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Perception in Remote Navigation

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Perception in remote navigation

by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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2013

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ACKNOWLEDGMENTS

I would like to take this opportunity to express my thanks to those who helped me with various aspects of conducting research and the writing of this dissertation.

First and foremost, I want to express gratitude to my family, my Dad Lin Zhong and Mom Lin Chen, for their unending support and love. They not only gave me precious advices on my academic life, they inspired my interest on the field of engineering and my love of learning new things. More importantly, they constantly encouraged me to face and solve any difficulties I encountered.

I am also grateful for Dr. Richard T. Stone's guidance, patience and support throughout this research and the writing of this dissertation. His insights and words of encouragement have often inspired me and renewed my hopes for completing my graduate education.

I would also like to thank my committee members for their efforts and contributions to this work: Dr. Stephen Gilbert, Dr. Frank Peters, Dr. Stephen Vardeman, and Dr. Johnny Wong.

I would additionally like to thank my friends who accompanied me along this journey.

ABSTRACT

This dissertation focus on the enhancement of human-robot collaborated remote navigation performance, specifically from the perception perspective. Three independent factors in the navigation-related perception were studied respectively, and enhancements for each of the factors were proposed, implemented and evaluated.

To study the nature of remote navigation, an extensive analysis of nature of navigation as well as difficulties in remote navigation were conducted. Basing on the understanding of remote navigation, scale perception (perception of the controlled vehicle's size relative to other object's size), distance perception (perception of distance between two objects), and orientation awareness (the awareness of current location, moving direction, and object's location relative to current location) were identified as critical factors. For the distance and scaler perception, two experiments were designed specifically for each of them to quantify the remote perception condition's impact. It was found that under a remote perception condition, where human operator was separated from the environment where the navigation took place, both distance perception and scale perception were significantly impaired as compared with that obtained under a direct perception condition. Moreover, robust ways to enhance each of these three factors were also proposed and scientifically verified.This study successfully proved that with each specifically designed enhancement, the corresponding factor was significantly improved.

Result of this dissertation work can be applied to various human-robot collaborated applications, such as urban search and rescue. With an integration of the three enhancement, human operators will have less failure in driving robot through hallways, doors or getting around obstacles, as well as have a more accurate understanding of the area's layout when a map is not available.

CHAPTER 1. INTRODUCTION

This chapter is an introduction to the research field and an overview of the research problem. Detail will be discussed in the following chapters.

1.1   Overview of Human-Robot Collaborated Exploration

Human-Robot interaction is a broad area, from fine motion manipulation to search and rescue or sole exploration (e.g., outer space exploration). The automation level also varies a great deal, from manually controlled by human operator, to semi-automation which takes both human and autonomous control as input, and finally full automation which requires no human input at all. Figure 1.1 illustrates a typical setting for the human-robot collaboration. Human is provided with an interface displaying video/image of the remote environment as well as other possible information, and controls the robot via a joystick (or other types of device). The robot actually travels around in the environment and send back video/image along with other information to the interface.

Figure 1.1   Example of a Typical Human-Robot Collaboration Application Setting

Among all kinds of application areas, navigation or partial-navigation (when the robot is traveling autonomously or semi-autonomously, human operator needs to observe the environment and gain awareness of surrounding environment as well as traveling status including orientation, which is still part of navigation task) is a basic task for accomplishing the system goal. Navigation is the process or activity of accurately ascertaining one's position, planning and following a route. It consists of locomotion and wayfinding (Darken and Peterson (2001); Montello and Sas (2006)). Locomotion refers to the task-execution part, while wayfinding defines the task-planning part which is goal-directed. Figure 1.2 demonstrates a brief decomposition of the task. The human operator is responsible for perceiving and understanding the situation, forming decision about the next (several) step(s) basing on what is comprehended, and putting the plan into execution.
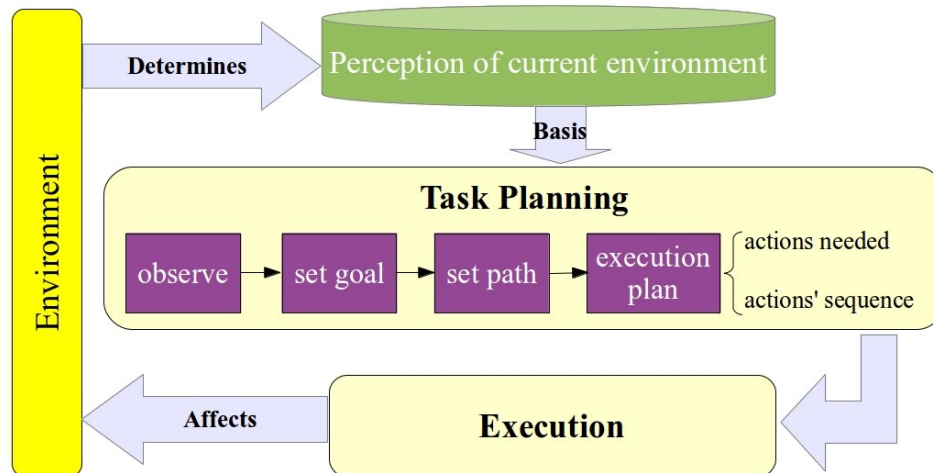
Figure 1.2   Task Analysis of Navigation

According to Wiener, Buchner, and Holscher (2009), wayfinding can be categorized into different groups according to the system goal and availabilities of different resources as follows: 1) wayfinding aid; 2) destination's existence; 3) destination knowledge; 4) route knowledge; and 5) survey knowledge (familiarity with the environment). Tasks differ among categories, resulting in different requirement for task planning and information needed.

Considering the navigation issues in human-robot collaborated exploration, the wayfinding

part of navigation in such scenario is scoped as "uniformed search" from the taxonomy proposed by Wiener, et al. (2009), which is a goal-directed search in an unfamiliar environment. This is very common among human-robot collaborated exploration applications, such as military reconnaissance, and urban search and rescue. In these applications, the system's goal is to identify and localize certain targets, which can be victims, potential dangerous objects, enemies and so on, in an unfamiliar/unknown environment. Tasks in such applications include 1) exploring the environment, 2) searching for targets, 3) localizing targets, and most likely 4) mapping out the environment. Taking the search and rescue task at world trade center as example (Casper and Murphy (2003)), robots were sent to the area and controlled by operators to finish the search and rescue task. Human operators and robots mainly collaborated on the search/exploration task. In that application, robots sent back video as well as other information of the environment from cameras and other sensors mounted on them for human operators to perceive what was going on at the remote end. Basing on what was perceived and comprehended, human operators navigated the robot from place to place, looking for targets and victims, figuring out paths to get there, as well as learning the situation around places of interest.

Communication between the robot and the human operator, especially the information sent from robots to human operator is critical to the systems success. As can be explained from figure 1.2, being the input for task planning, perception of the remote environment affects the goal, path, and execution plan including actions needed and their sequence. According to Casper and Murphy (2003)'s report, a lack of information about the state of a robot and that of the world, as well as what had been seen, accounted for the degraded performance. In an observational study by Riley and Endsley (2004) on situation awareness in human-robot collaborated exploration, it was found that awareness of robot's location and heading direction during exploration was a major problem; other problems such as lacking support for visually demanding task and robot's status (for example if it got stuck) were also identified.

1.2 Perception in Remote Navigation

A particular type of perception, which is called "remote perception", arises in the remote navigation scenario. The remote perception refers to the perception gained through any kinds of media when the observer is away from the environment being observed. The most common kinds of media are image and video stream. Due to the nature of such type of perception, difficulties that do not exist in direct perception condition are brought up, such as degraded image quality, limited field of view (FOV), different point of view (POV), lack of reference, and so on. All these problems affect the understanding of the environment, leading to degraded performance in remote navigation (Chen, Hass, and Barnes (2007); Witmer and Sadowski (1998); Van Erp and Padmos (2003)). On the other hand, even in a direct navigation task, perception is still critical. Orientation awareness, being the awareness of current location, moving direction and objects location relative to current location, is crucial (Montello and Sas(2006); Riley and Endsley (2004); Ishikawa, Fujiwara, Imai, and Okabe (2008)).

In order to develop a thorough understanding about perception in remote navigation, factors from both aspects need studied. Specifically, this dissertation investigated three factors: 1) distance perception, 2) scale perception, and 3) orientation awareness.

1.2.1 Distance Perception

Distance perception is the judgment of an object's distance from current location or distance between any two objects. This is important in navigating a robot (especially regarding the movement plan considering time and speed), locating targets during exploration, and even shooting in particular cases. Studies on virtual environments (VE) point out that observers are less accurate in estimating distance in VE than in real world (Witmer and Kline (1997)). Wrigt (1995) reported an underestimate rate ranging from 28% to 59% in VE. No study on remote perception has been conducted so far. Nevertheless, considering the fact that limited FOV and impoverished binocular vision in remote perception, distance perception is hypothesized to be affected similarly as that in VE. According to Chen, Hass, and Barnes (2007)), because of the degraded depth perception, which is caused by the monocular views and affected by

environment's apparent size cues, can also affect distance perception.

1.2.2   Scale Perception

Scale perception, being the judgment of size of objects relative to one's own size or the controlled vehicle's size (width, length or height), is most crucial when determining whether one is able to pass a door or get around an obstacle or not. In remote perception, a phenomenon of mis-estimating the scale/size of objects called "scale ambiguity" arises. This may lead to failure in passing through doors or over obstacles thus results in collision. In direct perception, s human has a strong sense of the relationship between his/her own body size and movement and other objects within view (Bruce and Green (1990)); however, in remote perception, such sense is impoverished. Number of cameras and the location of camera on robot can be two direct factors that lead to different level of scale ambiguity. As is the case with distance perception, this is also affected by the degraded depth perception in remote perception.

1.2.3   Orientation Awareness

Considering situation awareness in navigation task, knowing the current location, objects' locations relative to current location and moving direction is crucial. Montello and Sas (2006) did an analysis on human factors issues of wayfinding, according to which orientation awareness is the fundamental information requirement for wayfinding performance, and this is in accordance with what Riley and Endsley (2004) found in an observational study. Disorientation, or the so-called experience of "getting lost", occurs in both direct and remote perception circumstances. However, it is even harder to maintain spatial orientation under remote perception situation, making performance worse. This is a challenging problem as stated by Chadwick and Pazuchanics (2007). They found that even with navigation aids, such as global positioning receivers, gaining information about environment and object within view remained a problem. Disorientation is also a problem in endoscopic surgery, and"getting lost is a common experience for endoscopists" (Cao and Milgram (2000)) in terms of not knowing the current location as well as moving direction.

1.3 Objective and Research Questions

As perception of environment is critical to the success of navigation activity, understanding the impact of remote nature on it as well as enhancing it become a necessity. This research aimed at filling the gaps in the knowledge of perception of distance, scale and orientation, and also designing enhancement for each of these factors. It attempted to answer the following two questions through scientific studies from a human factor's perspective:

1. How are distance perception and scale perception affected by the remote nature quantitatively?

2. How to effectively enhance each factor?

More specifically, this dissertation work studied

1. Remote nature's impact on:

   (a) Distance perception in terms of distortion and distortion rate, and

   (b) Scale perception in terms of accuracy of judgment on whether the controlled vehicle would be able to fit through a given door or not

2. Effectiveness of:

   (a) Enhancing the distance perception by pre-distorting the displayed image

   (b) Enhancing the scale perception by providing dimension cue in the remote environment

   (c) Enhancing the orientation awareness by providing a real-time route map

1.4 Dissertation Organization

This dissertation studied three important factors perception in remote navigation: 1) distance perception, 2) scale perception, and 3) orientation awareness individually. For each factor, an individual experiment was designed and conducted to study how perception was affected

in remote navigation condition and enhancement for that particular factor was proposed and evaluated. Each study resulted in an individual journal paper, thus this dissertation follows the journal paper format and consists of these journal papers (either in preparation or submitted), with each paper presented the research on one of the three factors, followed by a general conclusion chapter summarizing all the dissertation work.

CHAPTER 2. DISTANCE PERCEPTION AND ENHANCEMENT IN REMOTE NAVIGATION

A paper submitted to *Human Factors*

Peihan Zhong and Richard T. Stone

Abstract

The objective of this study was to: (1) investigate how distance perception is affected under remote navigation conditions, and (2) design an interface to compensate for the distortion. In human-robot collaborated navigation applications, a human's perception of the surrounding environment is critical. Distance perception, referring to the understanding of distance between objects/targets and self-location is important for navigating a robot toward certain destinations. Two experiments were conducted, with the first one quantitatively assessing the distortion of distance perception under direct perception conditions as well as that under remote perception conditions. An enhancement was proposed based on the finding in the first experiment. An evaluation of this enhancement was then conducted. To obtain the distance perception, "blindwalking" method, in which participants were required to view a distant object first and then drive an remotely-controlled car (RC-car) to travel the same distance as perceived, was adopted. The distance perception in remote navigation was found to be significantly worse than that in direct navigation conditions. While human subjects underestimated distances for both conditions, the underestimation was significantly greater in remote navigation conditions. This study also proposed an enhancement that compensates for distortion by using a distorted display. It was proven that with such display, distance perception was significantly enhanced. The distance perception was significantly affected by perception type, and

with a distorted display it could be enhanced. The finding can be applied in interface design in human-robot interaction applications to enhance human operator's distance perception of the remote environment.

