BotFire - Comparing Visual- vs. Audio-Cues for a Fire-Evacuation-Robot

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***Abstract*—In terms of fire evacuation scenarios, specialized robots can enhance the evacuation process, saving precious time before first responders and rescue forces arrive. This documentation summarizes our process of defining and executing a virtual reality experiment as part of the Human-Robot Interaction Seminar at the University of Osnabrück. We tested two different robot models, a visual- and audio-cue based evacuation robot, in the same evacuation scenario. Results and descriptive statistics showed no significant difference between the two different robot models with respect to the time a participant needed to find the exit, the amount of time the robot waited, the distance between evacuee and robot as well as the distance of the evacuee to the shortest evacuation route. Lastly, since only ten participants took part in the experiments, interpretation needs to be done carefully.**

***Index Terms*—Human Robot Interaction, Evacuation, Fire Evacuation, Virtual Reality**

I. Introduction

Life-threatening emergency situations such as fire outbreaks in a building require a fast and safe evacuation of all present people. Between smoke, loud noises, emerging obstacles and the impending sense of danger, a person inside a burning building will have to find the exit under extreme levels of stress. Firefighters are trained to find and guide people to safety, but precious, potentially life-or-death deciding minutes will have passed by the time they arrive, not to mention the dangers the firefighters face, when inside a burning building. In our experiment, we considered the use of robots for this scenario.

In the same manner that fire extinguishers are placed across large buildings such as offices, small robots could be positioned across rooms and hallways. They would then be activated simultaneously with the fire alarm and act as an evacuation guide for the people in their vicinity, leading them to the exit using the safest available route. In our experiment, we simulated an office fire in Virtual Reality (VR) and placed a small, capsule-shaped robot in the participant's path. When the participant stayed close to it, the robot would move and guide them to the exit. The design of the robot was based on a model by Kim (2009) [6], which in their study proved to perform well as a fire evacuation guide.

Due to the high stress level evoked by a fire outbreak, it is important that following the robot is easy and as effortless as possible for the person to be evacuated. To gain an insight on what kind of stimulus is more helpful in locating the robot, we compared the effects of two versions of our model. In one condition, the robot emitted a bright blue light to make it easier to spot among dark smoke. In the other condition, instead of standing out visually, the robot played a loud sound to communicate its position to the evacuee. We hypothesized that the robot using the visual signal will be easier to follow than the one using the acoustic signal.

The following documentation will start by presenting our hypothesis (section II), followed by a short chapter on the theoretical literature work (section III). We will further give some insight in our project organization and progression (section IV). More implementation details (e.g. smoke and fire, robot movement and more) are given in section V while section VI discusses details of our experimental setup in general. We present the analysis result in section VII and conclude by a reflective discussion (section VIII) on our project.

II. Hypothesis

The main interest of the study was, to find out if a robot would be more helpful in evacuating participants from a fire emergency situations if it used visual cues compared to audio signals.

For us humans, the main perceptual information about our environment comes from the visual system [5]. Therefore the assumption, that it would be easier to follow a robot that sends out cues addressing this visual system, seems obvious and was adopted for the further conduction of the study.

The first step for defining the hypothesis, following the research question, was to identify the independent and dependent variables as well as the number of experimental groups. The number of experimental groups was set to two, same as the number of robot models. Due to the frame of the project, it was assumed, that only a small sample size could be reached. The number of experimental groups was therefore set to two, to ensure the biggest possible sample size for each group. The two compared robot models, the *visual* and *audio robot*, were determined as the independent variables.

The time it takes to evacuate people from a building can be a crucial criteria for the success of an evacuation, and the survival of evacuees [12]. Therefore, the *evacuation time* was considered to be the first dependent variable. Equally it was assumed, that a robot had to wait less for a participant if the robot was more easily to follow, contrarily to a robot that was harder to follow, e.g. because it was less visible. Therefore the *time that the robot has to wait for the participant* was considered the second dependent variable. The *distance between player and the robot*, was determined as a dependent variable, because it is probable that participants are able to stay closer to a robot, if it is easier to follow. Since the robot would always stay on the ideal path leading towards the exit, it is probable, that the participant would stay closer to it as well, if the robot was easier to follow. Therefore the *distance between player and the ideal track* was chosen as the last dependent variable.

These considerations led to the main hypothesis H_1: In a fire emergency scenario with limited vision, people tend to evacuate better if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

This main hypothesis can be separated into the four sub-hypotheses:

H_{1a}: In a fire emergency scenario with limited vision, people tend to have a lower evacuation time if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

H_{1b}: In a fire emergency scenario with limited vision, a robot has to wait less for the participants if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

H_{1c}: In a fire emergency scenario with limited vision, people tend to stay closer to the robot if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

H_{1d}: In a fire emergency scenario with limited vision, people tend to stay closer to the ideal path if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

The corresponding null hypothesis H_0's are assuming, that the visual robot does not perform better than the audio robot. This results in the following primary H_0:

H_{01}: In a fire emergency scenario with limited vision, people do not tend to evacuate better if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

From that the subsequent sub-hypotheses can be derived:

H_{01a}: In a fire emergency scenario with limited vision, people do not tend to have a lower evacuation time if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

H_{01b}: In a fire emergency scenario with limited vision, a robot does not have to wait less for the participants if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

H_{01c}: In a fire emergency scenario with limited vision, people do not tend to stay closer to the robot if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

H_{01d}: In a fire emergency scenario with limited vision, people do not tend to stay closer to the ideal path if the robot has illuminating signals compared to a robot that tries to communicate via audio signals.

These sub-hypotheses were tested using Student's t-tests (see Section VII-G).

Additionally it was assumed, that the closeness of the participant to the robot was correlating with the amount of smoke accumulated. To test this, the following hypothesis was formulated:

H_2: There is a negative correlation between the amount of smoke in a room and the distance the participant keeps to the robot.

The corresponding H_0 that was derived from this was:

H_{02}: There is no negative correlation between the amount of smoke in a room and the distance the participant keeps to the robot.

III. Theoretical Background

To gain an overview on the current research, we began our project with literature research focusing on the use of robots in evacuation scenarios and the interaction between emergency robots and humans. Furthermore, we wanted to gather information on effective robot design in an emergency context to help us develop the model we would later use in the experiment.

Quite a lot of research has been done into the question of trust towards robots. In a life-threatening emergency situation, even the best path-finding and obstacle-removing robot will be useless if the people it is supposed to rescue are too skeptical to follow it. Trust towards robots seems to be affected by whether or not the human agent has observed the robot making mistakes, particularly if the committed mistake is severe and occurs at the beginning of the interaction [13].

Generally however, there seems to be a tendency to follow the directions of robots, even to the point of irrationality. In a study by Robinette (2012) [10], one third of participants followed an emergency robot, independent of its appearance. In another study [11], all participants followed the robot instead of leaving through the entrance through which they entered the building, even if the robot behaved questionably. Nayyar (2020) [9] found that even uninformative explanations given by the robot encourage the overtrust effect and increase the likelihood of the person deciding to follow. In light of these findings, we decided against the initial idea to investigate what kind of models evoke more trust and instead to focus more on how to improve the efficiency of the evacuation.

One aspect we considered but ultimately did not include in our study out of technical restraints is the behavior of crowds during an evacuation as opposed to a single person interacting with the robot. In a realistic version of our office fire scenario, it would be more likely that the building is full of other people besides the participant. Would individuals still be as likely to follow the robot when other humans are present? In order to avoid overcrowding and bottleneck effects when large groups of people are all trying to quickly leave a building, robots could be particularly useful as evacuation guides. However, Nayyar (2019) found that seeing groups of people evacuate in a certain direction can prevent people from deciding to follow the guidance of a robot, nevertheless a moving robot still seems to be more persuasive than a stationary one giving instructions [8]. A study by Boukas (2015) has shown that the use of mobile robots can significantly improve the evacuation time by dispersing and redirecting groups of people along less crowded, safe paths [2].

When it comes to the design of the robot, multiple aspects such as the physical appearance and the type of behavior have to be considered. For our experiment, we based the shape of our robot on the portable fire evacuation robot system developed by Kim (2009) [6]. The spool-shaped small robots offer high temperature protection, impact resistance and waterproofing. Furthermore, they were designed for easy portability and low manufacture cost in the case they got destroyed during the assignment [6]. Since we envisioned robots that could be easily installed throughout the building but could still navigate a burning environment, the model matched our requirements well. There are two general behavior styles we considered for the robot in our evacuation simulation. The first style is the so-called hand-off approach. For this, multiple robots across the building move to strategic points like junctions and hallways. Using arm movements and verbal instructions, they guide the evacuees along the path from one robot to the next while each remains in its previously taken position [17]. In the shepherding approach, only one robot is needed to guide a person or a group from the starting point all the way to the exit. The robot moves to typical points of congregation or searches for people to evacuate and will then guide the evacuees to the exit by moving in front of them. The way the robot communicates to the evacuees that they should follow it differs and can for example take the form of it verbally offering help or demanding that they follow. After leading one group or individual out of danger, the robot then returns inside to look for other people to evacuate [17]. Seeing that shepherding seems to be more effective in evacuating people than multi-robot hand-offs [2], we decided to focus our experiment on how to improve evacuation efficiency within the shepherding approach. Instead of verbal instructions that rely on the evacuee speaking the same language as the robot, we set out to test and compare non-verbal communication styles. Wagner [16] introduces five guiding principles for the development of evacuation robots, one of which is that communication should be understandable to a large range of people. A single communication type, like for example verbal instructions, excludes those who do not speak the language, are hard of hearing or deaf and should therefore be combined with other, visual cues. Our experiment only employs one communication style for each condition, therefore by themselves our two robot types would not be appropriate for a realistic deployment. Out of consideration of our limited available sample size, we decided against a combined condition in this experiment. However, a better understanding for which individual kinds of cues are particularly effective might nevertheless prove useful for the development of combined communication strategies.

