALL SOMEWHAT COMPLETELY

3. How much did your experiences in the virtual environment seem consistent with your real-world experiences*

|_______|_______|_______|_______|_______|_______|_______|
NOT CONSISTENT SOMEWHAT VERY CONSISTENT

4. How completely were you able to actively survey or search the environment using vision?

NOT AT ALL SOMEWHAT COMPLETELY

~~5. How well could you identify sounds?~~

~~NOT AT ALL SOMEWHAT VERY ACCURATELY~~

~~6. How well could you localize sounds?~~

~~NOT AT ALL SOMEWHAT VERY ACCURATELY~~

7. To what degree did you feel confused or disoriented at the beginning of breaks or at the end of the experimental session?

NOT CONFUSED SOMEWHAT VERY CONFUSED

8. How quickly did you adjust to the virtual environment experience?

NOT AT ALL SLOWLY LESS THAN 2 MINUTES

9. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

NOT PROFICIENT REASONABLY PROFICIENT VERY PROFICIENT

10. How much did the visual display quality interfere or distract you from per- forming assigned tasks or required activities?

NOT AT ALL INTERFERED SOMEWHAT PREVENTED TASK PERFORMANCE

11. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|________|________|________|________|________|________|________|

NOT AT ALL INTERFERED SOMEWHAT PREVENTED TASK PERFORMANCE

Did participating in this study increase your interest in virtual reality?

Any remaining comments regarding this study are welcome:

Thank you very much for participating!

Appendix K **Normality Test for Total Times**

Total Times (s)

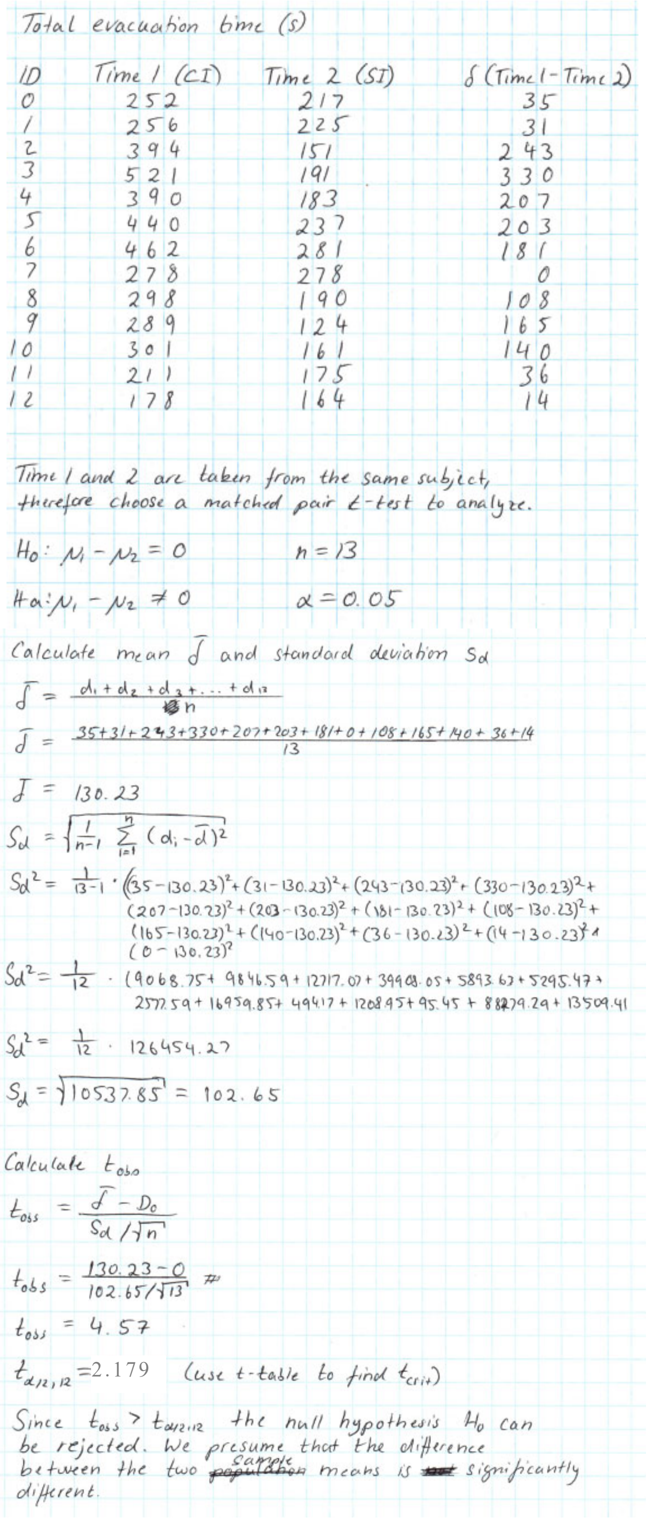
CI-SI	
Mean	130.2307692
Standard Error	28.47111758
Median	140
Mode	#N/A
Standard Deviation	102.6540743
Sample Variance	10537.85897
Kurtosis	-0.756542613
Skewness	0.359672071
Range	330
Minimum	0
Maximum	330
Sum	1693
Count	13