2.1 Introduction

2.1.1 Distance Perception

Remote navigation is a common task among human-robot collaborated exploration applications. It refers to when a robot travels within a physical environment while a human operator navigates the robot or simply supervises it at the remote end. In such applications, human operators are separated from the environment, and the only way to gain awareness of the environment is through image or video sent back from cameras mounted on the robot.

Level of automation (LOA) can vary from manually controlled by a human operator to full automation where a robot performs a task entirely autonomously without (or requiring little) human operator intervention. In most applications, the LOA of human-robot collaborated exploration is characterized as either a manually controlled condition where a human operator must manipulate the robot for every move, or a semi-automated condition where the robot can autonomously complete a movement according to the human operator's direction by inputting commands (Chen (2010); Casper and Murphy (2003); Fong, Thorpe and Baur (2003); etc.). In such applications, remote perception and remote manipulation are the two main categories for human performance issues (Chen, Hass, Pillaliamarri and Jacobson (2006)). Remote perception is the perception obtained through images/videos of the remote environment. Limited field of view (FOV), unnatural point of view (POV), degraded image quality, and impoverished interaction with the environment all lead to difficulty with such kinds of perception.

As part of the perception of environment, the judgment of distance between objects or between a current location and a certain object is important in remote navigation, as it affects action planning: before taking action, an operator needs to know how far it is from point A to point B to estimate how long it will take to get from A to B. This kind of perception is particularly important when the time lag between an operation and an action is significant.

Accurate distance perception can lead to a more effective action plan, saving time that might be wasted on correcting motion due to underestimating or overestimating distance, and also results in safer operations because a robot is less likely to run into obstacles or even human victims (e.g., search and rescue applications).

Theoretically, distance perception, being part of the depth perception, is affected by a limited FOV, an unnatural POV, and impoverished binocular vision. According to Thomas and Wickens (2000), projecting a 3-dimensional (3D) scene onto a 2-dimensional (2D) display results in compression of distance information, which is more severe with ground robots because of the lower viewpoint as compared with human adult's natural viewpoint. According to Witmer and Sadowski (1998), distance perception in a VE is significantly degraded as compared to that in real world condition. Participants were found to underestimate distances from 28% to 59% in VE, while the underestimation was 2% to 8% in real-world condition (Witmer and Sadowski, 1998). Similar conclusions are found in studies by Messing and Durgin (2005); Sinai, Krebs, Darken, Rowland, and McCarley (1999); Willemsen and Gooch (2002), etc. However, Interrante, Ries and Anderson (2002) had a different conclusion. They tested distance perception in a high fidelity, low latency, immersive virtual environment, and found that distance perception was not significantly compressed relative to that in the real world. The difference between this study and previous studies lies in the perception condition: the VE in this study was highly immersive, and consequently, binocular vision was greatly maintained. Moreover, each participant stood right in the environment and viewed everything from his/her eye through a pair of glasses; therefore the interaction between people and environment was also maintained. Understanding this, it can be inferred that these findings actually support the hypothesis that in remote navigation, distance perception might be negatively affected because of the impoverished binocular vision and lack of interaction with the environment in remote perception conditions.

2.1.2 Distance Perception Enhancement

Given the possible reality of distance underestimation with remote perception, how to enhance it becomes a concern. Restoring binocular vision by providing 3D vision can be one

possible way. Drawbacks with such an approach lie in the feasibility issues and cost. Because of the difference between perception in a virtual environment and perception in a remote environment, it might not be feasible for most of the human-robot collaborated exploration applications, such as urban search and rescue, as this technology can currently only be implemented in a laboratory environment and requires extensive equipment (for example, multiple cameras) that might not function properly in outdoor environment. Moreover, whether a high fidelity display enhances distance perception remains unclear. Interrante et al. (2002) proved that distance perception was improved in a high fidelity, low latency, and immersive virtual environment while Wright (1995) as well as Witmer and Kline (1997) did not find an impact of virtual environment display devices on distance perception.

As discussed above, providing advanced equipment might be useful for enhancing the distance perception, but due to the complexity of environment, it might not be even feasible to implement. Considering the most common environment for human-robot collaborated applications, which is usually ruins or destroyed buildings, the structures are very complex. It is thus difficult to provide equipments such as multiple cameras and so on. Moreover, with in-door environment providing an exocentric view from unmanned aerial vehicles is of great difficulty. Therefore it is of great importance to enhance the distance perception under the most common yet simple equipment setting. This study thus looks for approaches to compensate for distorted display given the constraints of a single camera mounted on the robot and a 2D display.

2.1.3   Research Question and Hypothesis

While most of the previous studies only investigated distance perception in a VE, considering the difference between a VE and a remote environment, there is a need for exploring how distance perception is affected by remote perception. This study examines the degree of distortion of distance perception in remote navigation conditions, as well as gaining enhancement insight. Specifically, it is hypothesized that distance perception is significantly degraded in remote navigation as compared to direct navigation conditions.

2.2   Distance Perception Evaluation

2.2.1   Methodology

Participants.   Thirty-four Iowa State University (ISU) students participated in this study, all of whom were from engineering majors. They were randomly assigned to one of the perception types in this experiment: direct perception group or remote perception group.

Independent Variables.   This experiment was a 2 by 4 design. There were two independent variables:

1. Perception Type: this is a between-subject variable, with 2 levels: 1) direct perception and 2) remote perception. Participants were evenly assigned to each perception type randomly (direct perception group or remote perception group).

2. Target Distance: this is a within-subject variable, with 4 levels: 5 ft., 10 ft., 15 ft., and 20 ft. Five trials were required for each distance, resulting in 20 trials in total. The order of the trials was randomized for each participant.

Dependent Variables.   The dependent variable in this experiment was distance perception, measured by

1. Distortion: calculated as (traveled distance - true distance), being the absolute value of distortion in distance.

2. Average Distortion Rate: calculated as (distortion / true distance), being the percentage of distortion over true distance.

3. Average Variation of Distortion: this is the variation among four trials for each participant at each distance, reflecting the stability of performance at each distance. It was calculated as the standard deviation among the traveled distance at each of the 5 trials of the same distance.

Distance Perception Assessment. Blindwalking has been proved to be a reliable method for assessing a person's distance perception (Witmer and Sadowski, 1998; Elliott, 1987; etc.). This method requires that a person first observe a distant object for a certain period of time, and then walk the same distance as is between the person and the object with his/her eyes closed. This method results in more accurate distance perception as compared with a verbal report of the perceived distance. This experiment utilized blindwalking for distance perception assessment.

Experimental Setting and Procedure. The experiment took place in a lab in the Black Engineering building on ISU campus. A remotely-controlled (RC) car was used as the "robot" in this experiment. A camera was mounted on the RC car which sent video of the remote environment back to the human operator, who was sitting in front of a laptop. A target was created as the "distant object", in this experiment, two white boards were set up to form a door through which the RC car was to be driven through to complete the task, as can be seen in figure 2.1.

Participants were asked about their gaming experience and frequency of use before they participated in the experiment. Each participant's stereo vision was also tested. Prior to the experiment, participants were given 10 minutes of driving practice under the assigned condition, and instructed to get a general sense of car speed. Upon completion of the driving practice, the required task was explained to participants: that they should look at the target for 5 seconds, perceive the distance between the car and the target, turn around (or turn off the screen), and drive the car for the same distance as from the car to the target. Followed by this instruction, participants were given two practice trials to ensure that they were familiar with the task. During the experiment, each participant went through 20 trials, with the target being placed at four different distances, and with five repetitions per distance. The order of trials was randomized. There was no feedback about how they performed after each trial to eliminate a learning effect.

Figure 2.1   Experimental Setting: Screenshot of video provided to the participant in remote perception group

Data Analysis.   This experiment was a mixed design; therefore, a split-plot ANOVA was used for data analysis. During the experiment, two participants (one in each group) were found to be outliers: one participant in the direct perception group had a priori knowledge about the experimental procedure, and intentionally measured distance by counting seconds when controlling the RC car; one participant in the remote perception group accidentally obtained audio feedback during the experiment (the sound of the RC car hitting a door). Therefore, only data for the remaining 32 participants were included in the data analysis.

2.2.2   Result

Performance.   Distortion (calculated as true distance minus traveled distance), distortion rate (the percentage of distortion over true distance), and variation of distortion (the standard deviation among five trials for each distance) were calculated from raw data for analysis.

Root mean squares were calculated to get an average of five trials for each distance. To analyze the effect of perception type and target distance, ANOVA was used. Results are summarized in table 2.1. Note that the p-value listed in the table is the adjusted p with Tukey adjustment.

Table 2.1   Summary of ANOVA results for Each Item

Effect	F Value	Adj P
Distortion		
Perception Type	$F(1, 30) = 6.25$	0.0181*
Distance	$F(3, 90) = 258.92$	$< .0001*$
Type * Distance	$F(3, 90) = 4.20$	0.0078*
Distortion Rate		
Perception Type	$F(1, 30) = 6.10$	0.0194*
Distance	$F(3, 90) = 36.57$	$< .0001*$
Type * Distance	$F(3, 90) = 0.45$	0.7180
Variation		
Perception Type	$F(1, 30) = 0$	0.9503
Distance	$F(3, 90) = 37.62$	$< .0001*$
Type * Distance	$F(3, 90) = 0.76$	0.5217

Distortion. Significant effects of perception type and distance, as well as their interaction were found. The interaction is demonstrated by figure 2.2. As distance increased, the distortion went up. Moreover, the difference of distortion between the direct perception group and remote perception group also increased. A further test with Tukey adjustment was employed to test the simple main effect of perception type at each distance and the simple main effect of distance at each perception type. It was revealed that at a distance of 20 feet, perception type had a significant impact on distortion (p-value = 0.0111).

The 95% confidence interval revealed that the distortion with direct perception was 4.34 feet to 1.29 feet less than that with remote perception. For each perception type, the distortions at every pair of distances were significantly different with a p-value < 0.0001.

Distortion Rate. Main effects of perception type and distance were found. The mean distortion rate by the direct perception group was 41.05% while that by the remote perception group was 53.78%. The distance distortion with direct perception was 22.83% to 2.63% lower
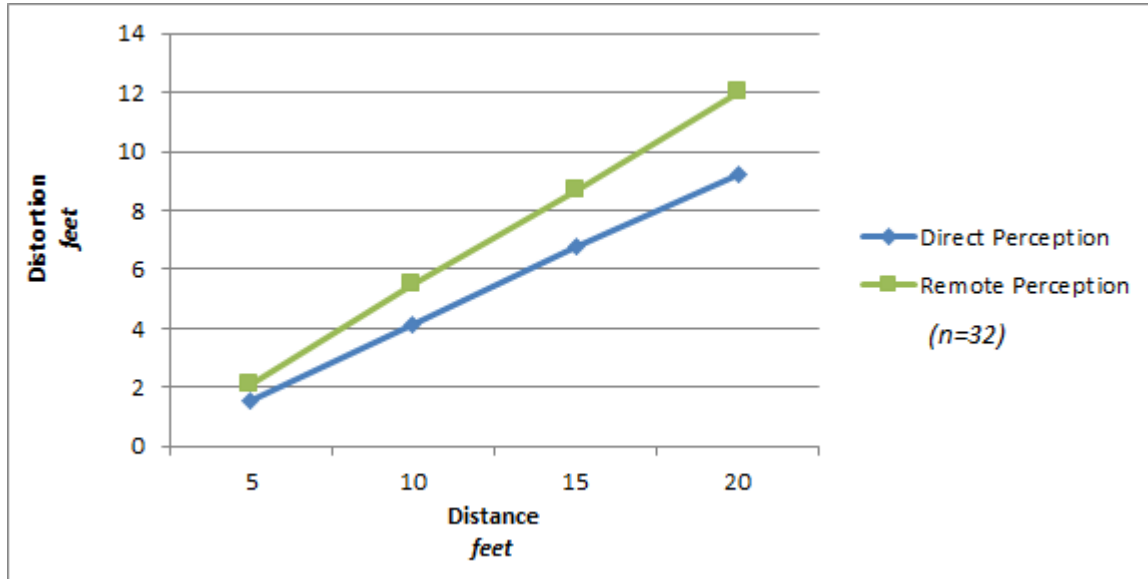
Figure 2.2   Distortion: Interaction between Perception Type and Distance

than that with remote perception within a 95% confidence interval. Figure 2.3 shows the distance's impact on distortion rate. It was revealed by furthering test with Tukey adjustment that the distortion rate at a distance of 5 feet was significantly different from that at any other distance, and a significant difference occurred between 10 feet and 20 feet. The results of the pairwise comparison are summarized in table 2.2.