IV. Organizational Background

A. Project Organization and Tools

For organizing and implementing our project, we used a variety of technical and project management tools. In terms of management tools, we used *Github Projects* for creating an agile oriented scrum board for organizing our tasks and assignments (see Fig. 2). This also allowed for simple issue creation in combination with Github. Further, *Mural boards* and *Google Docs* were used for brainstorming and idea collection. In terms of synchronous and asychronous communication, *Discord*, *Telegram* and *BigBlueButton* were our choice. Regular meetings were hold thursdays, after the weekly course update and feedback meeting for task distribution, and mondays or tuesdays for reviewing the results.

In terms of the technical environment, we chose *Git* for file versioning in combination with *Github* for repository hosting. After the first weeks of development, we encountered a Git Large File Storage (LFS) problem, since the free tier usage of Github only allows for 2 GB of storage. Consequently, we migrated our project to *GitLab*, which offers an integrated migration function from Github to GitLab. It is also worth to mention that hosting a repository under the dedicated Github or GitLab server of the university is also a viable option to consider. Using the GitLab service, we increased our storage capacity from 2 GB to 10 GB (GitLab Free LFS tier). In addition, we decided on using *Git Extension* as a common Git UI option and a common Git workflow

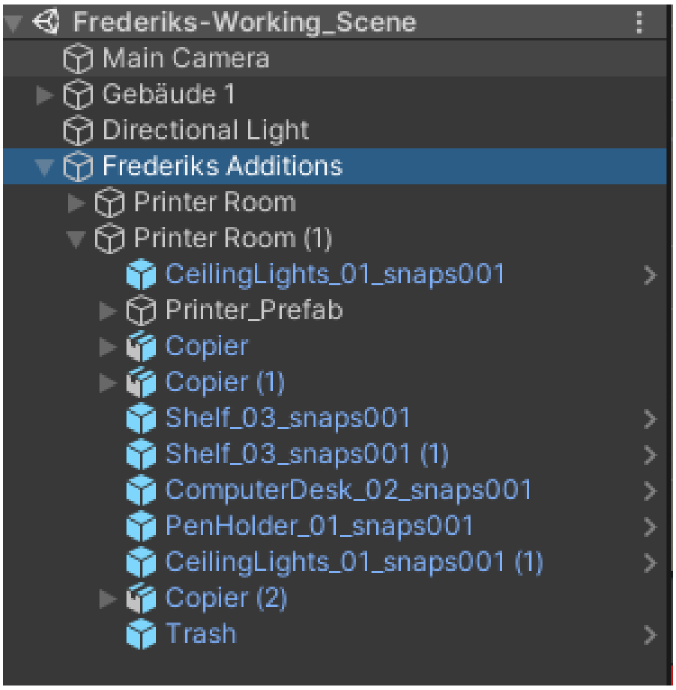


Fig. 1: An example of a separate unity working scene

was established. This also served as a orientation guide for project members unfamiliar with the Git processes. The established Git workflows can be found in the GitLab ReadMe documentation, a link collection can be found in the appendix B. In general to avoid major merge conflicts in the unity scene files, every project member created a separate unity scene for a task and grouped scene additions under a separate empty game object (see Fig. 1). This way multiple people could work on the same scene at the same time, the newly created game objects were copied over to the original scene in regular merging sessions.

For implementing our VR experiment, we used the *Unity* engine (version 2020.3.23f1) for scene and animation creation, *Jetbrain ´s Rider* or *Microsoft Visual Studio* for script coding and *Blender* for modeling our robot models as well as our office model. In addition we used a variety of free assets from the unity asset store and other open source libraries for the office interior 3D models, environment and robot sounds (again a full list can be found in the appendix A). For porting the plain unity 3D project into VR, we used the *SteamVR* asset from the unity assets store. For the VR environment, *HTC Vive Pro* devices were used with track pad-supported controllers for movement. Devices were supplied by the University of Osnabrück, Institute of Cognitive Science VR Lab.

B. Project Progression

In general, the project started with more theoretical work on possible project ideas and concluded with more practical work and experiments. After several brainstorming meetings in the beginning, we narrowed our project ideas down to two topics. The First topic was an robot-aided fire evacuation scenario and the second topic was an robot destruction scenario with focus on human empathy. Agreeing on the first topic, we conducted a literature research on the topics of evacuation and trust, robot design in fire evacuation scenarios. Based on the findings, we formulated our hypothesis (section II) of comparing the performance of a sound robot and visual robot model and also thinking about the possible independent variables to measure during our experiment.

With the hypothesis and ideas set, supported by the theoretical background research we conducted, we started the technical implementation of our experiment by modeling the robot and the office building in Blender. Simultaneously, we finished a first draft of our experiment storybook, describing interaction possibilities and the general experiment procedure. Also an office room plan was generated and sketched. Over the course of the following weeks,

- an unity project with git versioning was initialized on Github,
- 3D models were imported from Blender,
- the office interior were designed with free unity assets,
- SteamVR necessary assets and installations were added,
- storybook was finalized
- necessary unity scripts were introduced.

Due to the Github LFS storage limitations, we migrated our project to GitLab and continued to work in the new repository. To be able to continue working on the experiment scene, we decided to deactivate the SteamVR plug-in in the unity settings and reactivated it later when the project was completely ported to VR, since working with the scene without a VR headset connect led to additional errors.

After finishing importing the first robot model and the interior design, a preliminary dummy player was implemented which could be controlled via the ”WASD” keyboad keys and the mouse, allowing for moving around our scene. Additionally, smoke and fire emission systems and robot movement were implemented. During this stage, we also encountered performance issues due to the amount of particle systems used. Thus more effort was put into optimizing the smoke particle creation (see section V-A for more details). Furthermore, an Experiment Manager for recording and saving experimental data was introduced, which automatically writes out recorded experiment data every 10 seconds into a tab-separated-file. Environmental sounds and lights were added last as well as scripts for the analysis of the recorded experiment data.

With a functional first draft of our experimental scene, we proceeded to visit the VR Lab for porting and finalizing our experiment. The dummy placer was replaced by a SteamVR player rig and necessary unity references were readjusted. Simultaneously, briefing and debriefing instructions (see appendix C and D) as well post experiment questionnaires were created. After ensuring that the experiment scene is working properly, a first test participant was invited. Upon confirming that experiment was working, a build version of the project was created to ensure that all participants are working with the same experiment version. At the same time, we created a post-experiment questionnaire.

Several participants were invited then into the VR-Lab for the experiment (for more details on the experiment process see section VI). In total ten non-project members participated in our experiment.

V. Implementation

A. Smoke and Fire

To create smoke in the environment, we used Unity's Built-In Particle System, which simulates particle behaviour on the CPU and allows to create various dynamic effects, such as liquids, clouds, or flames. The first step was to get familiar with the Particle System, since it has many components that influence and change how the system is behaving. The components, also referred to as modules, of the Particle System can be seen in Fig. 3. The settings of the modules where adjusted so that the smoke appeared as natural as possible. The properties of the modules of the particle systems that were changed, to give it a more smoke-like appearance can be found in Table I.

Multiple Particle Systems were placed inside the scene, to cover the space of the whole building. For approximately each 6×6 square of the building (see Fig. 4), one Particle System was placed. This made sure that the amount of smoke would be similar across the whole building and would only be influenced by the changes made to the Particle Systems.

A C#-script was set up and added to a parent of all smoke Particle Systems, to adjust the smoke behaviour globally throughout the experiment. The smoke was increased with time and occluded the players view more and more. Fig. 5a and 5b show the differences in the field of view of the player between a low and a high smoke density.

Two variables of the Main module, *Start Size* and *Start Lifetime* were calculated from within the script, to increase the size of individual particles of a system and the total amount of particles at a certain point in time. The third variable that was calculated from within the script, was the *Y*-position value of the systems transform. This was necessary, because even with increased size the particles would float in the air, leaving the ground uncovered. Changing other values, e.g. increasing the *Gravity* setting of the main module did not lead to the desired visual effect of occluding more of the visual field of view, but rather lead to the particles directly floating to the ground, leaving parts of the ceiling uncovered. For all three values a starting and a maximum value where set inside the script, as well as the desired step size with which each value was changed. The final values that were used for the experiment can be seen in Table II. The values were changed alternately using a Switch Case Condition from within a co-routine, that was called every second.

To actually change the values of the individual Particle Systems, a second C#-script was set up and attached to each smoke Particle System. The parent was referenced and each time a new value was calculated, it was called by the new script and changed for the Particle System.

Finally, a value was needed to determine the smoke density at each point in time. For this, a percentage value of each of the three changing values was calculated, with the start value being equal to 0, and the max value being equal to 1. Then, those three percentage values were added up. Since the size value had the biggest perceivable influence on the occlusion of the visual field, this value was factored in more strongly then the other two. The formula used for the calculation of the final value for smoke density was:

$$SmDen = pS * (3/5) + pLT * (1/5) + pY * (1/5) \tag{1}$$

with *SmDen* being the Smoke Density, *pS* the percentage value of the Start Size, *pLT* the percentage value of the Start Lifetime and *pY* the percentage value of the Y-position, resulting in a value range for the smoke density of 0 to 1.03 (rounded down to 1).

For the fire, a Particle System prefab was added from the Asset Store and placed in the scene at multiple locations. A smoke column prefab was added to the fire, creating the perception, that the smoke was coming directly from the fires. Both prefabs can be found under Appendix A. For most prefabs the light source was removed, so that for each 6×6 square of the building one light source from fire remained. This was necessary, because the amount of light coming from the fires was unrealistically bright. Also, the light intensity for the remaining prefabs was reduced slightly, for the same reason.