CD-SD	
Mean	37.33333333
Standard Error	13.16772148
Median	32
Mode	32
Standard Deviation	39.50316443
Sample Variance	1560.5
Kurtosis	1.250094879
Skewness	-0.588542194
Range	139
Minimum	-41
Maximum	98
Sum	336
Count	9

CD-CI	
Mean	85.11111111
Standard Error	29.03658824
Median	72
Mode	#N/A
Standard Deviation	87.10976473
Sample Variance	7588.111111
Kurtosis	0.403110399
Skewness	0.446810512
Range	282
Minimum	-34
Maximum	248
Sum	766
Count	9

SI-Sd	
Mean	26.55555556
Standard Error	10.69671693
Median	33
Mode	#N/A
Standard Deviation	32.09015079
Sample Variance	1029.777778
Kurtosis	-1.048786045
Skewness	0.136365047
Range	95
Minimum	-18
Maximum	77
Sum	239
Count	9

Appendix L **Manual Matched Pair t-Test**



Total evacuation time (s)

ID	Time 1 (CI)	Time 2 (SI)	δ (Time 1 - Time 2)
0	252	217	35
1	256	225	31
2	394	151	243
3	521	191	330
4	390	183	207
5	440	237	203
6	462	281	181
7	278	278	0
8	298	190	108
9	289	124	165
10	301	161	140
11	211	175	36
12	178	164	14

Time 1 and 2 are taken from the same subject, therefore choose a matched pair t-test to analyze.

$H_0: \mu_1 - \mu_2 = 0$ $n = 13$

$H_a: \mu_1 - \mu_2 \neq 0$ $\alpha = 0.05$

Calculate mean $\bar{\delta}$ and standard deviation S_d

$$\bar{\delta} = \frac{d_1 + d_2 + d_3 + \ldots + d_{13}}{n}$$

$$\bar{\delta} = \frac{35+31+243+330+207+203+181+0+108+165+140+36+14}{13}$$

$$\bar{\delta} = 130.23$$

$$S_d = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (d_i - \bar{d})^2}$$

$$S_d^2 = \frac{1}{13-1} \cdot ((35-130.23)^2 + (31-130.23)^2 + (243-130.23)^2 + (330-130.23)^2 + (207-130.23)^2 + (203-130.23)^2 + (181-130.23)^2 + (108-130.23)^2 + (165-130.23)^2 + (140-130.23)^2 + (36-130.23)^2 + (14-130.23)^2 + (0-130.23)^2$$

$$S_d^2 = \frac{1}{12} \cdot (9068.75 + 9846.59 + 12717.07 + 39908.05 + 5893.63 + 5295.47 + 2577.59 + 16959.85 + 494.17 + 1208.45 + 95.45 + 88279.29 + 13509.41$$