Table 2.2   Pairwise Comparision between Distances for Distortion Rate

Pair *(feet)*	t Value	Adj P	Lower 95% CI	Upper 95% CI
5 - 10	-2.34	$< .0001*$	-14.81%	-8.00%
5 - 15	-6.28	$< .0001*$	-18.34%	-11.52%
5 - 20	-9.83	$< .0001*$	-19.84%	-13.02%
10 - 20	-7.49	$0.0242*$	-8.44%	-1.63%

Variation.   There was not a significant difference between variations at two perception types. Distance was found to be a significant factor, and its impact is depicted in figure 2.4. As distance increased, variation among five trials became greater and greater. A series of pairwise comparison between any two distance conditions revealed that there was a significant difference between every pair except for that between 5 feet and 10 feet. Results are summarized in table 2.3.
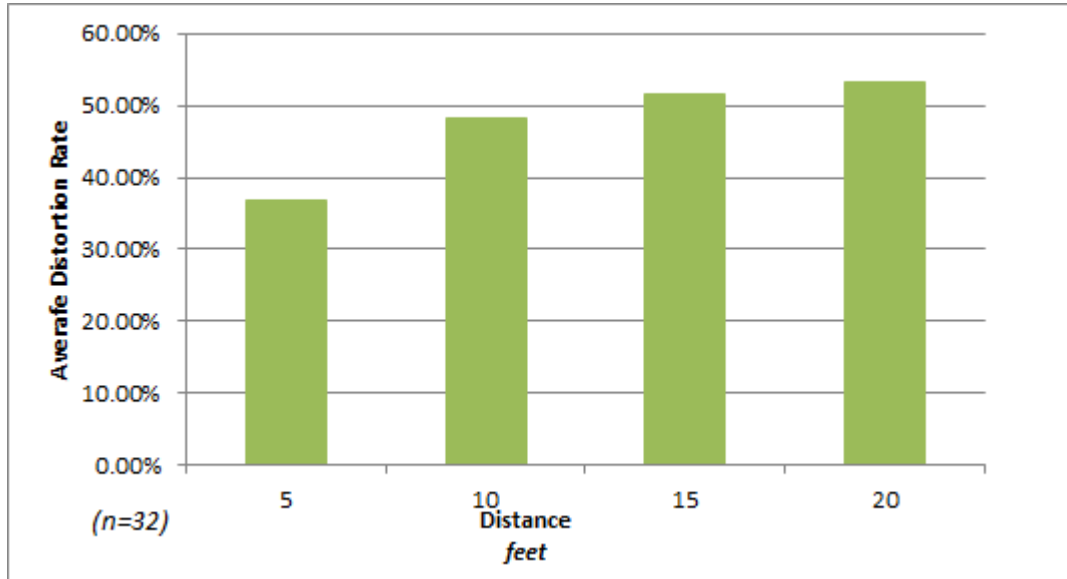
Figure 2.3   Average Distortion Rate: Significant Effect of Distance Found between 5 ft. and all other distance, and between 10 ft. and 20 ft.

Table 2.3   ANOVA results for Variation

Pair *(feet)*	t Value	Adj P	Lower 95% CI	Upper 95% CI
5 - 15	-6.28	$< .0001*$	-0.99	-0.52
5 - 20	-9.83	$< .0001*$	-1.42	-0.95
10 - 15	-3.93	$0.0009*$	-0.71	-0.23
10 - 20	-7.49	$< .0001*$	-1.14	-0.67
15- 20	-3.56	$0.0033*$	-0.66	-0.19

2.2.3   Discussion and Enhancement Insight

Findings.   Results of this study proved that distance perception was significantly affected by perception type, and that impact increases with distance. A significant impact of perception type on distortion and distortion rate was found, supporting the hypothesis and previous studies that investigated into the distance perception in real world environments and virtual environments (Elliot (1987); Witmer and Sadowski (1998)).

The direct perception result found in this study was different from previous ones in that both distortion and distortion rate were higher than previous findings (40% in this study while 2% to 8% in the studies by Elliot (1987); Witmer and Sadowski (1998)). To understand this difference, how this study differed from previous ones is explained. Compared with those
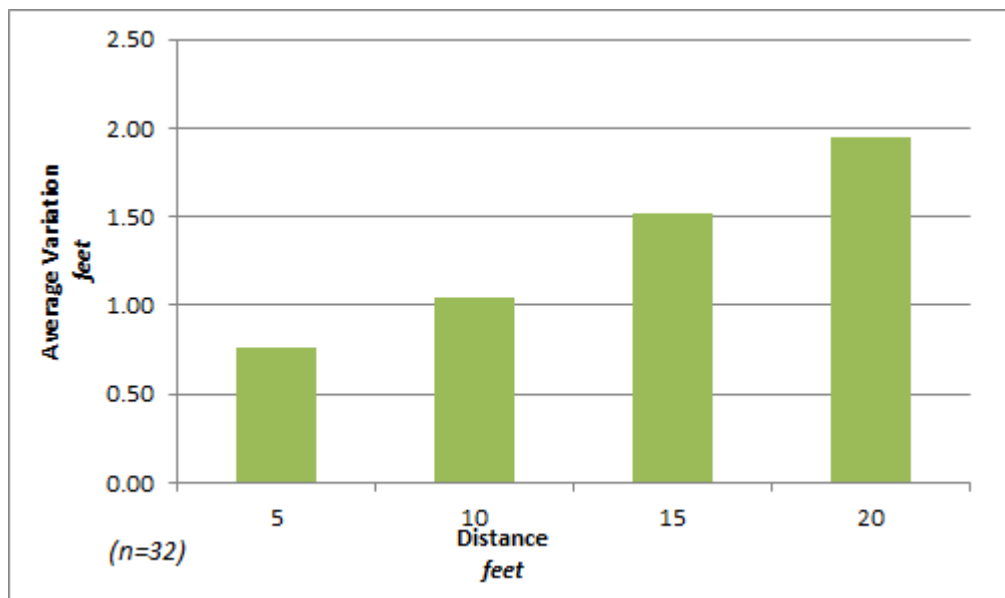
Figure 2.4   Avarage Variation among Five Trials Taken by Each Participant: Significant Effect
of Distance Found

studies, one significant difference is that in this experiment, participants were not walking the
distance themselves but driving an RC car instead. After the experiment, most participants
in both groups commented that they underestimated the car speed. The incorrect sense of
car speed can be a confounding factor, which possibly affected the direct perception result on
some level. However, since this factor existed for both groups, the impact was blocked when
comparing the two groups.

The variation increased with distance but was not significantly affected by the perception
type, which supported previous findings (Witmer and Sadowski (1998)). Being an indicator
of the stability of distance perception at each distance as it reveals the consistency among
repetitive trials, it is not surprising that as target distance increased, the judgment or perception
of distance varies more.

Enhancement Insight. Results of the distance perception experiment revealed that per-
ception type significantly affected distortion rate, and remote perception led to a roughly 50%
degradation of distance perception. In order to improve distance perception under a remote
perception condition, two directions can be considered: 1) restoring binocular vision, inter-

action with the environment or any other kind of information degraded in remote perception conditions; 2) enhancing display under the current hardware setting. As discussed before, due to the complexity and uncertainty of the surrounding environment, the first approach is costly and sometimes even infeasible, while the results of this experiment shed some light on the second approach: to utilize the distortion and provide a pre-distorted image to counterbalance the distortion to occur when an operator sees the image.

Before further elaborate this approach, three different "distance" terms are defined as follows: true distance refers the actual distance between robot and target, displayed distance refers to the distance displayed to operator, and perceived distance refers to the distance perceived by the operator after viewing the displayed distance. Assuming the distortion rate is stable at 50% as distance to target increases, it can be inferred that when the displayed distance is 10 feet, the perceived distance would be approximately 5 feet. Therefore, when the true distance is 5 feet, the distorted display provides an image of 10 feet (true distance); with 50% degradation, it can be expected that the perceived distance would be 5 feet, which is the true distance (as depicted in figure 2.5).
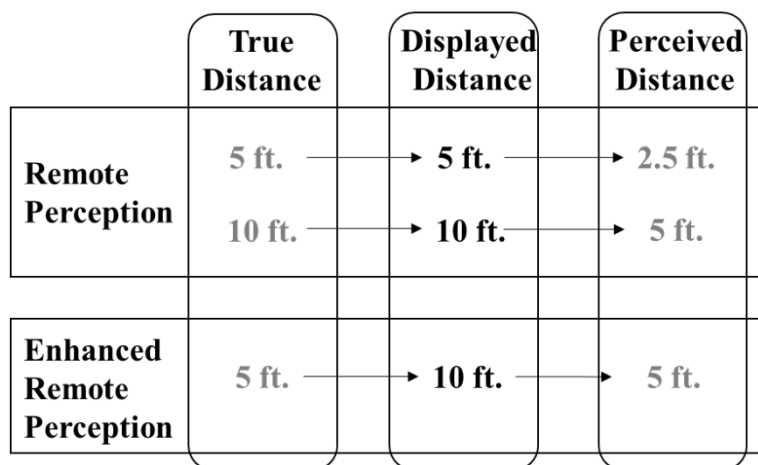
Figure 2.5   Diagram of Distance Perception Enhancement

2.3 Enhancement Evaluation

2.3.1 Hypothesis

A follow-up experiment verifying the effectiveness of the proposed enhancement was then designed. It was hypothesized that with a distorted display, a human's distance perception of a remote environment is significantly improved as compared to remote perception without such aid. It was further hypothesized that no significant difference exists between the distance perception gained through the distorted display and that gained through direct perception.

2.3.2 Distorted Display Implementation

A simplified design was implemented for the purpose of evaluating this enhancement idea. Considering the distortion rate result in previous experiment, it was approximately 50% when true distance was over 5 feet. Therefore, in this simplified design, the distortion rate was fixed to 50%. To implement the enhancement, for each true distance condition, a screenshot of the image provided by camera mounted on the RC car placed at two times of true distance to target was displayed to participants. In other words, when the true distance was 5 feet for example, the RC car was placed at 10 feet and a screenshot of the image was pre-recorded and provided to participants during experiment (figure 2.6, when the true distance was shown in the left, the picture at right was the one that displayed to the participants).

Figure 2.6   Distorted display with true distance being 5 feet (left: true distance; right: displayed distance)

2.3.3 Method

Sixteen Iowa State University students participated in this experiment, with all of them being assigned to the enhanced display group, where pre-distorted image was displayed. Data of this distorted display group was compared with the previous two groups.

The experimental design was exactly the same as the previous experiment. Independent variables were perception type at three levels and distance to target at four levels. For each distance, five trials were required. The dependent variable was distance perception, measured by distortion, distortion rate, and variation. Participants were required to look at an image for 5 seconds, and then drive the RC car to travel the same distance as it would be from the position shown on the image to the target without that visual information. A split-plot ANOVA was used for data analysis.

2.3.4 Result

Performance. Distortion, distortion rate, and variation of distortion were calculated from raw data for analysis, similar to distance perception experiment. Root mean squares were used to calculate an average of five trials for each distance. To analyze the effect of perception type and target distance, ANOVA was used. Results are summarized in table 2.4. Note that the p-value listed in the table is the adjusted p with Tukey adjustment.

Table 2.4   Summary of ANOVA results for Each Item

Effect	F Value	Adj P
Distortion		
Perception Type	$F(2, 45) = 9.43$	$< .0001*$
Distance	$F(3, 135) = 195.71$	$< .0001*$
Type * Distance	$F(6, 135) = 25.21$	$< .0001*$
Distortion Rate		
Perception Type	$F(2, 45) = 10.82$	$0.0001*$
Distance	$F(3, 135 = 0.88$	0.4534
Type * Distance	$F(6, 135) = 9.68$	$< .0001*$
Variation		
Perception Type	$F(2, 45) = 4.28$	$0.0199*$
Distance	$F(3, 135 = 32.10$	$< .0001*$
Type * Distance	$F(6, 135) = 1.34$	0.2440

Distortion. Significant effects of interaction between perception type and distance were found, which was demonstrated by figure 2.7. While distortion increased with the distance in the direct and remote perception group, the enhanced group showed a decreasing trend. Moreover, the difference of distortion among the three groups increased as distance increased.