Finally, some performance issues were encountered, due to the high amount of particle systems in the scene. In order to solve those issues, a function was added to the script of the individual particle systems, that was able to turn them off, when the player was far away or facing a different direction. For that the distance between player and particle system was calculated, as well as if the player was looking towards the system or away from it. Three threshold values were set, that determined the maximum, an "in-sight", and a minimum distance to the player. If the player was within the minimum distance, the particle system would be active, emitting particles and changing the smoke density simultaneously. This was regardless of the facing direction of the player, because individual particles of the system were usually still in the field of view. Therefore movement of the smoke was visible, even when facing away. If the player moved outside of the minimum distance, but was still facing the particle system, it was also playing. However, when the player was in sight distance to the

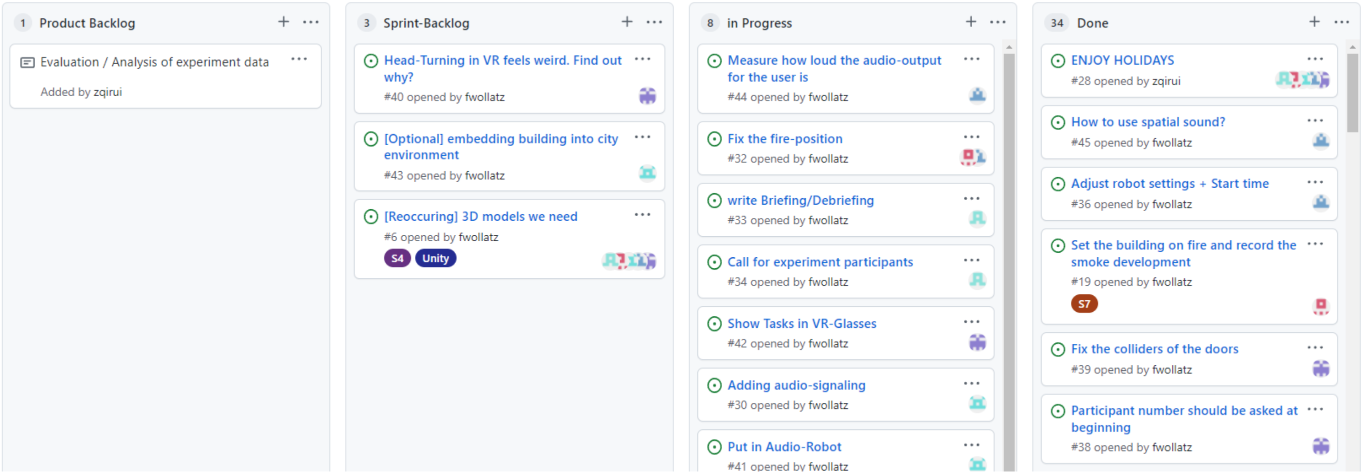


Fig. 2: Scrum Board in Github Projects

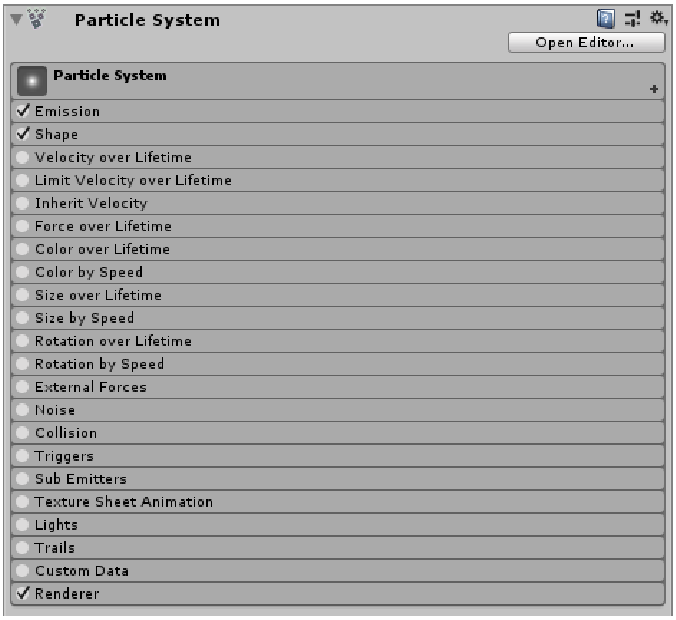


Fig. 3: Overview of all modules included in a Particle System.

Fig. 4: Size of the 6 × 6 square of the building that was used to place Particle Systems.

particle system, but was facing away from it, the system was paused, meaning no more particles where emitted, and existing ones were not updated, leading to no more movement of the system. This was also true, when the player moved outside of the in-sight distance, but was still within the maximum distance. Here, it additionally did not matter if the player was facing to or away from the particle system. If the player moved outside of the maximum distance, the particle system was stopped and all existing particles were cleared from the scene. This functionality managed to improve the performance, whilst ensuring that the pauses were not noticeable by the player. The distances of the player to the particle system and it's activation states are depicted in Fig. 6a - e.

B. Audio

Throughout the experiment the participant was surrounded by increasing levels of background noise to simulate a real emergency and to create a more stressful environment. As the participant moved through the building, the initial low rumbling and crackling of a nearby fire combined with the jarring fire alarm were one by one layered with the sounds of fire truck sirens, screeching car brakes and a crowd of people gathering outside. To achieve this, each Audio Source was attached to invisible 3D Objects which were set as Triggers and placed in spots that the participant would have to pass through. Since participants might move back and forth and pass the trigger again, the sounds were scripted to be activated only once.

For the audio robot we decided for an alarm-like sound, to invoke urgency. At the same time it was important, that it was not too similar in sound and frequency to the normal building alarm, since otherwise it was hard to understand. To

TABLE I: Adjusted settings of the Particle System Modules

Module	Property	Setting	Value	Description [15]
Main	Prewarm	—	True	Puts system in a state, as if it had already emitted one loop
	Start Speed	Random between two Constants	0 - 0.86	Start speed of particles, randomized for more natural appearance
	Start Rotation	—	20	Start rotation of particles in degrees
	Play on Awake	—	False	System is activated automatically, when enabled
Emission	Rate over Time	—	15	Number of particles emitted per second
Shape	Shape	Cone	—	Shape of the volume from which particles can be emitted
	Angle	—	20.44	Angle of the cone
	Radius	—	0.1	Radius of the shape
	Spherize Direction	—	0.5	Particle direction is blended towards a spherical direction; particles travel outside of the center of the transform
Size over Lifetime	Size	Increasing Curve	—	Controls Size of each particle during its lifetime
Rotation by Speed	Angular Velocity	—	25	Controls angular velocity of each particle based on it's speed
Collision	Type	World	—	Can either be set to collide with a list of planes or the Physics World
	Collision Quality	Medium	—	Quality of the collisions, medium can leak particles but requires less computing
	Collides With	Mixed (Ground & Building)	—	Configures with which layers the particles collide (new layer was created for the ground & building)
	Dampen	—	0.1	Particle will loose this friction of speed; will become slower after colliding
	Bounce	—	0.1	determines force applied to particle; how much the particle bounces off after a collision
Texture Sheet Animation	Mode	Grid	—	Allows to treat a texture as a grid of separate sub-images that can be played back as frames of animation
Renderer	Material	SmokeLightParticle (Appendix A)	—	Material used to render particles
	Sort Mode	Oldest in Front	—	Draw order of the particles
	Max Particle Size	—	1	Size that a particle is allowed to be, to be displayed on screen

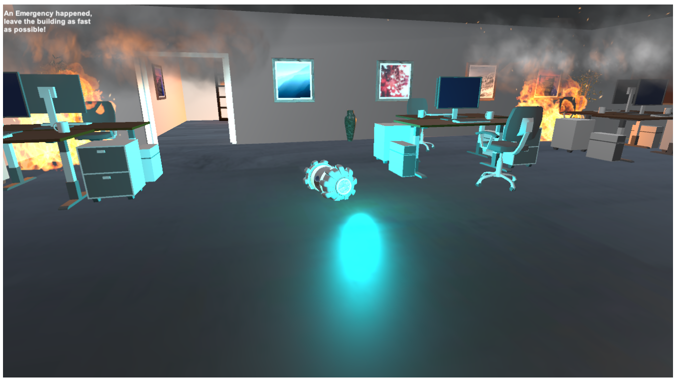
TABLE II: Particle System Values for Increasing Smoke

Variable	Start	Max	Step
Start Size	1	2.8	0.1
Start Lifetime	5	20	1
Y-Position	1.8	1	- 0.1

simulate that the sound was coming from the robot we attached an Audio Source to the robot-object, set the spatial blend to 3D and the Volume-roll-off to logarithmic. Thereby the volume decreased logarithmic to the distance between player and robot, having 100% volume when very close and 0% after 20 meters.

C. Building Plan

The building was designed to be an office building with a total of 26 rooms. A blueprint of the building can be found in Fig. 7. The building was modeled in 3D using blender and the archimesh-extensions for architectural modeling. To increase credibility of the situation we chose the types of rooms based on existing blueprints of offices. We decided to create an office with multiple small, two person office-rooms, two copy



(a) Example of low occlusion of the visual field

(b) Example of high occlusion of the visual field

Fig. 5: Low and high occlusion of the visual field, equaling low and high smoke density

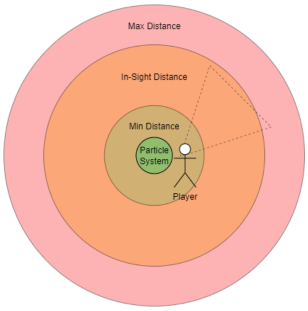
rooms, two big open-plan offices, as well as sanitary rooms and break-rooms with kitchens. Finally we added two server rooms as well as an entrance area, where possible customers could wait. The rooms have been decorated according to their use, using free assets from the asset-store or by creating assets using Blender. A full list can be found in Appendix A.

It was important for the experiment, that the users had the choice between multiple doors to leave any room, to check, if they actually follow the robot, or just enter the next door they see.

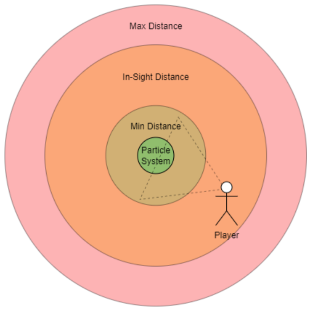
Other requirements included a tutorial area. In this area the participants were allowed to become familiar with the controls, ask questions and move around freely. They were given the task to find a key in one of the adjacent rooms. This key could be collected by walking close to it. It allowed to get through a two-winged green-colored door, where the real experiment began.