$$S_d^2 = \frac{1}{12} \cdot 126454.27$$

$$S_d = \sqrt{10537.85} = 102.65$$

Calculate t_{obs}

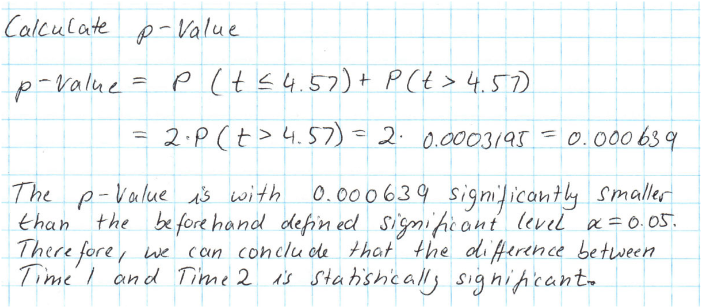
$$t_{obs} = \frac{\bar{\delta} - D_0}{S_d / \sqrt{n}}$$

$$t_{obs} = \frac{130.23 - 0}{102.65/\sqrt{13}} \#$$

$$t_{obs} = 4.57$$

$t_{\alpha/2,12}$ =2.179 (use t-table to find t_{crit})

Since $t_{obs} > t_{\alpha/2,12}$ the null hypothesis H_0 can be rejected. We presume that the difference between the two ~~population~~ sample means is significantly different.