A further test with Tukey adjustment was employed to test the simple main effect of type at each distance and the simple main effect of distance at each type. Significant results were summarized in table 2.5. For the direct and remote perception group, the distortions at every pair of distances were significantly different with a p-value < 0.0001, while for the enhanced display group, significant differences were only found between 5 feet and 15 feet (p = 0.0324) as well as 5 feet and 20 feet (p = 0.0062). No significance existed between any other pairs, indicating distortion tends to be stable as distance increases.
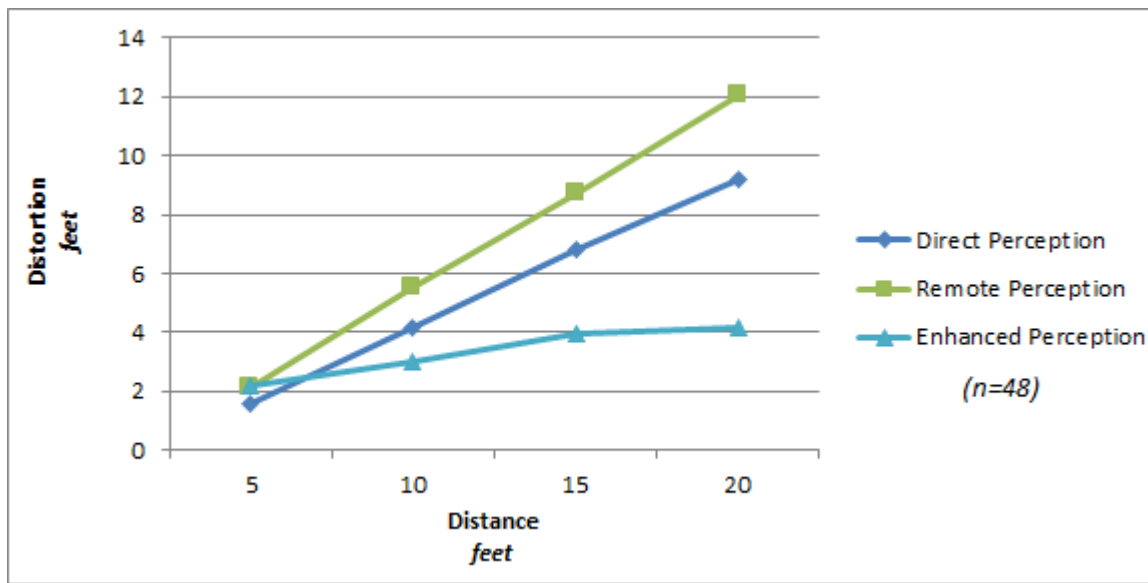
Figure 2.7   Distortion: Interaction between Perception Type and Distance

Distortion Rate. Interaction between perception type and distance was found, as depicted by Figure 2.8. It was revealed that the remote perception group and enhanced display group resulted in significantly different distortion rates at distances of 10 feet (p = 0.097), 15 feet (p = 0.0001), and 20 feet ($p < 0.0001$), while the direct perception group and enhanced display group were significantly different at 20 feet (p = 0.0069). For the direct perception

Table 2.5   ANOVA results for Simple Main Effect of Type at each Distance

Pair	Distance (feet)	t Value	Adj P	Lower 95% CI	Upper 95% CI
Direct - Remote	20	-3.81	0.0110*	-4.3	-1.4
Direct - Enhanced	15	3.86	0.0091*	1.4	4.3
	20	6.84	$< .0001*$	3.6	6.5
	10	3.33	0.0490*	1.0	3.9
Remote - Enhanced	15	6.48	$< .0001*$	3.3	6.2
	20	10.65	$< .0001*$	6.4	9.3

group, a pairwise comparison of each distance resulted in no significant difference; however, for
the remote perception group, distortion rates were significantly different between 5 feet and 15
feet (p = 0.0258), as well as between 5 feet and 20 feet (p = 0.0056). Similar results were found
in the enhanced display group: distortion rates were significantly different between 5 feet and
15 feet (p = 0.0073), as well as between 5 feet and 20 feet ($p < 0.0001$). However, as shown in
figure 2.8, the rate was increasing as distance increased in the remote perception group, while
decreasing as distance increased in the enhanced perception group.
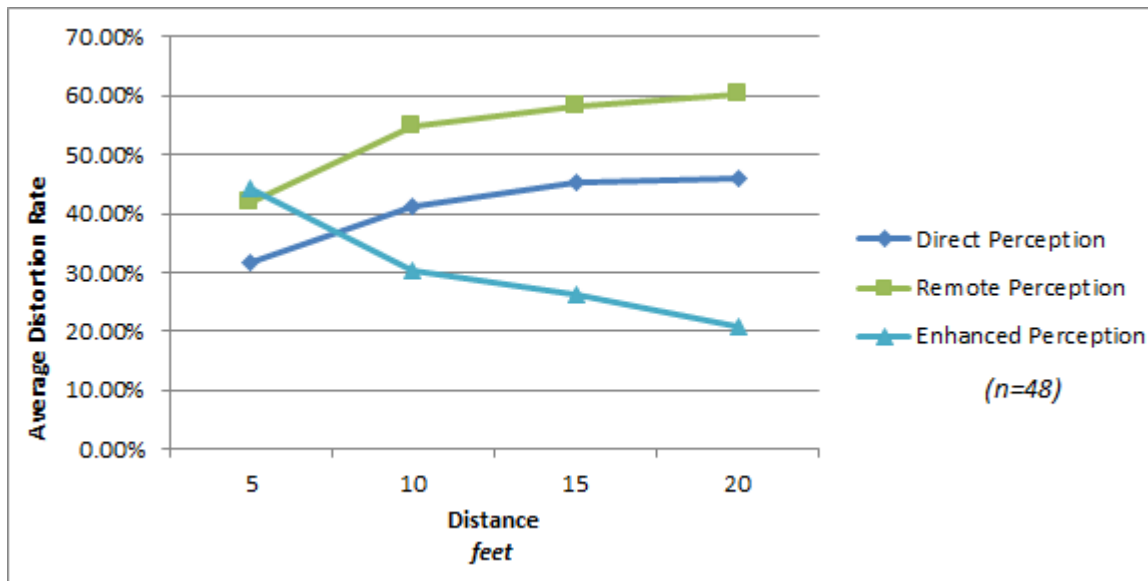
Figure 2.8   Distortion Rate: Interaction between Perception Type and Distance

Variation.   A significant difference was found for the variation among the three groups.

Post hoc analysis revealed that variation in the enhanced display group was significantly higher

than that in the direct perception group (p = 0.0414) or that in the remote perception group (p = 0.0363). Distance was also found to be a significant factor, and its impact is depicted in figure 2.9. It was revealed that between every pair, there is a significant difference with p-values < 0.0001 except for those between 5 feet and 10 and between 15 feet and 20 feet.
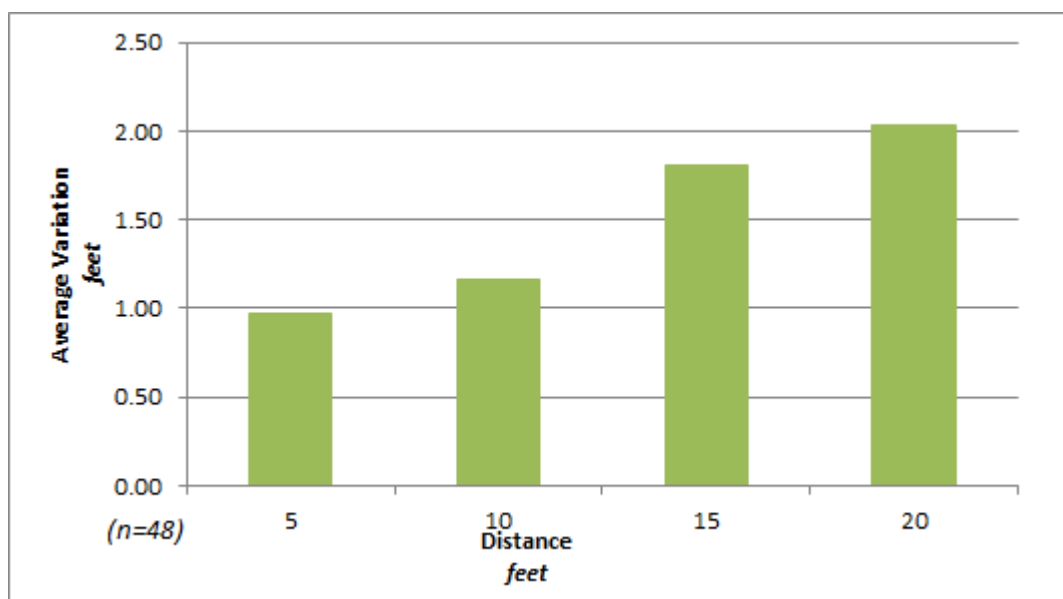
Figure 2.9   Average Variation among Five Trials Taken by Each Participant: Significant Effect of Distance Found

2.3.5   Discussion

Enhancement Evaluation.   With a distorted display, the trends of distortion as well as distortion rate were different from those with direct or remote perception. Distorted display resulted in significantly less distortion as compared to direct or remote perception (table 2.5 and figure 2.7). Moreover, the slope of distortion with distorted display was smaller than that of the other two conditions. In other words, the differences between distorted display group and the other two groups increased as distance to target increased. It was further proven that distorted display effectively reduced distortion rate by showing an opposite trend in the relationship between distortion rate and target distance as compared to the trends under direct or remote perception conditions (figure 2.8).

While a significant improvement was proven in the accuracy of distance perception, the

variation was also significantly affected by the distorted display. With such a display, participants had more variation among trials at each distance. This is understandable as distorted display actually provided an image of further displayed distance than the image provided in the remote perception group. Take the 5-feet distance condition as an example, the displayed distance in the enhanced group is actually 10 feet while that in the remote perception group is 5 feet. Considering the fact that variation goes up with the increase of target distance, which is proved in the first experiment as well as previous studies such as Witmer and Sadowski (1998), it is not surprising that those who look at 10 feet distance result in greater variation among trials.

Distplay Parameter. The parameter for distorted display implemented in this experiment (fixed at 50% distortion rate) as based on results from the distance perception. An underlying assumption for this fixed parameter is that the distortion increases linearly or closely to linearly (or in other words, the distortion rate remains constant or close to constant) with target distance. According to Witmer et al. (1998), the approximately linear relationship between distortion and target distance persists up to at least 100 feet. Since for remote navigation tasks, objects that are 100 feet or even further away may not even be clearly visible due to camera quality, and perceiving distance is not a main concern in such a situation, it is reasonable to take this assumption into design consideration.

However, the parameter might not be optimal, especially when the target distance is 5 feet in this study. From the distance perception experiment, while no interaction between distance and perception type was found, it was revealed that the distortion rate was numerically lower when the distance was 5 feet (35%) as compared to that obtained when the target was farther away. It suggests that the parameter should be adjusted to the target distance. A series of follow-up experiments should be carried out to determine a precise relationship between distortion rate and distance within 100 feet, and trade-offs should be made to determine the parameter.

2.4   Conclusion and Future Work

This study scientifically proved that distance perception is affected by remote perception: both distortion and distortion rate obtained through remote perception are significantly higher than those obtained through direct perception, while variation among trials at each distance is not affected by perception type. Moreover, this study proposed a new approach to compensate for the distortion by providing a distorted display. Its effectiveness in improving the distance perception in a remote perception condition has also been proven. This new enhancement approach can serve as a guideline for further enhancement, while a follow-up study on display parameters needs to be completed.

CHAPTER 3. SCALE PERCEPTION PROBLEM IN REMOTE NAVIGATION

A paper submitted to *Applied Ergonomics*

Peihan Zhong and Richard T. Stone

Abstract

In human-robot collaborated navigation, perception of object's dimension relative to the robot size is critical to determine whether the robot can fit through a door, or get around an obstacle or not. A wrong judgment might lead to collision. However, it is challenging for human operator to perceive at the remote end where he/she is not physically in the area where a navigation task takes place. This study quantitatively analyzed a remote perception condition's impact on scale perception, finding out that scale perception was significantly impaired by the remote perception conditions as compared with that gained under a direct perception condition. Moreover, in this study an enhancement that provides external dimension cue was proposed and evaluated. It was proven that with such cue scale perception could be significantly improved. The finding of this study can be applied to various remote operation applications in which perception of dimension is required, and there are multiple ways to provide the dimension cue, such as projecting the robot onto a door or hallway in distant where users plan to drive the robot so they are able to preview what is going to happen before they take action and evaluate their action plan.