D. Robot Design

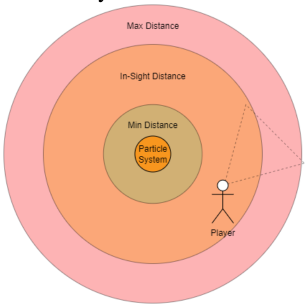
According to the hypothesis (section II), we have designed two robot models: one with illuminating and another with auditory communication style. Motivated by a study on portable evacuation robots by Kim et al. [6], we have created two sketches of the models as the basis for their 3D



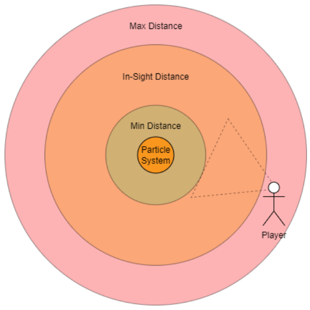
(a) In Minimum distance to Particle System



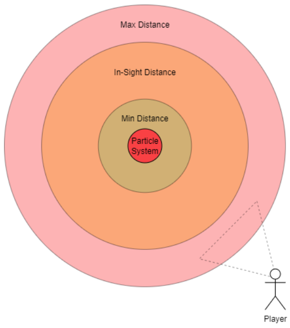
(b) In-sight distance to Particle System, facing Particle System



(c) In-sight distance to Particle System, facing away from Particle System



(d) Outside of in-sight distance to Particle System



(e) Outside of Maximum distance to Particle System

Fig. 6: Distance to Player and Activation State of Particle Systems

prototypes. The sketches represented a capsule-shaped robot with wheels, either LED lamps or grey speakers for visual or auditory communication. The body of both robots had a camera in the center and, depending on the model, either large LED light circles or grey speakers wrapped around the body.

For the 3D robot modeling step, we used *Blender*. After becoming familiar with many functionalities that the software has, we started designing the 3D model of the visual robot first, followed by its audio counterpart.

The 3D visual robot prototype (*VisualBot*) (Fig. 8a) had bright, blinking LED lights that aimed to contrast the colors of the fire emergency background so to attract the

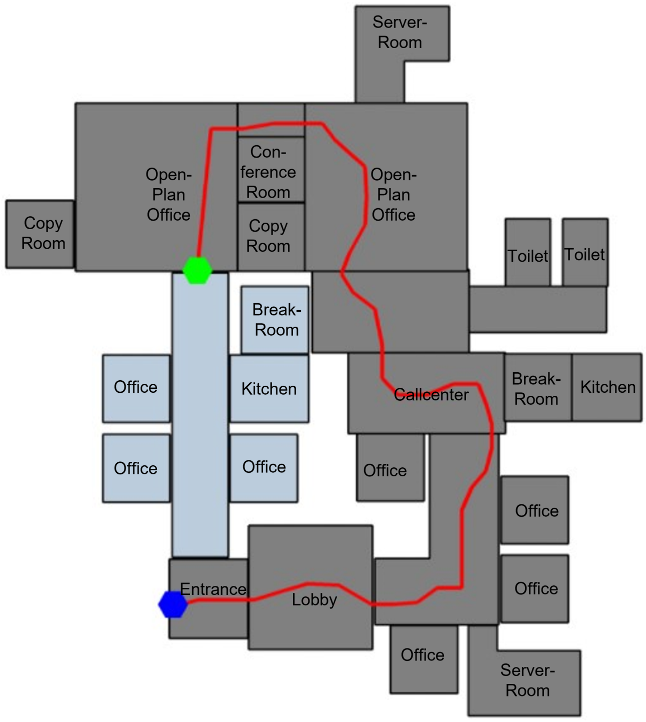
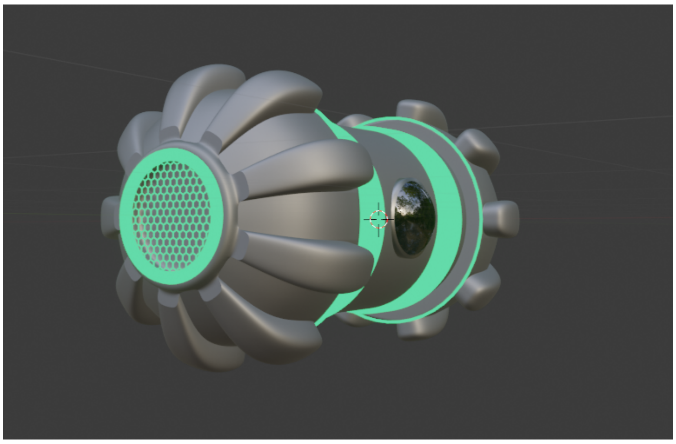
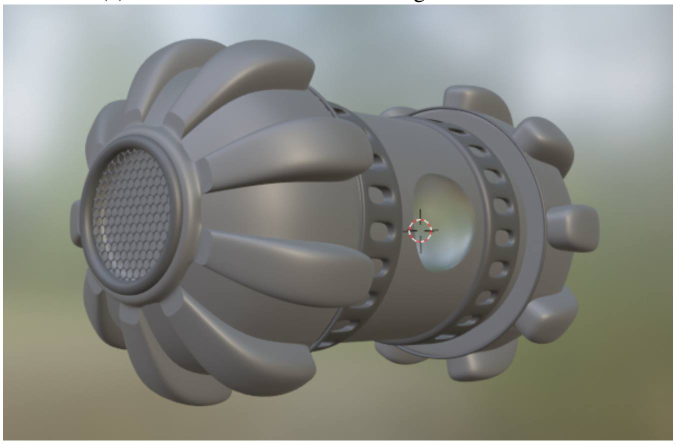


Fig. 7: Blueprint of the Building. The light gray area is the training area. After leaving through the green door (green hexagon), they have to escape through the exit (blue hexagon). The red line is the shortest path.



(a) Model of the VisualBot designed in Blender.



(b) Model of the AudioBot designed in Blender.

Fig. 8: Visual vs. audio robot models.

participants to follow it through the fire to the exit. Once the emergency started, the scene became dominated by dense orange hues - to contradict that, the robot exuded visual stimuli from turquoise to light neon-blue color. To have that light-emitting effect, we used *Blender's* emission material.

The 3D audio robot prototype *(AudioBot)* (Fig. 8b) was designed to be visually less noticeable when compared to the model with a visual communication style. We, therefore, added a loud siren-like sound (section V-B) to attract the participant's attention instead. The model components that emitted light in the visual version got remodeled or replaced by a texture resembling a speaker.

The C# script was added to the parent of the robot prefab to control the robot movement and, additionally, two more scripts were added to the robot components' to achieve the animation effect. Although the modeling of the robots was done in *Blender*, importing the *.fbx* file with textures and materials to Unity failed. Eventually, we reapplied those in Unity.

E. Robot Movement

The robot moved along a path of 45 checkpoints at the ideal path (red line in Fig. 7). There were three important phases in every loop: The long-term-target selection, the current-target-selection and the movement phase. In the long-term-target selection, the robot decided, based on the players position to the track and the checkpoints on it, where it should be in the long run. During the current-target-selection it defined how to get to the long-term target, and selected an immediate, current goal, based on, where the long term-target was in relation to its current position. In the movement-phased, it moved further towards the current target or waited for the user, if it already was at it's current target. A more detailed view on the different phases can be found in Fig. 9.

The robot always stayed on the path and tried to stay five checkpoint in front of the user. If the user went too far off the path, the robot moved to the closest checkpoint and waited there till the user came closer to any other. If the user was closer to a checkpoint further down the path, the robot increased its speed. While waiting, the robot turned to the user.

VI. Methodology

A. Experimental Setup

The Scene we created was run on the VIVE pro Eye, using the RTX 2080ti as GPU. The Computer that was used, was