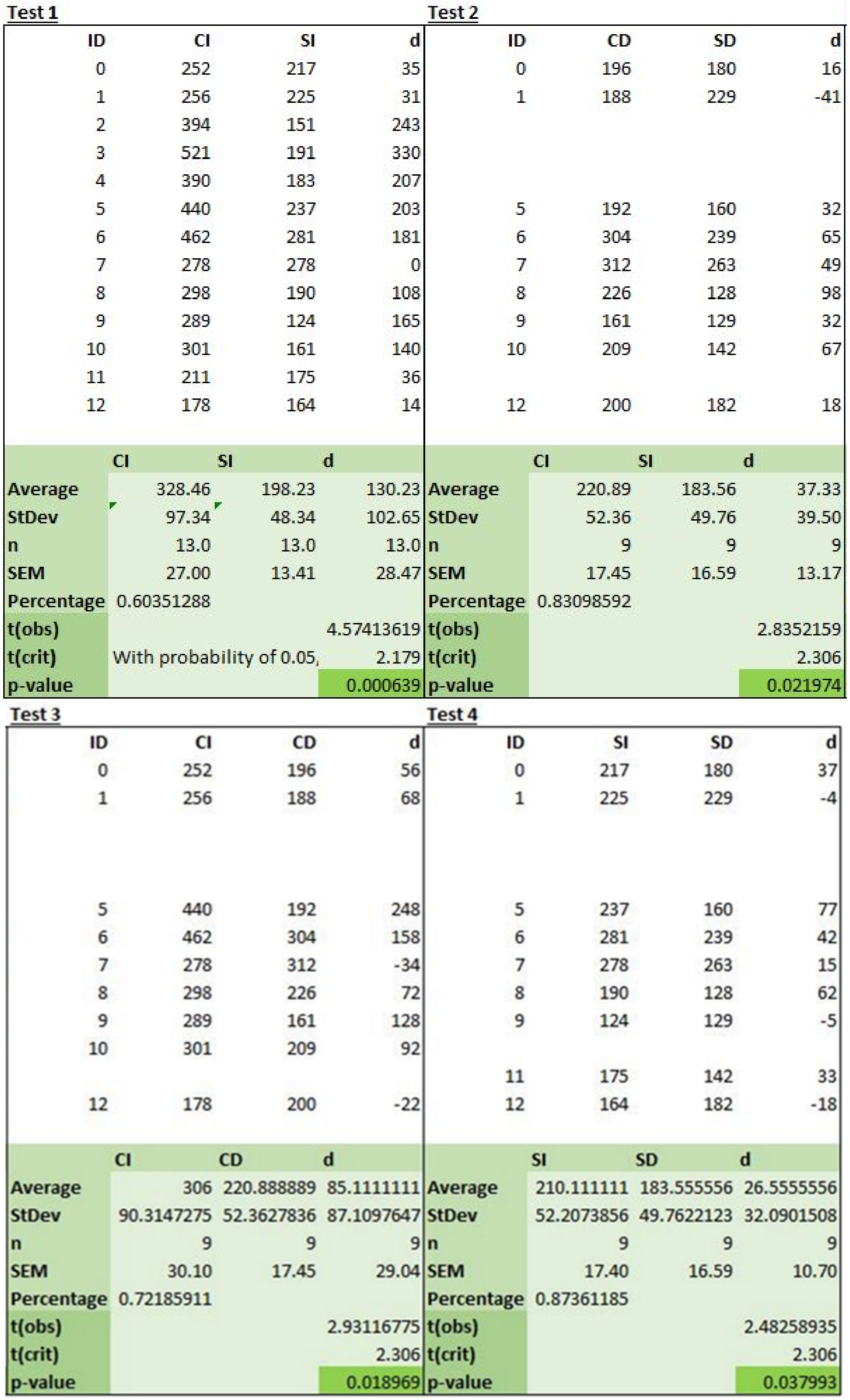
Calculate p-Value

$$p\text{-Value} = P\,(t \leq 4.57) + P(t > 4.57)$$

$$= 2 \cdot P\,(t > 4.57) = 2 \cdot 0.0003195 = 0.000639$$

The p-Value is with 0.000639 significantly smaller than the beforehand defined significant level $\alpha = 0.05$. Therefore, we can conclude that the difference between Time 1 and Time 2 is statistically significant.

Appendix M Statistical Results for Total Times



Test 1

ID	CI	SI	d
0	252	217	35
1	256	225	31
2	394	151	243
3	521	191	330
4	390	183	207
5	440	237	203
6	462	281	181
7	278	278	0
8	298	190	108
9	289	124	165
10	301	161	140
11	211	175	36
12	178	164	14

	CI	SI	d
Average	328.46	198.23	130.23
StDev	97.34	48.34	102.65
n	13.0	13.0	13.0
SEM	27.00	13.41	28.47
Percentage	0.60351288		
t(obs)			4.57413619
t(crit)	With probability of 0.05,		2.179
p-value			0.000639

Test 2

ID	CD	SD	d
0	196	180	16
1	188	229	-41
5	192	160	32
6	304	239	65
7	312	263	49
8	226	128	98
9	161	129	32
10	209	142	67
12	200	182	18

	CI	SI	d
Average	220.89	183.56	37.33
StDev	52.36	49.76	39.50
n	9	9	9
SEM	17.45	16.59	13.17
Percentage	0.83098592		
t(obs)			2.8352159
t(crit)			2.306
p-value			0.021974

Test 3

ID	CI	CD	d
0	252	196	56
1	256	188	68
5	440	192	248
6	462	304	158
7	278	312	-34
8	298	226	72
9	289	161	128
10	301	209	92
12	178	200	-22

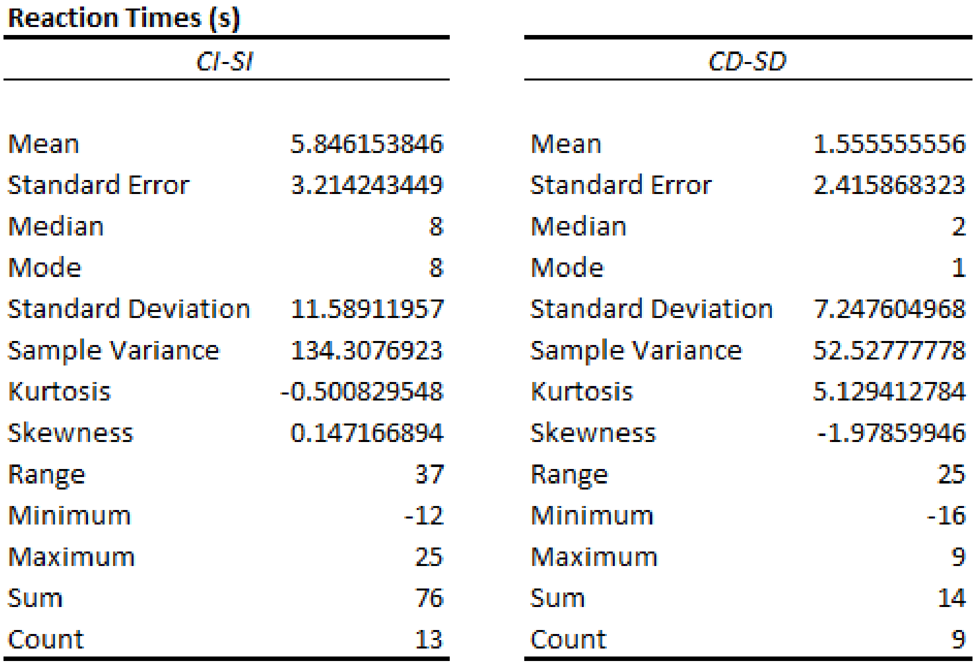
	CI	CD	d
Average	306	220.888889	85.1111111
StDev	90.3147275	52.3627836	87.1097647
n	9	9	9
SEM	30.10	17.45	29.04
Percentage	0.72185911		
t(obs)			2.93116775
t(crit)			2.306
p-value			0.018969