3.1 Introduction

Wayfinding and locomotion are the two essential components in navigation (Montello and Sas (2006)). Being the task planning part, wayfinding includes knowing where to go (destination) and how to get there (path and motions/actions required to get there), while locomotion refers to the execution of this task plan. Since wayfinding is a cognitive process which forms an execution plan based on ones knowledge of the surrounding environment and oneself, "situation awareness" is critical to the success of wayfinding. Such kind of awareness includes perception of elements in current situation, comprehension of current situation and projection of future status (Endsley (1995)).

In remote navigation applications where human operator and remotely-controlled robot collaborate on a task, the human operator is usually responsible for wayfinding and controlling the robot's movement, while the robot travels around in the area where navigation takes place. Such applications are common in urban search and rescue, exploring outer space or any area that is dangerous or even impossible for human to get into. Since human operator can only gain knowledge about the environment from video along with other kinds of information (usually descriptive) provided by camera or sensors mounted on the robot, he/she cannot gain sufficient situation awareness, leading to the difficulties in wayfinding under remote navigation scenarios. According to Casper and Murphy (2003)'s report regarding the human-robot collaborated search and rescue at World Trade Center after September 11, the lack of information about state of a robot and the state of world, as well as what had been seen, led to the degraded performance. For example, failing to judge a door or hallway's width relative to the robot's dimension might lead to collision. Such judgments are related to scale perception, which refers to the perception of object's dimension as well as the awareness of self-dimension.

Scale perception is difficult in remote navigation applications due to the remote nature in several ways. In direct navigation an operator can observe environment directly from his/her own eyes and interact with the environment. In fact, the visual perception is constrained by action (Coello (2005), Gibson (1979)). Moreover, a human has a strong sense of self-dimension and accurate judgment when comparing the size of oneself with that of other objects. On one

hand, the wide field of view (FOV) and binocular vision enable human to gain and form a 3-dimentional (3D) image of the environment. As a human turns his/her head around or changes his/her position and observe the environment from a new angle/position, he/she can calibrate the image (maintained in his/her working memory) so it becomes more accurate. On the other hand, a human (specifically, an adult) has already had sufficient practice to calibrate his/her own sense of self-dimension throughout daily life, for example entering doors, getting through hallways, walking around obstacles, and so on, so it becomes an easy or even automatic task to perceive objects size relative to him/her own. Unfortunately, these characteristics no longer exist in the remote navigation scenario. The FOV (usually 90 degree) provided by camera is usually much narrower than human eye FOV (over 180 degree). This not only results in less visual information that can be gained, but also leads to a degraded depth perception in that it compresses objects to a smaller frame so they appear closer (Witmer and Sadowski (1998)) thus bigger than they actually are. Moreover, depth cues are further degraded as a result of representing the 3D environment in a 2-dimentional (2D) image (Chen, Hass, and Barnes (2007)). Since the interaction between operator and environment is broken (the video/image will not change as the operator turns around), it becomes difficult to calibrate the image built up in his/her working memory. Meanwhile, the sense of robot's dimension is also worse than the sense of self-dimension in at least two ways: 1) in an egocentric viewpoint where operator views the environment from a first person perspective, operator cannot see the robot so he/she has no idea about the dimension of robot; 2) calibrating the sense of robot dimension is different in that operator has to avoid mistakes (specifically, collisions) instead of learning from them.

Given all these constraints in a remote navigation scenario, how to enhance the scale perception under a remote perception condition become the next yet an important question. Among the studies on this problem, Tittle, Roesler and Woods (2002) proposed an enhancement that provides both egocentric and exocentric perspectives, but they did not evaluate its effectiveness. However, according to studies on evaluating the effect of providing both perspectives in human-robot collaborated search and rescue, integrating and processing information from both views "can be a challenging task" (Chadwick and Pazuchanics (2007)). Moore, Gomer, Pagano, and Moore (2009) did a quantitative analysis on scale perception under a remote per-

ception condition, and suggested providing operators with feedback about their performance. While feedback is an effective way for operators to calibrate their perception of scale in the remote environment, it takes a lot of training before the scale perception becomes accurate. Moreover, according to their result, scale perception was affected by robot's size and camera height. Therefore, scale perception is bound to a particular robot, which is to say, the trained scale perception is not transferable from one particular robot to another.

While the sense of self-dimension becomes hindered when remotely control a robot, providing external cues to indicate robot's dimension is one potential solution. Such cues can be obtained from laser pointers mounted on edges of a robot, or through augmented display that shows four virtual lines indicating robot's dimension. With such cues, the disadvantage of an operator being unfamiliar with the robot's dimension can be compensated for. What's more, since the cues are also in the remote environment and operator can only observe these cues from video/image, they are under the same frame of reference as all other objects viewed from video/image, making the cues and objects comparable.

The purpose of this study is to investigate perception types' impact on scale perception - the ability to perceive size of object relative to one's own size (or robot's size in remote navigation scenario). It is hypothesized that the accuracy of scale perception is significantly affected by perception type. It is also hypothesized that with external dimension cues the accuracy of scale perception under a remote perception condition can be significantly improved.

3.2   Method

3.2.1   Participants

Forty two participants were included in this experiment. They were all students from Iowa State University. They were randomly assigned to one of the three experimental groups in this study: direct perception group, remote perception group, or enhanced remote perception group.

3.2.2   Task

Taking the concept of scale perception – the judgment of object size relative to self-size into consideration, a task that presents operators with doors at various widths and requires them to estimate whether robot is able to fit through the door would be appropriate. This is also the task chosen by Moore et al.(2009) when they studied the perception of robot passability. Error rate of the judgment reflects the perceptions accuracy.

3.2.3   Independent Variable

The independent variables in this experiment were:

1. Perception type at 3 levels: Direct, Remote or Enhanced. The direct perception means participants can look at the car in the environment directly; the remote perception means participants have to observe the environment from image sent back from a camera mounted on the robot; the enhanced group was similar to the remote perception group with additional width cue provided by two red dots indicating robot's size. This is a between subject variable. Every participant was randomly assigned to one group.

2. Width of door at 5 levels: The widths of door were determined as ratio to the robot's width: 0.5, 0.75, 1.05, 1.25, and 1.5 times car width respectively. This is a within subject variable.

3. Distance to the door at 4 levels: The robot was placed at 5 feet, 10 feet, 15 feet, and 20 feet to the door. This is a within subject variable.

3.2.4   Dependent Variable and Measurement

The dependent variable in this experiment was the scale perception, measured by the accuracy of participant's judgment of whether the car would be able to fit through the door or not.

3.2.5 Experimental Setting

An RC car equipped with a wireless camera was used as a robot in this experiment. The door was constructed by using two foam boards. Figure 3.1 is the screenshot of one of the trials in this experiment. The picture on the left side shows the image viewed by participants in the remote perception group, while the picture on the right is the image viewed by participants in the enhanced group. Two red dots are provided to indicate the width of the RC car.

Figure 3.1   Example Screenshot of scale perception and distance perception: Remote Perception (Left) and Enhanced Remote Perception (Right)

3.2.6 Procedure

Prior to the experiment, each participant was given a 10-minute practice to drive the car (either by directly looking at it, or observing from screen, depending on which group he/she was assigned to) in order to become familiar with the car's mobility, and to gain a sense of the car's size relative to the environment. Upon the completion of the driving practice, participants were educated with the task and given two practice trial.

During the experiment, each participant had 20 trials at different combination of width and distance. They were required to look at the screen (if in remote perception group) or the door directly (if in direct perception group) for five seconds, and then response with their judgment.

3.3 Result

3.3.1 Overall Result

Scale perception accuracy was tested at different perception types, distances to door, and widths of the door (represented by the ratio of door width / RC car width) by 3-way ANOVA. Results were summarized in table 3.1. It was revealed that the effects of perception type, width of door, and interaction between type and width were significant. The interaction between type and width was demonstrated in figure 3.2.

Further tests with Tukey Kramer adjustment were employed to dig deeper. Main effects of perception and width respectively, simple main effect of width at different perception type, as well as simple main effect of type at each width were tested.
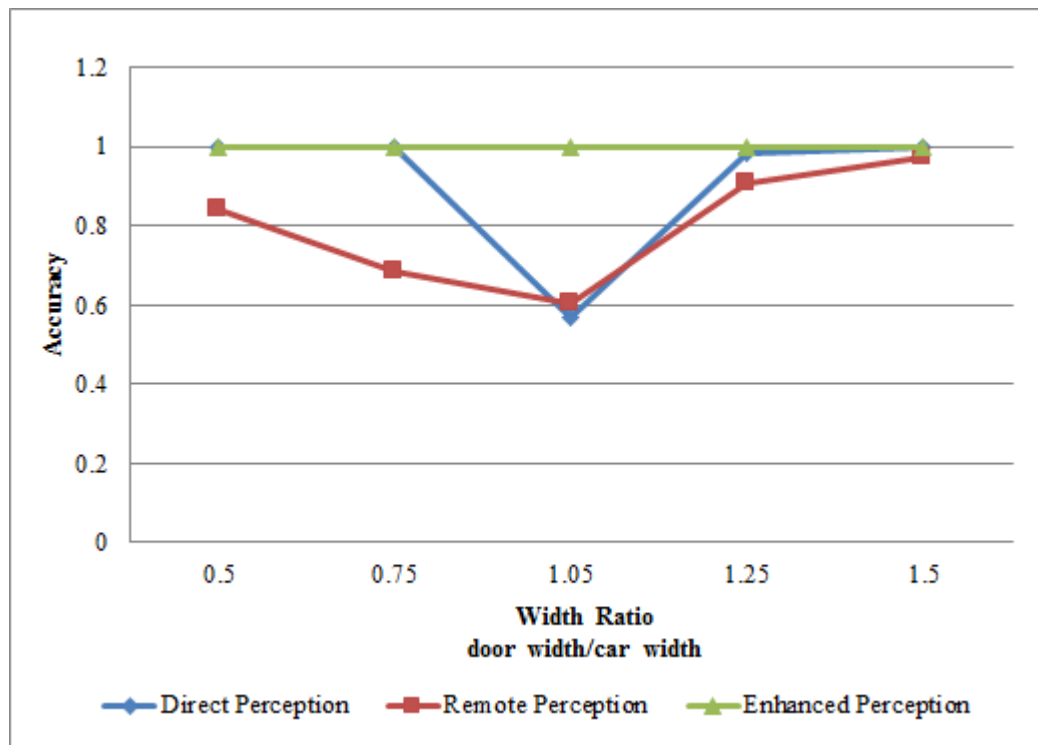

Figure 3.2 Interaction between perception type and door width

Table 3.1   Summary of ANOVA result

Effect	F Value	Adj P
Perception Type	$F(3, 39) = 21.16$	$< .0001*$
Distance	$F(3, 741) = 0.36$	0.7836
Type * Distance	$F(6, 741) = 0.49$	0.8166
Width	$F(4, 741) = 20.02$	$< .0001*$
Type * Width	$F(8, 741) = 7.59$	$< .0001*$
Distance * Width	$F(12, 741) = 0.25$	0.9953
Type * Distance * Width	$F(24, 741) = 0.63$	0.9133

3.3.2   Effect of Perception Type

Main effect and simple main effect of perception type were tested. It was found that with the enhanced remote perception group resulted in significantly more accurate scale perception over different widths of doors as compared to that of either direct or remote perception group. Remote perception led to significantly worse scale perception as compared to direct perception.

Pairwise comparison among pairs of widths between direct perception and remote perception group revealed that the significant difference was contributed by width ratio being 0.75, indicating when width of door is closer but smaller to car size judgment by direct perception was significantly more accurate than by remote perception.

Participants in the direct perception group gained significantly worse scale perception as compared with enhanced remote perception group when the ratio was 1.05, at which level the door width is very close to car size.

When comparing the enhanced remote perception group with the remote perception group, it was found that with an external dimension cue, scale perception was significantly improved when the ratio was 0.75 and 1.05. No significant improvement was found for the ratio being 0.5, 1.25 or 1.5 because the difference between door width and car size was great enough for user to recognize even under remote perception group, as can be seen from figure 3.2.

3.3.3   Effect of Width

Main effect of width ratio and simple main effect of width ratio at each perception were tested. It was found that when the door was only 0.5 inches wider than the car (ratio being 1.05),

accuracy of judgments was significantly worse than any other width. A significant difference was also found between width ratio being 0.75 and 1.5.

Further simple main effect tests revealed that for direct perception, significant difference only existed between ratio 1.05 and other ratios, while for remote perception, both 0.75 and 1.05 were significantly different from other ratios(except for the pair of 0.75 and 0.5). Taking the fact that no significant difference existed between 0.75 and 1.05 for the remote perception group (p = 0.8829), it can be inferred that with remote perception, the ability to distinguish between 0.75 and 1.05 was degraded. This thus indicated the threshold for people with direct perception to identify scale difference was lower than people with remote perception. No significant effect of width ratio at enhanced remote perception was found.