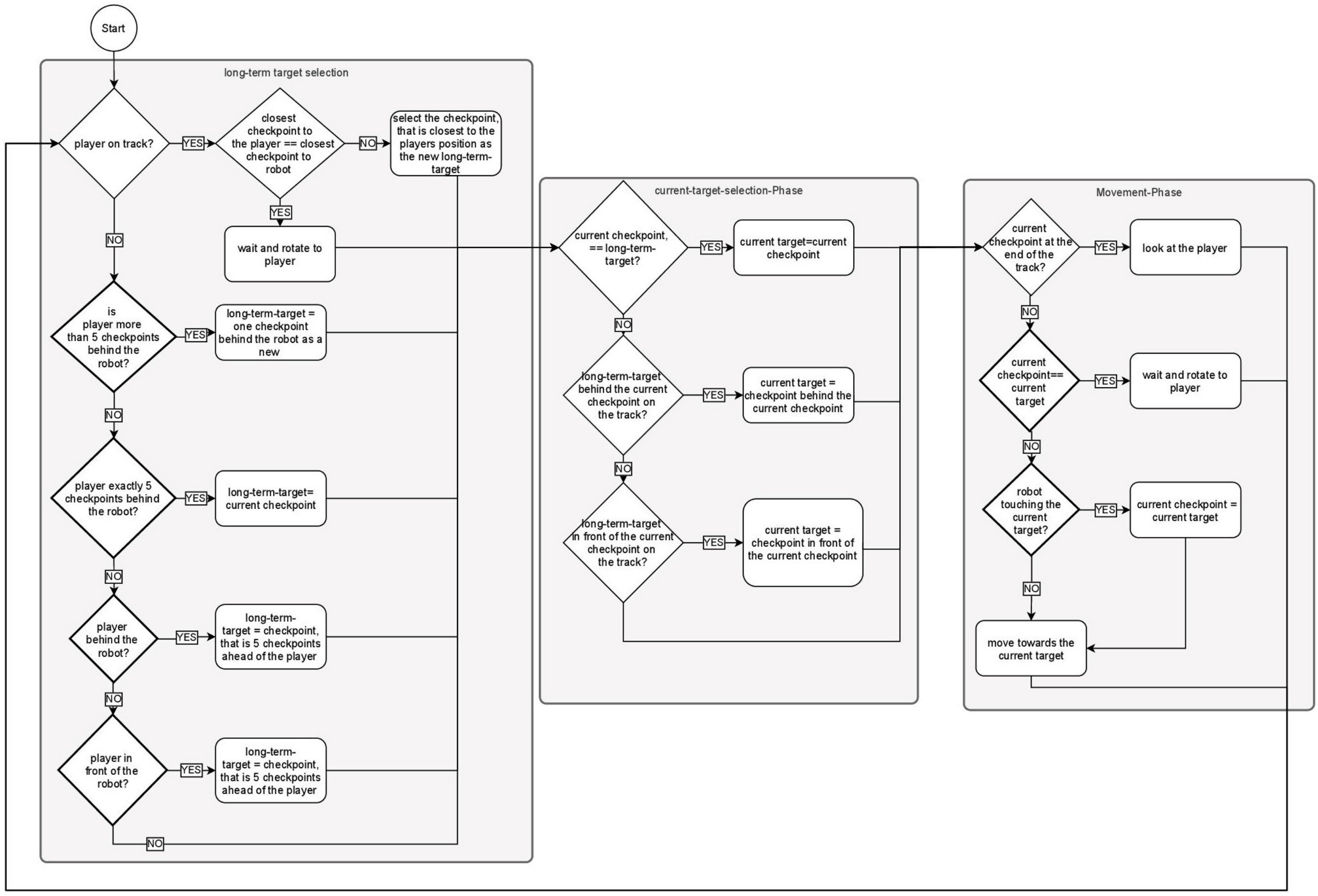


Fig. 9: Flow-Diagram of the robot movement

running on Windows 10 Pro. The users were sitting on a swivel chair, that they could use to turn their body. Forward-, Backward- and Sideward-Movement was controllable using the HTC-Vive controllers touchpad. If the participants touched it at the top, they moved forward, if they touched it at the bottom, they moved back. The further from the center of the touchpad they touched, the faster they moved. The cable of the HTC-Vive Pro was connected to the ceiling of the room, to avoid the users getting entangled in it.

B. Data

The data we collected from the experiment were the x- and y-coordinates of the user, the current room the user was in, the euclidean-distance to the robot and the closest checkpoint on the ideal track, the amount of time, that the robot had to wait for the player, as well as the robot position. Additionally the smoke density and the total evacuation time were recorded. This data was collected every 2 seconds. To collect and save the data, we created an Experimental Manager Script, that requested the measures from the Player, the Robot and the Smoke Manager. Every 10 seconds this data was exported to a *.csv* file, for later analysis. Alternatively we could also export it manually, using the F-button. Our complete data set can be found in the link collection under appendix B. In the questionnaire we asked the users how realistic the users found the scenario, how helpful they found the robot and how stressed they felt.

C. Experimental Execution

After greeting the participant they got a short briefing over the experiment. In this briefing we told them, that this is part of the “Human Robot Interaction”-course at the University Osnabrück and that we research human behavior in stressful situations. Therefore they should expect a stressful situation. We also stressed, that they are not in danger at any point and that their participation is entirely voluntary and could be stopped by them at any time during the experiment without giving any reason. Our briefing also included a small introduction into the scene and a short explanation about the movement. In the end, the briefing also told them that there is no right or wrong behavior and that they should act as they would in a real situation.

When they understood what we were about to do, they were asked to sign a paper of consent, where everything we told them, was written down again C. Once they did that, we gave them a short introduction into the VR glasses. When they had their glasses adjusted, we selected the robot model. Every second participant got the audio version of the robot. Then they started in the tutorial area. Here they tested how to move around and got used to the controls. We gave them the task to collect a key to go through the big green door, after which the experiment began. In this area they were allowed to ask any question they wanted. We also reminded them that, if at any point in the experiment, they wanted to stop, they could do so, without giving a reason. After going through the green door, the experiment started. Directly after the experiment they were asked to fill out our survey. After this we asked them, if they wanted to add something that they could not remark somewhere so far. Finally they got a short debriefing. After that, some users wanted to give some more input. This input was noted, directly after they left the lab. The whole process took about 15 to 20 minutes per participant.

VII. Results

In the following we will describe the sample, explain exactly what data we excluded and then analyse the sub-hypotheses one by one. Afterwards we will have a look at the correlation between the distance between player and robot and the smoke density. Furthermore we will analyse the paths, that the participants walked. Lastly the interview and the post experiment questionnaire will be evaluated.

A. Description of Sample

In total, ten participants took part in the study, with an age between twenty and thirty years, all being students of the university and acquaintances of the authors of this documentation.

The number of participants was equally split between the two robot model experiments. We had to exclude one trial (section VII-B) from the visual robot condition as the participant failed to find the exit out of the burning building. Therefore we analysed the data of four participants in the visual robot condition and five participants in the audio robot condition.

B. Excluded Data

Out of ten experiment trials, one participant unexpectedly did not manage to leave the building and the experiment was stopped upon reaching the time limit (14 minutes). Thus we excluded the data of this participant in our descriptive data analysis (section VII). Despite not exiting the building, we decided to include the post-experiment questionnaire data of the participant, since it served as valuable feedback for us. An elaborated pathing analysis was performed for this special case (see section VII-I). Besides that, no other data was excluded in our analysis.

C. Difference in Evacuation Time

When measuring the *Evacuation Time* (H_{1a}), (Fig. 10) the participants who took part in the visual robot experiment spent on average 130.5 seconds (SD = 60.21) to find the exit, whereas the participants from the audio robot experiment spent on average 121.6 seconds (SD = 46.20) to leave the building.

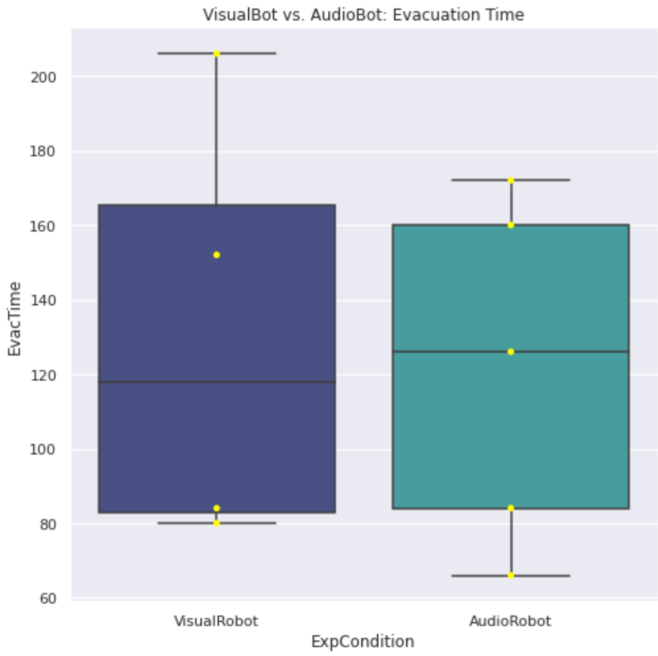


Fig. 10: Boxplot illustrating the data distribution for *evacuation time* in visual and audio robot experiments.

Additionally, the Student's t-test resulted in a p-value of 0.596 which was above the cut-off value of 0.05 (t(7) = 0.25, p = 0.596). Therefore, a robot that communicated via illuminating signals did not have a lower evacuation time when compared to the audio robot. See Table III for complete summary statistics.

TABLE III: Summary Statistics for *Evacuation Time*

Evacuation Time (in seconds)					
Condition	Mean	Median	Std	Min	Max
Visual Robot	130.5	118.0	60.21	80	206
Audio Robot	121.6	126.0	46.20	66	172

D. Difference in Waiting Time

The *Robot Waiting Time* (Fig. 11) variable measured the maximum of how long a robot waited for a participant (H_{1b}), in case they did not follow it. The visual robot model waited on average 90.34 seconds (SD = 94.60) for the participants to follow it. For the audio robot, the average was 61.84 seconds (SD = 42.12). See Table IV for complete summary statistics. Additionally, the Student's t-test resulted in a p-value of 0.719 which was above the cut-off value of 0.05 (t(7) = 0.61, p = 0.719). Therefore, a robot that communicated via illuminating signals did not have a lower total waiting time, then a robot using audio cues.

E. Difference in distance to the robot

The *Distance to the Robot* (Fig. 12) variable measured the average of how far away a participant was from the robot

TABLE IV: Summary Statistics for *Robot Waiting Time (in seconds)*

Robot Waiting Time (in Unity game units)					
Condition	Mean	Median	Std	Min	Max
Visual Robot	90.34	54.73	94.56	24.20	227.72
Audio Robot	61.84	38.33	42.12	25.57	108.89

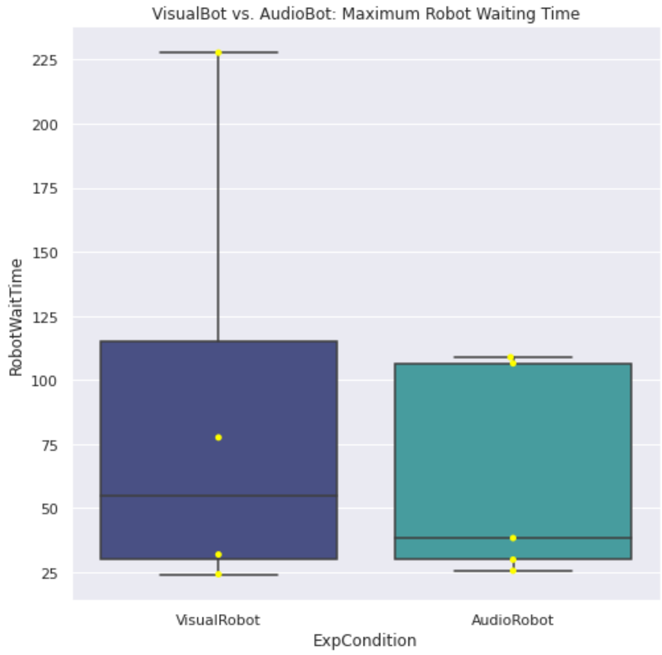


Fig. 11: Boxplot illustrating the data distribution for maximum *robot waiting time* in visual and audio robot experiments.

(H_{1c}). In the visual robot experiment, the average distance appeared at the value of 5.70 (SD = 1.18). For the audio robot experiment, the average distance was 6.17 (SD = 2.34). The participant who reached a 10-meter-distance from the robot was considered an outlier. See Table V for complete summary statistics. Additionally, the Student's t-test resulted in a p-value of 0.367 which was above the cut-off value of 0.05 (t(7) = -0.35, p = 0.367). Therefore, a robot that communicated via illuminating signals did not have a lower total distance between robot and user, then a robot using audio cues.