Test 4

ID	SI	SD	d
0	217	180	37
1	225	229	-4
5	237	160	77
6	281	239	42
7	278	263	15
8	190	128	62
9	124	129	-5
11	175	142	33
12	164	182	-18

	SI	SD	d
Average	210.111111	183.555556	26.5555556
StDev	52.2073856	49.7622123	32.0901508
n	9	9	9
SEM	17.40	16.59	10.70
Percentage	0.87361185		
t(obs)			2.48258935
t(crit)			2.306
p-value			0.037993

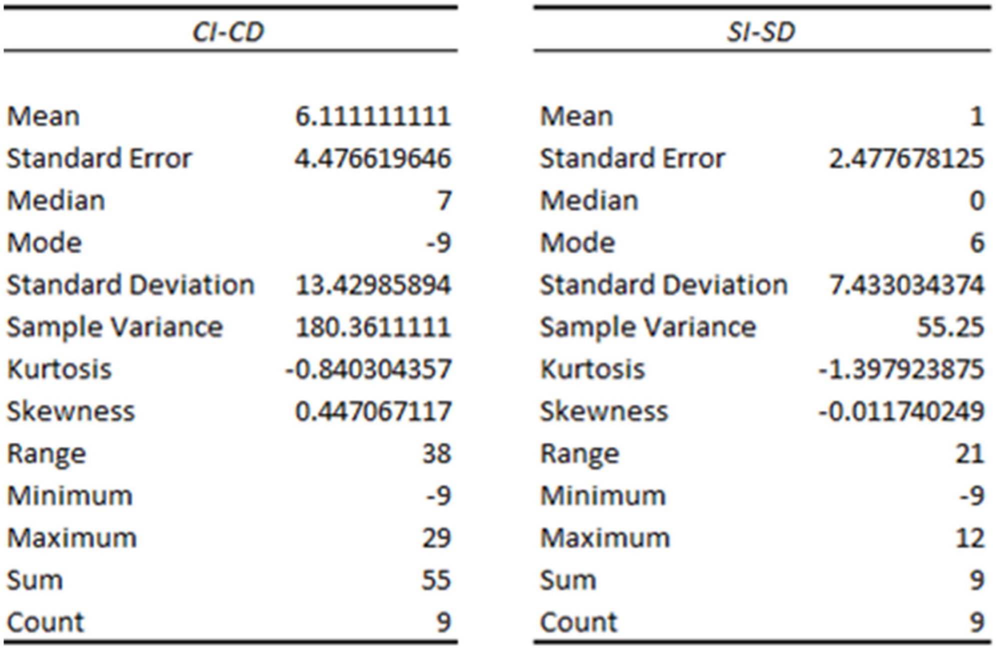
Appendix N Normality Test for Reaction Times



Reaction Times (s)

CI-SI	
Mean	5.846153846
Standard Error	3.214243449
Median	8
Mode	8
Standard Deviation	11.58911957
Sample Variance	134.3076923
Kurtosis	-0.500829548
Skewness	0.147166894
Range	37
Minimum	-12
Maximum	25
Sum	76
Count	13