3.3.4 Scale Perception and Individual Differences

Correlation between judgment accuracy and previous video game experience, as well as between judgment and stereotest score were tested. No significance was found in either pair.

3.4 Discussion

The main finding verified Tittle et al. (2002)'s conclusion that remote perception leads to scale ambiguities. Prior to the experiment, participants were given a chance to observe the RC car and how the camera was placed, as well as a 10-minute navigation practice. This ensured that they were familiar with the remote vision and size of RC car as perceived from remote perception. Therefore, the possible reason of unfamiliar with remote control or RC car size can be eliminated. It thus can be concluded that it's the nature of perception type that leads to the difference.

Width of door played a significant role in scale perception, which is not surprising. When the width of door is far narrower or wider than car width, it would be obvious whether the car is able to fit through it or not. Difficulty increases as the difference between door width and car width becomes smaller. Result of this experiment revealed that under direct perception, a human is able to perceive the difference accurately when the ratio is 0.75, while it is not the case under remote perception.

This study proposed an enhancement, providing dimension cue, which was evaluated and proven to be effective. It managed to enhance the scale perception in two ways:

1. Transferring knowledge in the head to knowledge in the world (Norman (1998): In a traditional remote perception condition, users have to develop a cognitive representation of the robot being controlled in their head. When comparing the robot's size with doors or hallways, they actually compare a cognitive representation maintained in their memory system to what is seen in the environment. Memory of the robot's size might become vague or even distorted. However, a dimension cue in the environment releases the memorizing responsibility, as the robot's size is always visible. This also decreases mental workload in that less cognitive processing is required.

2. Placing the objects need compared into the same frame of reference: As discussed above, in a traditional remote perception condition, users compare object in their memory with object in the world. Since these two objects exist in different domain: one in a mental world and the other in the physical world, comparison between the two is not reliable (Goodale and Haffenden (1998)). With the dimension cue which is projected into the physical world, the two are under same frame of reference, making them directly comparable.

3.5 Conclusion and Future Work

This work quantitatively studied a remote perception condition's impact on scale perception, and provided an enhancement for the remote perception condition. Scale perception was significantly impaired by the remote perception conditions as compared with that gained under a direct perception condition. However, with external dimension cue, which in this study was provided by two red dots indicating RC car's width on the image, scale perception could be significantly improved.

The finding of this study can be applied to various remote operation applications in which perception of dimension is required, and there are multiple ways to provide the dimension cue, such as projecting the robot onto a door or hallway in distant where users plan to drive the

robot so they are able to preview what is going to happen before they take action and evaluate their action plan.

Regarding the suggestions for future work, the reason why scale perception under a remote perception condition is so difficult needs to be investigated. Moreover, this study only evaluated the scale perception in a relatively static environment; however, in real remote operation applications such as human-robot collaborated navigation, perceiving dimension is a subtask within the navigating activity. How dimension cue affects the overall navigation performance needs to be evaluated.

Table 3.2   ANOVA results for Perception Type

Main Effect of Type		
Pair	**t Value**	**Adj P**
Direct - Remote	4.11	0.0006∗
Direct - Enhanced	−2.72	0.0259∗
Remote - Enhanced	−6.19	< .0001∗
Direct Perception Remote Perception at each Width		
Width *door width / car width*	**t Value**	**Adj P**
0.5	2.76	0.1524
0.75	5.52	< .0001∗
1.05	−0.67	0.9996
1.25	1.29	0.9491
1.5	0.46	1.0000
Direct Perception Enhanced Perception at each Width		
Width *door width / car width*	**t Value**	**Adj P**
0.5	0	1.0000
0.75	0	1.0000
1.05	−6.66	< .0001∗
1.25	−0.26	1.0000
1.5	0	1.0000
Remote Perception Enhanced Perception at each Width		
Width *door width / car width*	**t Value**	**Adj P**
0.5	−2.52	0.4260
0.75	−5.04	< .0001∗
1.05	−6.30	< .0001∗
1.25	−1.47	1.0000
1.5	−0.42	0.9799

Table 3.3   ANOVA results for Width

Main Effect of Width		
Pair *door width / car width*	**t Value**	**Adj P**
1.05 - 0.5	-6.71	$< .0001*$
1.05 - 0.75	-5.13	$< .0001*$
1.05 - 1.25	-7.20	$< .0001*$
1.05 - 1.5	-8.02	$< .0001*$
0.75 - 1.5	-2.90	$0.0316*$
Simple Main Effect of Width at Direct Perception		
Width *door width / car width*	**t Value**	**Adj P**
1.05 - 0.5	-7.43	$< .0001*$
1.05 - 0.75	-8.30	$< .0001*$
1.05 - 1.25	-7.98	$< .0001*$
1.05 - 1.5	-8.30	$< .0001*$
Simple Main Effect of Width at Remote Perception		
1.05 - 0.5	-5.11	$0.0003*$
1.05 - 1.25	-6.53	$< .0001*$
1.05 - 1.5	-5.84	$< .0001*$
0.75 - 1.25	-4.82	$0.0002*$
0.75 - 1.5	-6.42	$< .0001*$

CHAPTER 4. WAYFINDING IN HUMAN-ROBOT COLLABORATED EXPLORATION: ORIENTATION AWARENESS AND ITS ENHANCEMENT

A paper submitted to *Journal of Environment Psychology*

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Abstract

Orientation awareness, being the awareness of heading direction, current location and object's location relative to current location, is critical for wayfinding. Obtaining and maintaining the orientation awareness is a challenging task, and even more difficult in remote wayfinding, where the wayfinder cannot be in the environment physically. This study designed an interface to enhance the orientation awareness under a remote wayfinding condition, by providing a route map showing the previous path taken by the operator, and evaluated its effectiveness. Sixteen participants were tested in this study, with eight people in each group, either with the enhancement or without. Participants were required to remotely navigate a robot to explore an unknown environment, learning its layout as well as searching for exits and dangerous objects. They were then asked to draw the layout of the area, and mark out exits and dangerous objects on the map they made. It was found that with the previous route map available, participants resulted in better understanding of the layout as reflected by the quality of the maps they made, as compared to those that did not have any external information. It was also found even with more information to perceive and process for the users of the enhanced interface, efficiency and subtask performance stayed the same as those who had less information to perceive or process. Result of this study proved the effectiveness of the proposed enhancement.

4.1 Introduction

4.1.1 Human-Robot Collaborated Wayfinding

In most human-robot collaborations focused on the task of exploring, human operators usually are responsible for navigate the robot. At the very least the human supervises the robot while it travels around a search area autonomously; in this case the human typically gains an understanding of the layout of that area and location of objects of interest. As definitions for "wayfinding" varies depending on the context, the above scenario falls into the "goal-directed search in an unfamiliar environment" category, according to the taxonomy of wayfinding proposed by Wiener, Buchner, and Holscher (2009). Moreover, since the wayfinding discussed in this study occurs in a human-robot collaboration scenario, in which human operators are separated from the environment where the wayfinding takes place, it is thus referred to as "remote wayfinding".

Difficulties in remote wayfinding can be broken down into two types: 1) classic wayfinding, and 2) remote perception. "Classic wayfinding" refers to the difficulties existing even when someone explores an area with him/herself physically being there, while the second type, remote perception, refers to the perception difficulties arise when an observer is separated from the environment.

One of the greatest challenges in the classic wayfinding is orientation, the awareness of heading direction, current location, as well as current location relative to other places, which is the "fundamental information required for wayfinding" (Montello and Sas (2006)). Disorientation is common among people even in daily life (Hegarty, Richardson, Montello, Lovelace, and Subbiah (2002)). Disorientation not only directly affect wayfinding, but also easily leads to anxiety, frustration and tardiness, which increases a person's mental workload, resulting in deteriorated wayfinding performance. Remote wayfinding tasks are more cognitively demanding, because wayfinders cannot directly go into the environment, but instead observe everything through cameras and/or other sensors. Perception is impaired in both quality and quantity. Limited field of view (FOV), unnatural viewpoints, and degraded image quality all resulted in greater levels of difficulty related to perceiving and understanding the environment (Chen, Hass, and

Barnes (2007)). Riley and Endsley (2004) performed an observational study and found that orientation awareness was the most challenging part of human-robot collaborated wayfinding. The preponderance of the evidence indicates that remote way finding presents a host of issues that can easily lead to increased cognitive load and increased human error/confusion and disorientation.

4.1.2 Enhancing Orientation Awareness

Wayfinding tasks require the development of spatial knowledge related to a region, this knowledge includes the layout and elements location in that region, that is to say, a wayfinder needs to constantly maintain and update a cognitive map, which is the mental representation of a region's spatial information (Tolman (1948)), in his/her memory system. Human working memory capacity is limited and it requires special processing to convert information in working memory to long-term memory, this task is highly cognitive demanding. In the remote wayfinding, apart from the cognitive load for processing and maintaining the spatial knowledge, additional cognitive resource is required due to the remote nature: it leads to less information available, such as narrower FOV caused by limitation of camera, or inaccurate information gained, such as scale ambiguity where wayfinder's perception of object's width relative to self-dimension is in accurate (Tittle, Roesler, and Woods (2002). Therefore, it becomes even harder to maintain and update the cognitive map as a result of both insufficient information and divided cognitive resource.

A map is an external aid for forming, maintaining and updating the cognitive map in one's head, as it provides a global view of a region, helping with route planning before wayfinding activity. What's more, even with a map, a human still needs to form a cognitive map, which is his/her own understanding of a region in head, but this process can be less cognitive demanding with the presence of a map, since the physical map serves as a reference, with which a cognitive map can be built upon. With such aid, "knowledge in the head" is transferred to "knowledge in the world" (these two concepts comes from Norman (1998), with the former referring to knowledge maintained in one's memory and the latter referring to reminder or information stored in the real world), releasing one's cognitive workload.

However, one difficulty of the human-robot collaborated wayfinding lies in the fact that the area to be explored is totally unknown, which means the human has no priori knowledge, specifically no understanding of the layout and they have no physical external map. As a substitute for the map, a real-time route map which shows the previous route taken during exploration is proposed by this study. Darken and Peterson (2001) suggested that trails/footprints were helpful especially for wayfinders to recognize if they had been to a place and the traveled direction in exploration. But they also pointed out that "simply leaving a trail is marginally useful". It was also suggested by their study that directional information, such as compass, should be used in combination with positional information. Taking these two suggestions into consideration, it can be projected that the real-time route map would be a helpful tool for gaining and maintaining orientation awareness during remote wayfinding. Moreover, if the route taken follows every wall in a region, the route map is also able to reflect the region's construction.

That being discussed, the next question is: how much information is needed for that route map? According to the study by Meilinger, Hlscher, Bchner, and Brsamle(2007) comparing standard floor plan with schematized route maps at different levels of abstraction, it was found that providing less than standard information lead to better performance and that the most crucial information needed was turning information. This finding was in agreement with Butler, Acquino, Hissong, and Scott (1993)'s study that found users who were provided with directional signs resulted in better performance when compared with those with "you-are-here" map. They argued one of the possible reasons lied in the amount of information a person had to process when using a detailed floor plan. Basing on these findings, this study will focus on providing precise turning history along exploration, with an approximated traveled distance.

4.1.3   Research Question and Hypothesis

This study focuses on the orientation awareness of wayfinding in human-robot collaborated exploration. Specifically, it is hypothesized that orientation awareness is significantly enhanced with the presence of a real-time route map during wayfinding, in terms of a more accurate sense of current heading/direction as well as a more accurate understanding of the area layout.

4.2 Method

4.2.1 Participants

Sixteen Iowa State University (ISU) students participated in this study. They were randomly assigned to one of the experimental group in this experiment: unaided-wayfinding group or aided-wayfinding group. Each group had 3 males and 5 females. In the aided group, one female participant terminated participation before completion due to personal reason; therefore only data from the remaining fifteen participants were used in data analysis.

4.2.2 Independent Variable

The independent variable in this experiment was the presence of a route tracking map: the unaided-wayfinding group only had an interface showing the video sent back from camera mounted on the robot, while the aided-wayfinding group was presented with both video and a route map showing the path which the robot traveled.

4.2.3 Dependent Variable

The dependent variables in this experiment were

1. Efficiency, measured by the time to completion,

2. Number of objects/exits identified during exploration, and

3. Orientation awareness, measured by the quality of map drawn by each participant after the exploration.

The orientation awareness was further decomposed into three factors:

1. Logic Accuracy: this is the primary indicator for the accuracy of a participant's perception of the layout. The researcher first compared each "wall" drawn by a participant with the existence of "wall" at the same location on the actual floor plan: if they matched, it counted as 1 point; otherwise, 0 point. Upon analyzing every wall drawn by participants,

the research calculated the percentage of total points earned over the actual total number of walls (which was 24), which served as logic accuracy.