TABLE V: Summary Statistics for *Distance To The Robot (in Unity game units)*

Distance To The Robot					
Condition	Mean	Median	Std	Min	Max
Visual Robot	5.70	5.57	1.18	4.49	7.19
Audio Robot	6.17	5.60	2.34	4.14	10.17

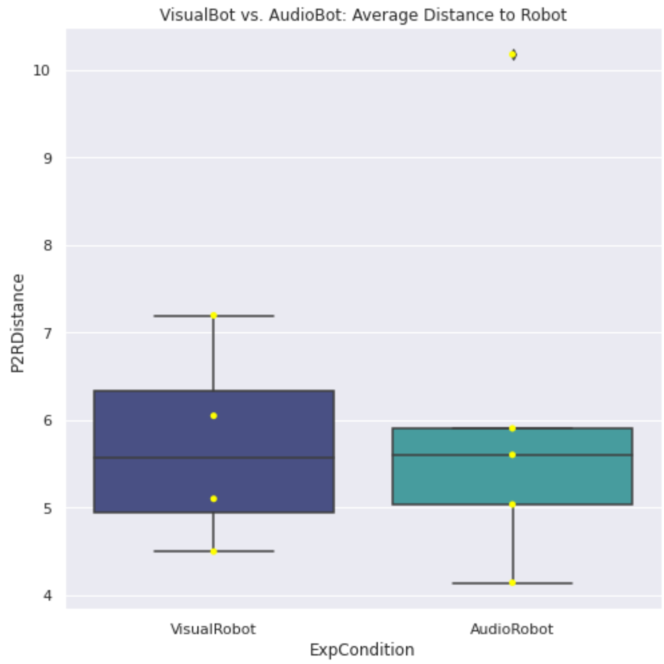


Fig. 12: Boxplot illustrating the data distribution for average *distance to the robot* in visual and audio robot experiments.

F. Difference in distance to the ideal track

The *Distance To The Ideal Track* (Fig. 13) variable measured the average of how far a participant deviated from an ideal exit route (H_{1d}). In the visual robot experiment, the participants deviated on average for 25.68 meters (SD = 18.00) from the ideal track. For the participants of an audio robot experiment, the average deviation distance was 25.15 meters (SD = 22.33). The participant who deviated 63 meters away from the robot was considered an outlier. See Table VI for complete summary statistics. Additionally, the Student's t-test resulted in a p-value of 0.515 which was above the cut-off value of 0.05 (t(7) = 0.04, p = 0.515). Therefore, a robot that communicated via illuminating signals did not have a lower total distance between robot and ideal track, then a robot using audio cues.

TABLE VI: Summary Statistics for *Distance To The Ideal Track*

Distance To The Ideal Track					
Condition	Mean	Median	Std	Min	Max
Visual Robot	25.68	21.84	17.10	8.35	50.71
Audio Robot	25.15	20.55	22.32	8.48	63.83

G. Null hypotheses testing

With respect to our sub-hypotheses H_{0a} - H_{0d} we performed an independent t-test for our four dependant variables. Table VII shows the results of our statistical analysis. In total none of our sub-hypotheses could be supported.

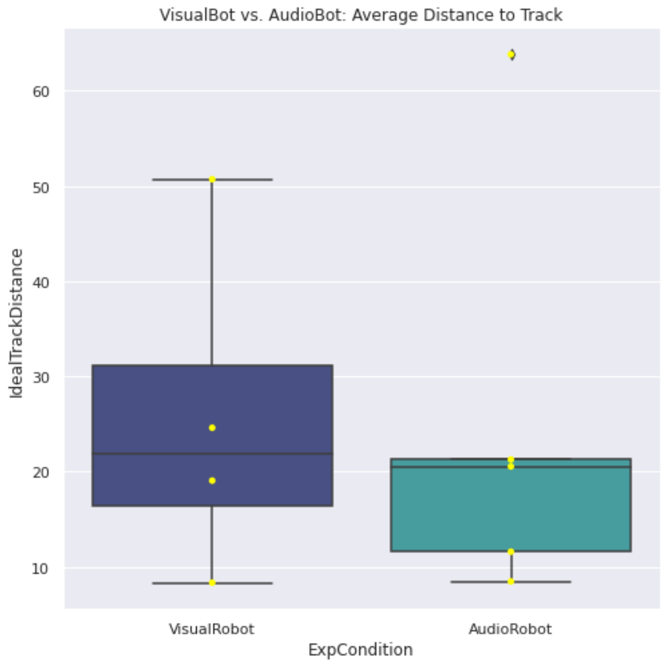


Fig. 13: Boxplot illustrating the data distribution for average *distance to the ideal track* in visual and audio robot experiments.

TABLE VII: Independent t-test for the four dependent variables

Independent Samples t-test			
	Statistic	df	p
H_{1a} Lower Evacuation Time	0.251926	70.000	0.596
H_{1b} Lower Robot Waiting Time	0.609338	70.000	0.719
H_{1c} Lower Distance To Robot	-0.354529	70.000	0.367
H_{1d} Lower Distance To Ideal Track	0.039074	70.000	0.515

H. Correlation between Distance to Robot and Smoke Density

In the beginning we also wanted to check if we could find a correlation between the Distance to Robot and the Smoke Density-Score (See H_2). Ultimately we decided against it, because we only noticed after the experiments that the data for this was imbalanced. This was mainly due to two key factors:

- The Particle Density increased too fast and was at its maximum (1) for the majority of the experiment. Therefore the pure existence of these data points results in a correlation.
- The data points were created by every participant, every two seconds. This leads to the data points of one participant being highly related upon one another.

To improve upon this, one could have increased the particle density slower or only room-wise. That way one could compute the average distance of the player to the robot per

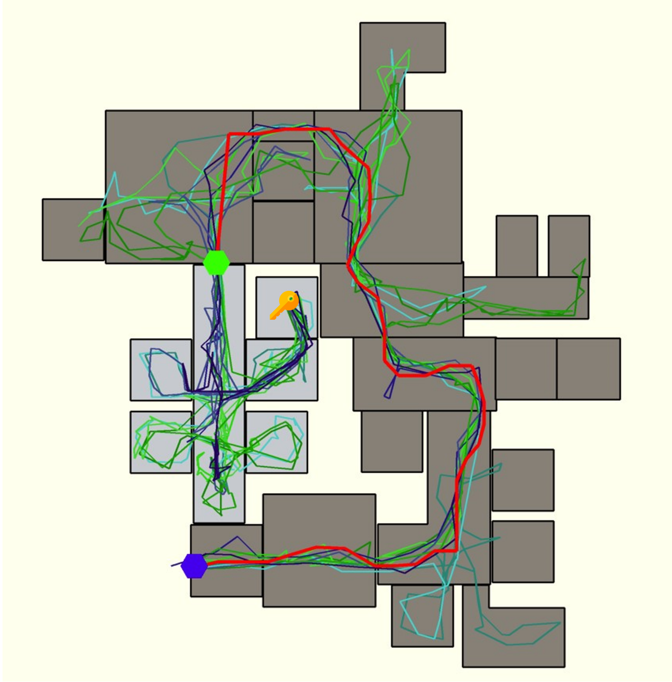


Fig. 14: Pathing of all participants, except the outlier case. Greenish lines are participants with the visual robot, blueish lines are participants with the audio robot

smoke density. This way we could have computed a correlation between this average distance per room and the smoke density in the room.

I. Pathing

We recorded the x and y positions of the participants during the experiment, also already starting from the tutorial stage. The general movement of all participants that managed to leave the building can be seen in Fig. 14. The map shows the experiment start point (green hexagon), the green door connecting tutorial stage and experiment stage, the single exit point (blue hexagon) as well as the optimal path (red line) for the quickest evacuation. All other colored lines belong to the different participants.

During the tutorial stage many participants explored some of the rooms. Since all participants needed to find the key to open the experiment stage, it is no surprise that every person visited the key room (yellow key symbol, Fig. 14). With the begin of the experiment most participants did not pay much attention to the robot at first and tried to explore and find an exit on their own, explaining the higher deviation from the ideal path in beginning. Interesting observations here are that some participants tried to escape through the windows or were searching for fire extinguishers to put out the fire themselves. Upon realizing that the robot may help them finding an exit, they started to follow the robot. Since the robot follows the ideal path, this explains the better alignment with the red line. The closer the

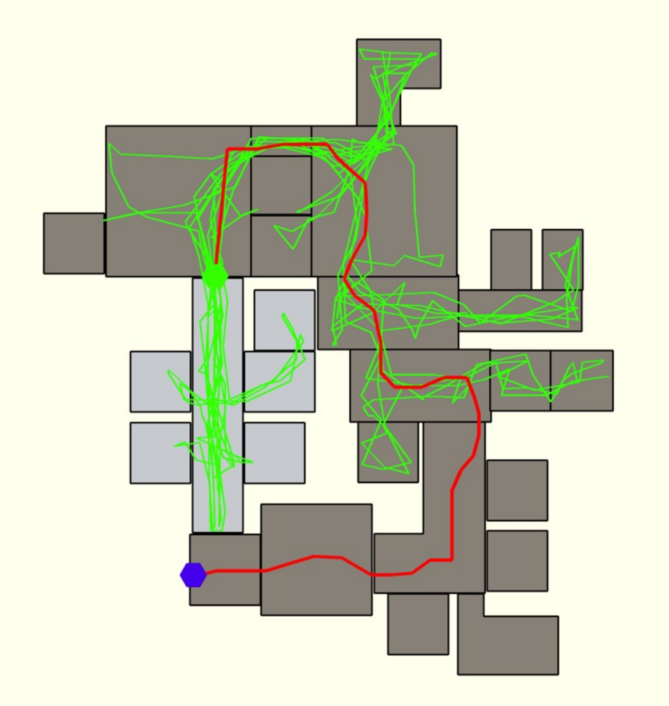


Fig. 15: Pathing of the outlier case

participants were to the exit the higher the smoke density and the worse the vision of the participants would be. These limitations caused some of the participants to get lost in other rooms in the later stage of the experiment, especially good visible in rooms of the lower right part of the office map.