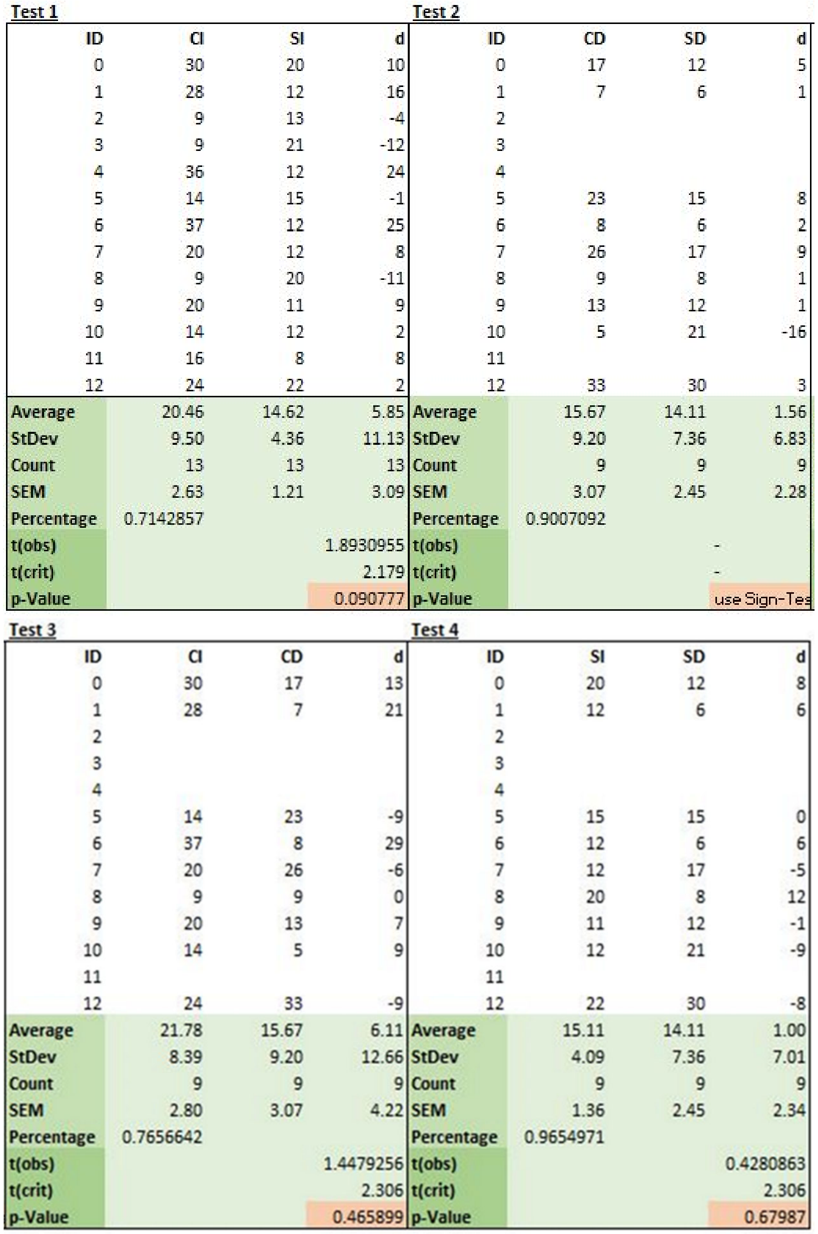
CD-SD	
Mean	1.555555556
Standard Error	2.415868323
Median	2
Mode	1
Standard Deviation	7.247604968
Sample Variance	52.52777778
Kurtosis	5.129412784
Skewness	-1.97859946
Range	25
Minimum	-16
Maximum	9
Sum	14
Count	9



CI-CD	
Mean	6.111111111
Standard Error	4.476619646
Median	7
Mode	-9
Standard Deviation	13.42985894
Sample Variance	180.3611111
Kurtosis	-0.840304357
Skewness	0.447067117
Range	38
Minimum	-9
Maximum	29
Sum	55
Count	9

SI-SD	
Mean	1
Standard Error	2.477678125
Median	0
Mode	6
Standard Deviation	7.433034374
Sample Variance	55.25
Kurtosis	-1.397923875
Skewness	-0.011740249
Range	21
Minimum	-9
Maximum	12
Sum	9
Count	9