2. Orientation score, indicating a participant's ability to recognize the overall layout relative to the starting direction. On the empty map given to participants, entrance and the starting heading direction was indicated. If the layout drawn by a participant was in accordance with them, then orientation score was 1; otherwise it was 0 as it showed the participant failed to recognize objects location relative to the starting position and direction.

3. Location score, demonstrating the accuracy of a participant's memory of objects and exit locations. This factor was calculated by summing up all the correctly located objects and exits marked on the map.

4.2.4   Interface Design and Experiment Setting

The robot used in this study was a boe-bot robot using a board of education and a BASIC Stamp 2 microcontroller from parallax, equipped with XBee 1mW Wire Antenna RF module and Honeywell HMC5883L compass module. A joystick was used to control the robot. An interface was designed and implemented using c# and PBASIC language. The precision of the angle reading is approximately $5°$ to $10°$ due to both compass module precision and the microcontroller limitation. For the unaided group, only joystick status and camera view were provided on the interface. For the aided group, current heading angle and previous route were provided in addition to those displayed for the unaided group (figure 4.1).

Users could also save current route map and clear the screen for generating a new route map by clicking two buttons "save map" and "clear map" provided on the interface. The route map was drawn according to the real-time reading of a compass and the duration of participant's holding the joystick in forward/backward position. Therefore the directional information was accurate while the distance traveled in each direction was an approximation.

The experiment took place in the human performance and cognitive engineering lab at Iowa State University. A 12 ft. by 15 ft. area for wayfinding was also designed and constructed
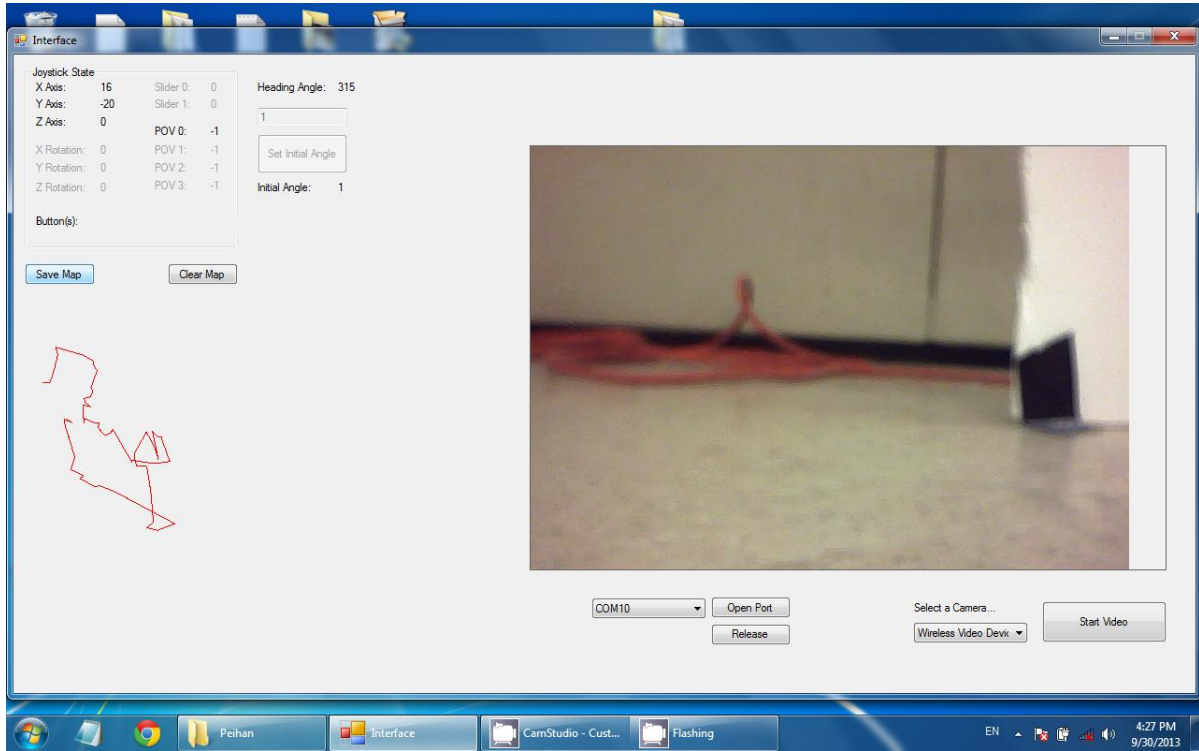
Figure 4.1   Enhanced Interface with Route Map and Heading Angle

by the researcher (figure 4.2 and figure 4.3). It had two exits and one entrance where the wayfinding started. Five red objects were placed in different corners in the area, which served as "dangerous objects" within the area, with one green object as a distraction.

4.2.5   Procedure

Participants were asked about their gaming experience and frequency of use before they participated in the experiment. Each participant's spatial ability, specifically spatial visualization ability and visual memory ability were tested using punch-hole paper folding test and building memory test respectively. In the paper folding test, participants were shown a series of pictures demonstrating how a squared paper was folded and punched by a pencil. They were then asked to imagine how the paper would look after unfolding it. In the building memory test, participants were first given a map with 12 buildings on it and required to memorize location of each building. Four minutes later, participants were given a list of buildings and
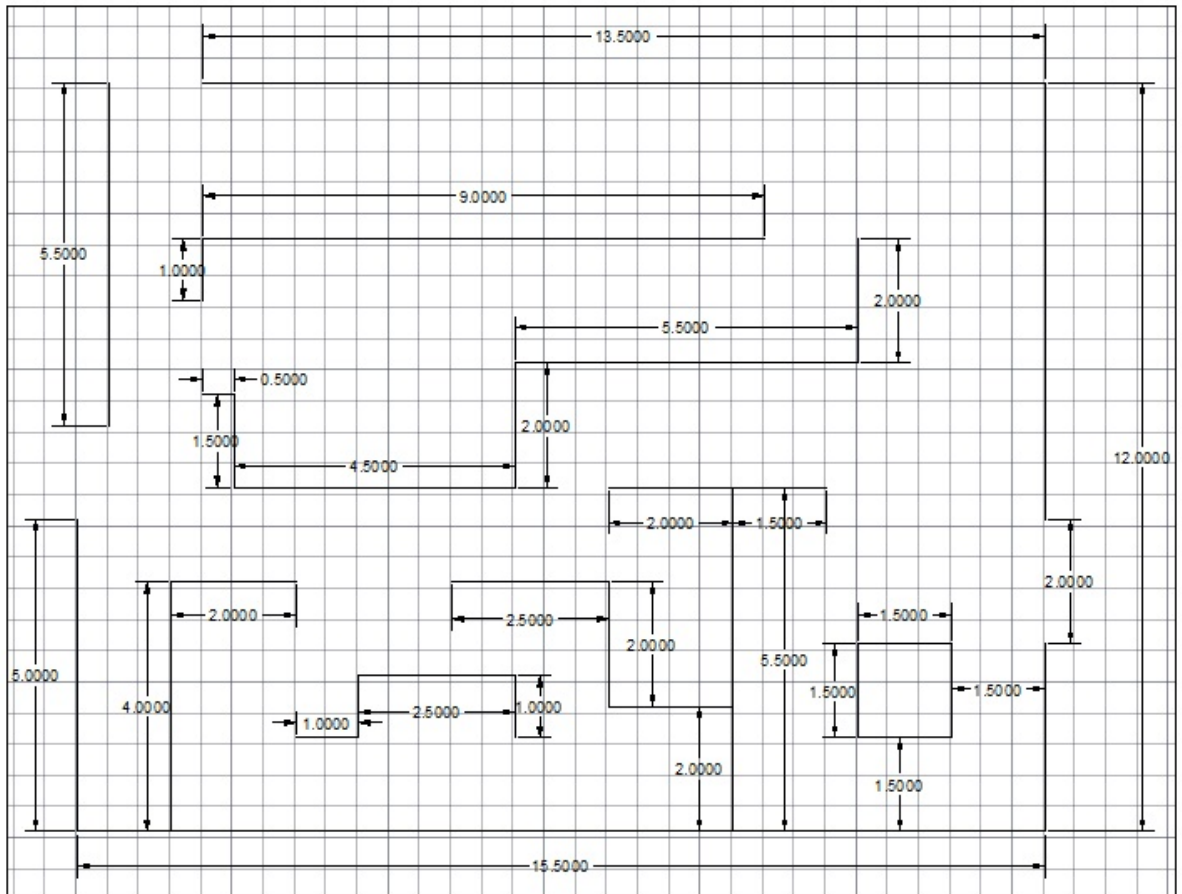
Figure 4.2 Exploration Region Floor Plan (unit: inch)

an empty map which were the same as the map they just saw. Their task was to mark all the buildings on that map. These two tests were selected because in this experiment, participant's ability of transferring a three dimensional information into a two dimensional representation, as well as their memory of object's location were important.

Prior to the experiment, participants were first told about the tasks they were to perform: 1) learning the layout of that area and draw a map after the exploration; 2) looking for exits and dangerous objects represents by any red-colored object. Then they were given two sections of practice: in section 1, participants are allowed to watch the robot directly while they were driving it, so that they could understand how the robot would respond to their control; in section 2, participants had to drive the robot remotely, only being able to observe the environ-
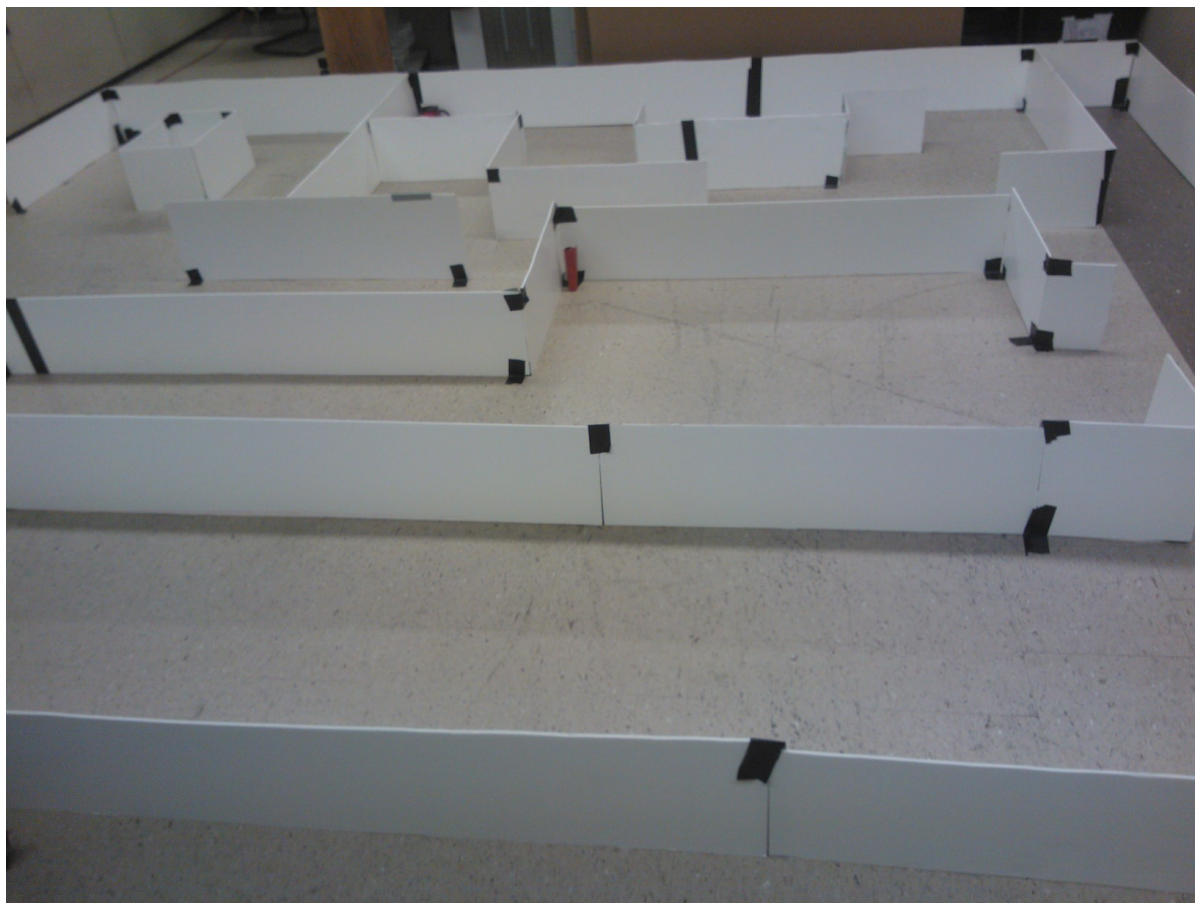
Figure 4.3   Exploration Region Setup

ment through camera mounted on the robot. For participants in the aided group, they were educated with the features provided on the interface during practice section 2.