All participants besides one person manage to leave the building. This one outlier case (see Fig. 15) did not trust the robot enough to follow it to the exit, explaining the high deviation from the ideal path. This participants unexpectedly went back to the tutorial stage, after trying to find an exit on their own (trying to escape through windows), to find a save spot to "breath and think about the next steps". This person later tried to follow the robot, but since several minutes has already passed, it was impossible to find the exit with the amount of smoke that has already accumulated. The experiment was concluded after a time limit of 14 minutes. We did not expect this outcome and only retrospectively thought of considering staying at a save spot to wait for rescuers as another valid outcome to successfully evacuate from this scenario. This option could be included in follow-up works.

J. Interview and Post Experiment Questionnaire

After the experiment (section VI-C) ended, the participants filled in the feedback questionnaire. The questionnaire contained ten questions with a linear scale, multiple-choice or free text answer option. Overall, participants found the robot helpful. However, some hesitated to trust the robot immediately after the experiment began and, hence, took more time to get to the exit area. The others who trusted the robot instantly found the exit quicker. Eight participants had no difficulties in following the robot. Two participants found it hard to follow the robot and gave the following reasons:

- not being able to see the robot in the fire and smoke;
- not being able to understand the purpose that the robot served, i.e., no association to an emergency robot.

Since we mentioned a stressful situation in the briefing, some of the participants assumed that the robot could be cause for stressful situation. Eight participants said they did not have any technical difficulties or trouble navigating the space, while two other participants gave their reasons against it:

- not being able to find the doors (no tactile feedback from the controllers);
- using a touchpad, chair rotation and turning head simultaneously caused motion sickness.

Eight participants found the emergency scenario quite realistic, while the others found it less. When evaluating the stress level of the emergency evacuation scenario, the opinions were split between two groups: one finding the experiment only a little to moderately stressful, and another - from reasonably to strongly stressful.

Exploring the data further, using additional students t-tests revealed some interesting side-effects that might be interesting to study more comprehensively. Participants generally found the visual robot to be more helpful (t(7) = 3.53, p = 0.005). and reported less stress when with the visual robot (t(7) = -5.81, p $<$ 0.001). Meanwhile they did not perceive a significant difference between the easiness of the experiment (p = 0.286).

VIII. Discussion

A. Findings

To recap, we generally expected the visual robot to perform better than the audio robot. In terms of the descriptive statistics, the evacuation time (H_{1a}) was on average lower for the audio robot condition compared to the visual robot condition. Thus surprisingly, the audio robot performed better than the visual robot, though it was not statistically significant. Looking at the robot waiting time (H_{1b}), the audio robot again performed slightly better with an on average shorter waiting time. Unlike we anticipated, the participants stayed closer (distance to robot, H_{1c}) to the audio robot than the visual robot, even though the difference is not large. Lastly, we expected the participants to stay closer to the ideal path following the visual bot (H_{1d}). This was the case as the average distance to ideal track was lower for the visual robot condition compared to the audio robot condition, even though the difference is only marginal.

Testing the null hypotheses H_{01a} - H_{01d}, whether there was a significant difference between the audio and visual robot condition, with a series of student´s t-tests has shown non-significance across all four main descriptive (evacuation time, robot waiting time, distance to robot, distance to ideal track), meaning that the main hypothesis H_1 has to be rejected. This can be explained with the small samples size of only nine samples (one participant excluded due to not leaving the building).

In terms of a potential correlation between the distance to robot and the smoke density to investigate whether participants stay closer to the robot if the visual field decreases (H_2 and H_{02}), we decided not to report the analysed data. Due to the low sample size and the consequently imbalanced data, the analysis showed no reliable result of the occurrence of a correlation. In order to allow for a proper correlation analysis in potential follow-up studies, one needs to slow down the smoke accumulation, to avoid having a majority of maxed out smoke density data points, or re-adapt to a room-wise smoke increase (see section VII-H). Having a proper correlation analysis might give insights on which robot model performs better under low- or high-smoke density circumstances, which could be helpful for improving the design of emergency evacuation robots.

Investigating the different pathings of the participants during the experiment, no condition-specific patterns were discovered when looking at the participants of the two conditions. All subjects tend to have a higher deviation to the ideal path in the beginning of the experiment with a higher alignment with the ideal path in the later stages of the experiment. Generally speaking, it was easier to leave the building, the faster the participant was, since the smoke accumulation have not advanced considerably.

Considering the post-experiment interviews and questionnaires, quite a few people misinterpreted the purpose of robot in the beginning, failing to follow the robot. It was also remarked that the participant were unsure of what to do in the beginning, since there was no fire and smoke in the first room, creating a false sense of security. With respect to realism, overall the participants found the emergency situation quite realistic and stressful. From the technical point of view, the participants had not much trouble navigating the space and following the robot in general.

B. Limitations

1) Technical Limitations: The first difficulties were already faced during the implementation phase of the project. These were mainly caused by the discrepancy between an artificial and a natural environment. Looking at, e.g. the implementation of the smoke it becomes quite clear, what this means. In the real world, smoke develops from a combustion process, and its behaviour is influenced by various physicochemical interdependencies [3]. However this complex behaviour could not be directly modeled in the Unity environment. Instead, the visual behaviour of smoke had to be recreated with the use of the Built-in Particle System, as described in Chapter V-A, which relies on various different components that are used to imitate real-world behaviour. And though changing different variables seems to achieve the desired visual results, it remains very different from the real world equivalent.

This means that the artificial smoke behaviour, though modeled to appear as natural as possible, might behave differently than it would in the real world. Furthermore, also the interaction between the smoke and the light sources, e.g. from the visual robot model, might have been different to the behaviour in a real environment. For example, at times a light source would be occluded by a single particle, leading to the light not being reflected by the smoke in one moment, and reappearing in the next. This type of behaviour is highly unlikely to occur in the real world. Furthermore, guidelines for safety signs and signals [4] suggest to use green colours for illuminated signals to indicate emergency exits. However, in the artificial environment these were less well perceived then the later used light blue colors. Though the results of the post-experimental questionnaire suggest, that the participants found the emergency scenario reasonably realistic, it remains unclear, whether the environment and behaviour of e.g. the smoke development was perceived as realistic as well. Additionally, it cannot be assumed that participants are experienced in fire evacuation situations, meaning that even if they would perceive the behaviour as realistic and natural, this does not guarantee that the modulation resembles a real world scenario. Therefore carrying the results of this study over into the real world should be handled cautiously. Further studies could resolve this issue by e.g. getting expert opinions on the closeness to reality of the artificial environment.

Similar problems were faced in the implementation of the auditory stimuli of the environment and the robot. It was hard to validate, if the sound level of the surrounding environment was sufficient and whether in comparison the sound chosen for the robot model was differentiated enough to be well perceived by the participants. Guidelines for safety signs and signals suggest that the sound level of acoustic signals should be 10dB above the surrounding sound levels of the same frequencies [4], this was again difficult to carry over into the artificial environment, since it was hard to measure a dB level.

Additionally, for better comparison of the two models, future studies should not only track the change of the amount of smoke emitted to the environment, but also the change of the sound level of surrounding auditory stimuli.

2) Sample Size: Before conducting the experiment, it was clear that due to the limited time of the project, the sample size would remain considerably small. This small sample size however could have effected the results, so that a potential difference between the two robot models might not have shown as significant in this study. This issue could be resolved with a larger sample size, which as mentioned before, unfortunately was not possible in the time frame of this project.

3) Motion Sickness: Some participants reported that the navigation in the VR environment caused motion sickness. Motion sickness is a well known side effect of virtual reality that can have a negative impact on the user experience [1]. It occurs, when there is a mismatch between vestibular and occulomotor senses [1], leading to the person perceiving motion, without it being present. In the case of this study, participants were seated on a chair, with which they could turn around in a 360° radius. They were also able to move their head around freely. Additionally, they moved in the horizontal plane using the touch-pad controllers. It is plausible that especially the horizontal movement could have led to the perceived motion sickness, since their is a high discrepancy between the stationary position in the real world and the observed movement in the virtual environment. Controller-based-movements have also been reported to cause a high amount of motion sickness [14], due to the mismatch of movement in the real and artificial environment. To solve this issue, it would be possible to change the horizontal movement from continuous, to a teleport system. This could reduce the amount of perceived movement and thereby also reduce the motion sickness. Even better would be to completely avoid controller-based movement, and have participants freely walk around. However, the realization of this option is limited by the lab environment and needs additional precaution measures to ensure the safety of the participant, as well as the lab equipment.

4) Induced Level of Stress: Another problem that could have influenced the results was the level of stress that participants were exposed to. The stress level stated in the post-experiment questionnaire was widely spread, but ranked in a low to medium/high spectrum, with the median at 6 (out of 10) over all conditions. It seems likely, that in a real-world fire evacuation scenario, the stress level would be considerably higher which might lead to different behaviour of the participants. This however is a problem posed by all Virtual Reality studies in this area [7]. The participants are aware, that they are in an artificial situation and that they are in fact not in any danger at all. Therefore when it comes to studies that investigate behaviour in stressful situations in an artificial environment the results should always be validated by repeating them in a more natural environment.

5) Ethical Concerns: One question that arose during the designing of the study, was whether participants should be informed about the impending emergency situation. Since it is possible, that they experienced prior traumatic situations, similar to the stressful situation of the study, it would be ethically reasonable to inform about all aspects of the experiment. However, in real-world scenarios, emergency situations tend to happen suddenly and without prior warning. This sudden occurrence of an unpredictable situation is also what causes stress in the participants and thereby directly influences their behaviour.

In the end, participants in this study were not informed about the type of stressful situation they were about to experience, but were told that they were not in danger at any point in time and could also stop the experiment at any point in time. There was however one participant that, after the experiment, reported previous negative experience with fire and felt therefore restrained to follow the robot into the seemingly dangerous burning environment. This led to the participant being unable to leave the building and the experiment had to be quit. Fortunately the participant did not report any re-traumatizing or otherwise negative emotions after the experiment was cancelled.