Appendix O Statistical Results for Reaction Times



Test 1

ID	CI	SI	d
0	30	20	10
1	28	12	16
2	9	13	-4
3	9	21	-12
4	36	12	24
5	14	15	-1
6	37	12	25
7	20	12	8
8	9	20	-11
9	20	11	9
10	14	12	2
11	16	8	8
12	24	22	2
Average	20.46	14.62	5.85
StDev	9.50	4.36	11.13
Count	13	13	13
SEM	2.63	1.21	3.09
Percentage	0.7142857		
t(obs)			1.8930955
t(crit)			2.179
p-Value			0.090777

Test 2

ID	CD	SD	d
0	17	12	5
1	7	6	1
2			
3			
4			
5	23	15	8
6	8	6	2
7	26	17	9
8	9	8	1
9	13	12	1
10	5	21	-16
11			
12	33	30	3
Average	15.67	14.11	1.56
StDev	9.20	7.36	6.83
Count	9	9	9
SEM	3.07	2.45	2.28
Percentage	0.9007092		
t(obs)		-	
t(crit)		-	
p-Value		use Sign-Tes	

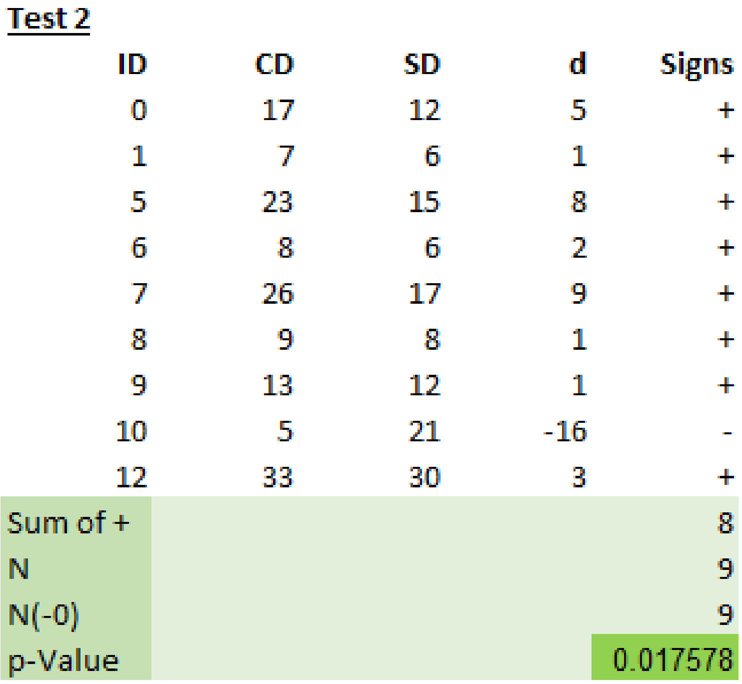
Test 3

ID	CI	CD	d
0	30	17	13
1	28	7	21
2			
3			
4			
5	14	23	-9
6	37	8	29
7	20	26	-6
8	9	9	0
9	20	13	7
10	14	5	9
11			
12	24	33	-9
Average	21.78	15.67	6.11
StDev	8.39	9.20	12.66
Count	9	9	9
SEM	2.80	3.07	4.22
Percentage	0.7656642		
t(obs)			1.4479256
t(crit)			2.306
p-Value			0.465899

Test 4

ID	SI	SD	d
0	20	12	8
1	12	6	6
2			
3			
4			
5	15	15	0
6	12	6	6
7	12	17	-5
8	20	8	12
9	11	12	-1
10	12	21	-9
11			
12	22	30	-8
Average	15.11	14.11	1.00
StDev	4.09	7.36	7.01
Count	9	9	9
SEM	1.36	2.45	2.34
Percentage	0.9654971		
t(obs)			0.4280863
t(crit)			2.306
p-Value			0.67987

Appendix P Sign-Test Results



Test 2

	ID	CD	SD	d	Signs
	0	17	12	5	+
	1	7	6	1	+
	5	23	15	8	+
	6	8	6	2	+
	7	26	17	9	+
	8	9	8	1	+
	9	13	12	1	+
	10	5	21	-16	-
	12	33	30	3	+
Sum of +					8
N					9
N(-0)					9
p-Value					0.017578