Upon completion of practice, participants were asked to explore the area with unlimited time. Whenever they felt they had gained enough information for drawing the map, they could terminate the exploration. A piece of engineering paper in which the frame of area drawn and starting position and direction had already been marked on was given to participants for them to draw the layout on it.

4.3   Result

4.3.1   Orientation Awareness

Orientation awareness was decomposed into three factors: logic accuracy, orientation score and location score, all of which were obtained from the map drawn. A series of two sample t-tests were performed to compare group means for each variable. The results are presented in table 4.1 below. Note the 95% confidence intervals were calculated by unaided group - aided group.

Table 4.1   Two Sample t-test Result for each Variable of Orientation Awareness

Variable	t Value	p Value	Lower 95% CI	Upper 95% CI
Logic Accuracy	$t(1, 13) = -2.13$	$0.05*$	-48.58%	0.00%
Orientation Score	$t(1, 13) = -2.75$	$0.02*$	-1.08	-0.13
Location Score	$t(1, 13) = -1.62$	0.13	-3.88	0.56

Logic Accuracy.   Significant difference between the unaided and aided group was found. Group mean for the aided group was 51.21% while that for the unaided group was 27.08%. It showed that with the previous route information, accuracy of map was increased by 24.13% with a 95% confidence interval being 0% to 48.58%.

Orientation Score.   The sense of orientation was also significantly improved with the route map. While only 2 out of 8 participants in the unaided group correctly recognized the layout's orientation relative to the given starting direction, 6 out 7 in the aided group managed to figure this out.

Location Score.   Since there were 5 dangerous objects and 2 exits in the region, the full score for location score was 7. Participant's memory about objects and exits location was not significantly affected by the presence of route map.

4.3.2 Wayfinding Efficiency

Next we tested how our enhanced interface affected wayfinding efficiency, a two-sample t test was conducted to compare the group mean of time to completion. There was no significant difference between the two groups in the time spent on exploration, indicating that with more information to perceive and process, the wayfinding was equally efficient as compared with wayfinding without any aid. This result indicated the route map information did not significantly affect the cognitive workload during wayfinding.

4.3.3 Objects Identified

A two-sample t test was employed to examine the impact of the enhanced interface on the number of objects/exits identified during wayfinding. No significant effect of the presence of heading angle and route map on objects and exits identified during exploration was found, which was not surprising, as the interface was not designed for enhancing performance in this aspect. Moreover, similar to what can be inferred from the result of time to completion, this result also indicated that the extra information displayed for the aided group did not require significantly more cognitive processing from users.

4.3.4 Spatial Ability

Two two-sample t tests were used to examine the participant's spatial ability difference on the result of each test separately.

Paper Folding Test. No significant difference was found between the two groups, indicating participants in both group had equal spatial visualization ability.

Building Memory Test. Participants in the two groups had significantly different visual memory test (p = 0.02). 95% confidence interval result showed that participants in the unaided group scored 10.61 to 1.18 lower than those in the aided group.

Correlation between Spatial Ability and Performance. A series correlation tests were then performed to investigate if any correlation existed between each factor in the spatial

ability and each factor of orientation awareness. No significant correlation was found between any pair.

4.4   Discussion

This study proved that orientation awareness, including awareness of a region's layout and sense of orientation could be significantly enhanced by providing a real-time route map during wayfinding. When drawing the map, participants in the aided group had their previous route available for reference. This enabled them to compare what's in their head to an external objective recording, which also helped them to recall what had happened during the wayfinding. The participants in the unaided group, however, had to memorize everything by themselves. Therefore, they tended to miss more information or had inaccurate information stored.

While it has been pointed out by several studies that map's usage requires user's spatial ability and mental effort to transfer from a two dimensional representation to a three dimensional structure from an egocentric (first-person perspective) view of objects and their locations (McGee, (1979); Thorndyke and Stasz (1980); Bulter, et al. (1993)), task in this study requires the converse: converting a three-dimensional representation to a two dimensional drawing. Few studies have looked into this problem but it can be inferred that their level of difficulty are similar. The route map, not only helps store information, but also makes that transformation for users.

This study provided a general conclusion on the effectiveness of providing route map, yet there are still questions regarding this enhancement. Referring to the route map while drawing the layout is a task similar to observe remote environment when presented with both egocentric and exocentric (third-person perspective) views. Studies have shown that difficulty in integrating information from both views arose, especially when the exocentric view is presented in an angle that is different from that of the egocentric view (for example, in the egocentric view robot is heading east but the exocentric view is north-up) (Chadwick and Pazuchanics (2007). In the current study, participants needed to integrate both route map and their cognitive map which might not necessarily be in the same angle or even of the same dimension. Moreover, the route map is different from an actual map. In fact, they are opposite in that lines in route

map actually indicated hallways in a layout map. One participant in the aided group came up with a wired layout map. From the conversation after experiment it was found out that this participant was confused by the difference between a route map and a layout map just as discussed before.

Another important observation needs pointed out is that the usefulness of the route map is affected by user's wayfinding strategy. As mentioned in the introduction section, if the route taken follows each wall in that region, the route map will be a precise reflection of the region's construction. During the experiment, participants employed various strategies. In general, they can be generalized in two categories: top-down and bottom-up. Some participants traveled along the frame walls of the area first, noticing the number and location of each room, and then explore those rooms one by one. This strategy is called "top-down". Other participants traveled from room to room and then put each piece of the puzzle together, which is referred to as "bottom-up". Constrained by the approximated travel distance on the route map, the bottom-up strategy resulted in intricate maps which were less helpful. However, this limitation can be overcome by improving the precision of the route map.

4.5   Conclusion and Future Work

This study proposed an enhancement for orientation awareness in human-robot collaborated wayfinding, evaluated and proved its effectiveness. It was proven that with a real-time route map, user was able to gain better orientation awareness in terms of overall layout and direction. Result of this study can be applied to a variety of human-robot collaboration tasks, including urban search and rescue, military reconnaissance and other tasks requiring exploration. As augmented reality technology advances, this idea can also be utilized in traditional wayfinding aided by augmented reality.

Because of the approximated distance, the route map did not precisely reflect the actual route taken by users, making it difficult for them to recognize if they had been to a location or not. It would be interesting to test to what level a user's orientation awareness can be enhanced with a precise route map. Providing users with the feature of marking on the route map where they find a target would be another improvement for this interface, as it further release the

memory workload of human users to an external medium. The effectiveness of this aid needs also be evaluated in the future work.

CHAPTER 5.   GENERAL CONCLUSION

Understanding the impact of remote nature on navigation-related perception and enhancing the navigation-related perception are important to human-robot collaboration applications. Figure 5.1 serves as an overview of this dissertation work. In human-robot collaborated exploration, two typical types of task exist: 1) navigation, and 2) other tasks such as visually searching or fine motion manipulation. Navigation-related perception can be broken down into two categories: 1) remote perception, affected by the remote nature; 2) navigation perception, referring to the perception that is important for even direct perception. The scale perception and distance perception are mainly impaired by the remote perception, while orientation awareness gets affected by both categories. The human-robot system's performance relies on these perception factors due to their impacts on both navigation task and other tasks. This research quantified a remote perception condition's impact on human's judgment on distance from the robot's current location to a distant object and the judgment of robot's size relative to a door's width, designed enhancements for each factor as well as evaluated their effectiveness in improving human perception. Orientation awareness, being the most crucial part in wayfinding, was also studied and was enhanced through a proposed interface design.

In chapter 2, a study on distance perception was discussed. It was found that under a remote perception condition, distance perception, as measured through a "blindwalking" task, was found to be significantly worse than that obtained under a direct perception condition. An enhancement of displaying distorted image in which the displayed distance is further than actual distance was proposed and evaluated. Results proved the pre-processed images managed to compensate for the distance perception distortion, resulting in significant improvement in the distance perception.

Chapter 3 presented and discussed a study on scale perception. Result of the study showed
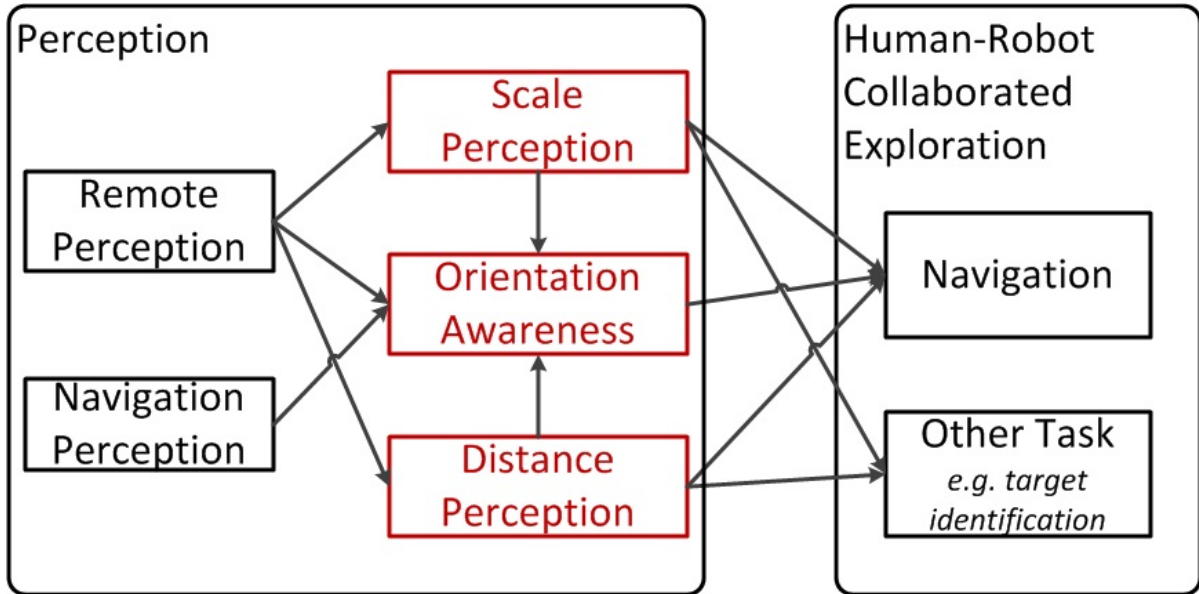
Figure 5.1   An Overview of the Dissertation Work: Perception's Impact on Human-Robot Collaborated Exploration

that it was harder for human to perceive the difference between the width of a door and the robot controlled under a remote perception condition. However, with an external dimension cue, which were two red dots on the screen indicating robot's size, the perception was greatly enhanced and was even more accurate than that under a direct perception condition. It was also found that distance to door was not a significant player in obtaining scale perception.

In chapter 4, an interface aiming at improving orientation awareness during human-robot collaborated navigation and its evaluation was introduced and discussed. This interface displays the robot's real-time heading angle as well as provides a route map that shows the path the robot has traveled during the navigation. Compared with those participants that did not have access to this information, participants with this enhanced interface exhibited more accurate understanding of the area's layout which was indicated by the map they made after exploration, as well as better sense of the robot's heading direction.

In summary, the findings of these studies not only quantified the impact of remote nature on navigation-related perception, but also provided robust ways to enhance these factors respectively. While these three factors independently reflect certain aspect of navigation-related

perception, their impacts on navigation performance can be cumulative. As observed during the experiment of the study on orientation awareness study, most of the participants encountered failure of navigating the robot through doors; some even had that problem constantly. Although all the doors were wide enough for the robot, inappropriate angle or wrong position accounted for the failure. It not only wasted time, but also led to disorientation in that when the robot hit the wall, usually it was only one edge of the robot get trapped, as participants continued driving the robot forward, they actually were turning the robot but hardly noticed. Although participants usually realized that within a very short amount of time, the robot had already turned 90 degree or even more, leaving the participants confused by the heading direction. Most of participants reported disorientation after such situation. Therefore, it can be projected that with a dimension cue which improved the accuracy of scale perception, less disorientation would occur because of out-of-expectation turnings caused by hitting walls. Distance perception, in a similar way, can also improve orientation awareness when gets enhanced. Also from observation during the experiment of the third study, it was a common phenomenon that participants underestimated the length of a hallway, so that they failed to drive the robot for long enough to get to a door or the end of a hallway and turned the robot when there were only walls around the robot. That also led to disorientation since it took extra mental effort to memorize the previous heading direction and calculate the current direction after turning. Moreover, with more turnings, it became more possible for a participant to make mistake on figuring out current heading direction, thus more likely to loss the awareness of that.

With these being discussed, it can be suggested that for future work an integration of all these enhancements needs implemented and evaluated. Especially for the distance and scale perception, they were only evaluated in a static environment instead of a real-time navigation task, the contribution of those enhancements to overall navigation performance needs investigated.

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