One way to prevent this, would be to e.g. hand out a questionnaire to the participants before starting the experiment, that asks about previous negative experiences with fire and how much it impacts their current perception of it. To ensure that subjects are still unaware of the upcoming stressful situation, questions about negative experiences with other possibly traumatizing situations, like floods, earthquakes or storms. Participants that report previous experiences that still impact them negatively, could then be excluded from the study beforehand.

The second option would be to inform the participant beforehand about the kind of emergency they are going to experience. This might reduce their experienced level of stress, but will significantly reduce the possibility of participants being harmed by the experiment.

For the benefit of the participants, future studies should resort to one of the two options. Additionally, further research in this area should always include the approval of an Ethics Committee.

6) "No-Exit" Participants: As mentioned in the previous section, one participant did decide not to follow the robot into the seemingly dangerous fire and smoke environment. This behaviour was not anticipated in advance, and therefore it was unclear how to analyse the resulting data. In the end, it was decided to exclude the participant from the experiment, to prevent a distortion of the data. However future studies should keep in mind that this type of behaviour could occur. They should either try to prevent it by e.g. closing the tutorial section, or making sure the smoke spreads through the whole building, or in advance decide how participants that show this type of behaviour should be handled. This could mean, that the experiment, like in this study, needs to be quit after a predefined time limit, and the data needs to be excluded, or it could be further analysed to determine why the participant was not willing to follow the robot. This additional analysis could help to improve the robot model to be more easily understood.

7) 'Video-Game-Effect': Lastly, since participants were only informed, that they were about to experience a stressful situation, some reported that they feared the robot would attack them, rather than try to help. Presumably this would not be the case in real world evacuation scenarios. Robinette et al. [11] showed, that participants had the tendency to even over-trust evacuation robots. They found that the only method to not have the participants follow the robots was to have it perform errors during the emergency evacuation. This stands in contrast to the reported perception of the robot in this study. One possible explanation for this could be, that the participants felt like they were in a video-game-like environment, rather than in the real world, where it is not uncommon, that a robot could pose a threat. In contrast, in the real world participants presumably don't expect to encounter a robot that was constructed to harm or threaten a person. However this 'Video-Game-Effect' could indicate, that the results of this study can not be transferred into the real world.

Another explanation could be, that the signals used for the communication between the robot and the participant (the illuminated and auditory signals) were not explicit enough for the participant to understand their purpose. Wagner [16] suggests, that evacuation robots should communicate via a variety of signals, e.g. illuminated and auditory, gestures and signs as to be understood by a wide variety of people. A previous study on different visual instruction types was done by Robinette et al. [12], where the usefulness of varying arm gestures and signs was investigated. Future studies could further investigate this theory by e.g. comparing the models with only one communication type (visual or auditory) to models that use both communication types.

C. Perspective

Due to the frame work of the study process, follow-up research can presumably not be provided by the group that conducted the experiment. Yet, possible following projects should pay attention to the limitations that were faced during this study (section VIII-B). Especially, the technical limitations, the small sample size and the ethical concerns (sections VIII-B1, VIII-B2, VIII-B5) posed major deficits to this study.

Furthermore it is suggested, to alongside investigate the combination of different communication types, e.g. illuminated and auditory, as mentioned in section VIII-B7. This would be valuable in order to help design a robot whose instructions will be understood easily by a wide variety of people, ensuring quick and safe evacuations.

To expand the understanding of human behaviour to evacuation robots in emergency scenarios, it would additionally be interesting to investigate how the evacuation is influenced, if not only a single person, but a group or crowd of people had to be evacuated. Would their reactions to the robot, and their willingness to follow it be affected and in what way?

The role of evacuation robots in fire emergency situations is important and gives room for a variety of further research. Instead of having to wait for emergency personnel to arrive, emergency robots can immediately start to evacuate [10]. This not only saves time, which can be crucial to save someones live, but can also help to not put the emergency personnel in danger [10]. Further research in this area should therefore be encouraged, considering previously mentioned resolutions for observed limitations.

IX. Conclusion

This study investigated if people would evacuate a fire emergency scenario with limited vision faster if a robot was using illuminating cues compared to audio signals. The results showed no significant difference between the two models, even though the audio robot performed slightly better regarding evacuation time and waiting time of the robot. A number of limitations were faced, including a small sample size and a number of implementation issues, that could have significantly influenced the results. For that improvements were worked out that can guide and enhance future research in this area. For example, future studies could consult experts of fire emergency situations, to determine how realistic the artificial environment is. It is also advisable to not only track the change of smoke emitted to the environment, but also the change of the sound level of the surroundings. On top of this, the change of the values for the smoke, as well as the surrounding sound should be adjusted, so that their increase will be more steadily. This will ensure a more balanced data set and prevent having maxed out data points for the majority of the time. Furthermore, a good addition to this study would be to add a third condition for the robot, combining both audio and visual cues. This could improve the understandability of the signals and facilitate the evacuation task for participants. Another interesting investigation could be to analyse how the behaviour of participants in this experiment would change, if not a single person, but a group of people were to be evacuated. Overall, the experiment was well organized, with minor deficits, that could be resolved in the future without greater effort. It was an effective step towards further investigating which communication styles of a robot are most helpful in fire emergency evacuation scenarios.

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Appendix A
Asset list

Asset	Link
City package	https://assetstore.unity.com/packages/3d/environments/urban/city-package-107224
Copier	https://www.cadnav.com/3d-models/model-20262.html
Couch	https://assetstore.unity.com/packages/3d/props/furniture/modern-minimalist-sofa-136398
Decoration plants	https://assetstore.unity.com/packages/3d/props/interior/yughues-free-decorative-plants-13283
Explosion sound 1	https://www.youtube.com/watch?v=KHkRrlr-EJU
Explosion sound 2	https://www.youtube.com/watch?v=KHkRrlr-EJU
Floor materials	https://assetstore.unity.com/packages/2d/textures-materials/floors/20-man-made-ground-materials-12835
Indoor Furniture	https://assetstore.unity.com/packages/3d/props/furniture/toon-furniture-88740
Keys for Introduction	https://assetstore.unity.com/packages/3d/props/furniture/key-and-lock-193317
Kitchen	https://assetstore.unity.com/packages/3d/props/electronics/kitchen-appliance-low-poly-180419 https://assetstore.unity.com/packages/3d/props/interior/kitchen-cabinets-low-poly-183890
Low rumble sound	https://www.youtube.com/watch?v=PFv71A9s8Cg
Office environment package	https://assetstore.unity.com/packages/3d/environments/snaps-prototype-office-137490
Office Furniture pack	https://assetstore.unity.com/packages/3d/props/furniture/office-room-furniture-70884#content
Outside crowd sound	https://www.youtube.com/watch?v=bKrrqrtxjOw
Particle Pack (Fire prefab & Smoke material)	https://assetstore.unity.com/packages/essentials/asset-packs/unity-particle-pack-5-x-73777
Plants	https://assetstore.unity.com/packages/3d/vegetation/plants/lowpoly-flowers-47083
Printer	https://assetstore.unity.com/packages/3d/props/electronics/printer-lowpoly-4996
Robot Sound	https://freesound.org/people/IanStarGem/sounds/341819/
SciFi Office Pack (incl. TV)	https://assetstore.unity.com/packages/3d/environments/sci-fi/free-sci-fi-office-pack-195067#content
Security Cam	https://assetstore.unity.com/packages/3d/props/electronics/free-pbr-security-camera-70061
Sink	https://assetstore.unity.com/packages/3d/props/interior/low-poly-sink-and-toilet-61018
Stopping car sound	https://www.youtube.com/watch?v=VcgpOYvKEu8
Telephone	https://www.cgtrader.com/free-3d-models/electronics/phone/cisco-phone-cp-6941
Toilet	https://assetstore.unity.com/packages/3d/characters/vr-ready-pbr-toilet-116576
Toilet paper	https://assetstore.unity.com/packages/3d/props/toilet-paper-roll-proto-series-165615
Trashbin	https://assetstore.unity.com/packages/3d/props/furniture/trash-bin-96670
Wall paintings	https://assetstore.unity.com/packages/3d/props/interior/picture-frames-with-photos-106907

Appendix B
Additional Web links

Reference	Link
GitLab Repository and Git Workflows	https://gitlab.com/qrno98/HRI_RescueRobot
Experiment video	https://gitlab.com/qrno98/HRI_RescueRobot/-/blob/main/documentation/Video/30s_VisualBot_Clip.mp4? expanded=true&viewer=rich
Mural Board	https://app.mural.co/t/alluos3745/m/alluos3745/1636478724384/5dedf701358b9b54853362c2d1067ea1f7ed9e0c? sender=f8d86d54-b5f0-49ed-8a03-160f13caef54
Our complete data set (without outlier)	https://gitlab.com/qrno98/HRI_RescueRobot/-/tree/main/experiment_data

Appendix C
Briefing

BRIEFING (read word for word)

Welcome and thank you for participating in our experiment. It is part of this winter's "Human Robot Interaction" course and researches Behavior in stressful situations. Expect a stressful situation, but be aware, that you are not in danger at any point of the experiment. Your participation is entirely voluntary, and you can stop at any moment without giving any reason. After putting on the VR headset, you will find yourself inside an office building. You can look around by moving your head and move by using the touchpad to move forward. To turn left or right, please turn your body on your seat. Feel free to try navigating until you feel comfortable, and to ask us/me if you have any questions.
Your first task is to search the rooms for a green key. Once you find the key, you can use it to open the green door to access the rest of the building. Please be aware that after opening the door the experiment will begin and we/I won't be able to answer questions anymore.
During the experiment we would like to ask you to act as natural as possible. There is no right or wrong behavior, just follow your intuition and act as you would in a real situation.

____
Participants Name

Appendix D
Debriefing

DEBRIEFING (cover the points as fit, not necessarily word for word)

- Our objective is to find out how a robot might help in an evacuation event.
- Our robot comes in two variations: One emits a blinking light, the other makes a sound. (Yours was the ___ type.) We want to find out which style is more helpful in guiding people out of the building.
- We measured how long it took until you made it out of the building, and how close you stayed to the robot during the escape.
- Thanks again, hope you had fun :)
- Questions?