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Perceiving Aperture Widths During Teleoperation

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PERCEIVING APERTURE WIDTHS DURING TELEOPERATION

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ABSTRACT

When teleoperating robots it is often difficult for operators to perceive aspects of remote environments within which they are working (Tittle, Roesler, & Woods, 2002). It is difficult to perceive the sizes of objects in remote environments and to determine if the robot can pass through apertures of various sizes (Casper & Murphy, 2003; Murphy 2004). The present experiment investigated whether remote perception could be improved by providing optic flow during robot movement or by positioning an on-board camera so that the forward portion the robot is in the camera's view. Participants judges the sizes of remote apertures viewed through a camera mounted on a remote robot. The participants were divided into two different viewing conditions; those with the forward portion of the robot in view and those without any portion of the robot in view. Each participant viewed a series of 60 videos, some of which provided optic flow and some of which did not. Results indicated no differences between the flow conditions, and a small yet statistically significant difference between the viewing conditions. On average the participants judged the apertures to be larger when the robot was not in view, which could lead to operators overestimating the ability of robots to fit through small openings. The implications of these findings for the teleoperation of remote robots are discussed.

DEDICATION

This thesis is dedicated to my wonderful mother without whom this would not have been possible. Your continual love and support over the last 24 years has given me the courage to dream big, the "determination" to go after what I want, and the strength to carry on when the road gets rough. You are my rock.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to Dr. Christopher Pagano for advising me during this process. I would also like to thank Dr. Rich Pak and Dr. Claudio Cantalupo for their key contributions as committee members. I am very fortunate to have had the opportunity to work with each of you. Finally, I would like to thank Josh Gomer and Kristin Moore for their endless help and support with this project.

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CHAPTER 1

INTRODUCTION

A Brief Overview of Applied Teleoperation

During and immediately following World War II, developers began focusing on improving the design of industrial manipulators and robots in the hope of improving efficiency and product quality in highly repetitive tasks in factory settings (Stassen & Smets, 1997). These unmanned robots worked accurately, at high speeds, and without the direct, continuous input of a human operator. In the 1970s the focus shifted from autonomous industrial manipulators to teleoperation and telemanipulation. Sheridan (1992) defines teleoperation as "the extension of human sensing and manipulation capabilities by coupling it to remote artificial sensors and actuators" (p. 393). Teleoperation involves the ability to control a remote robot using its sensors and cameras as a guide to manipulate objects. An early example of these robots can be seen in the teleoperators created by the Manhattan Project's weapon complex (Goertz & Thompson, 1954). Due to the highly toxic nature of the materials being handled, the need for telemanipulation was critical. The teleoperation systems that were developed at this time were called generalized teleoperation systems (Bejczy & Salisbury, 1983). Unlike the previous models that required the operator to move an exoskeleton, or replica of the robot, in the exact way they wanted the robot to move, these newer systems allowed the operator and the robot to have different patterns of movement. In other words, the actions and movements that were required from the operator to control the robot did not have to directly reflect the robot's specific actions. The new teleoperation systems allowed humans to function in environments where the intended tasks were too dangerous or beyond normal human capabilities, such as in confined spaces (e.g. Stassen & Smets, 1997). Subsequently, along with this change in remote robotic functioning came a change in the level of human interaction with the robot.

To date, teleoperated robots have been used in many different tasks. Some robots, such as the i-SOBOT Micro Humanoid Robot (Japan), are used simply as toys for entertainment. Others serve a more functional purpose; these functional robots enter into environments which humans cannot due to size, extreme temperatures, and toxic environmental conditions. These tasks and situations include medical applications such as endoscopy, military and police operations, space and deep sea applications such as exploration, and work in hazardous environments (Mailhot, 1996; Negahdaripour & Madjidi, 2003; Stassen & Smets, 1997). Telesurgery is another application in which remote control is required (Butner & Ghodoussi, 2003; Cavusoglu, 2000). Several of the possible teleoperation environments include the following: space, undersea wreckage investigation, toxic waste detection and cleanup, sewer inspection, mining, disaster recovery, and urban search and rescue (USAR). For example, Japan’s National Institute of Advanced Industrial Science & Technology has recently concentrated on the teleoperation of space robot technology in order to achieve effective ground-based control of manual manipulations in orbit (Yoon et al., 2004). Perhaps the most well known instance of modern day human manipulated robots is in the days following attacks on the World Trade Center in September of 2001.

In the aftermath of September 11, 2001, rescue teams deployed urban search and rescue (USAR) robots in order to gain access to areas of the rubble that were too dangerous for humans to enter. Response teams used the robots for several tasks, including conducting structural inspections, searching for victims, searching for paths that were quicker to excavate, and detecting hazardous materials (Casper & Murphy, 2003; Murphy, 2004, 2005). These robots were able to penetrate further into the rubble than traditional search equipment, they were able to determine if an entry location was stable enough for human entrance, and they were able to detect the presence of heat, gas, and other hazards. Because of this, these robots were valuable to the search teams. However, while using the robots the operators encountered several problems. One of these problems was that the remote view provided by the on robot camera had a very limited field of view and did not afford accurate depth perception for the operators (Tittle, Roesler, & Woods, 2002). This made the video extremely difficult to interpret. Operators had difficulty determining if the robots they were operating could pass through various apertures or maneuver around obstacles (Murphy, 2004). Operators tried adjusting lights and refocusing cameras in order to improve their perception of the remote environment, but they were mostly unsuccessful. Operators also had difficulty identifying objects and determining size in the remote environments. For example, operators had difficulty differentiating a piece of twisted metal from a firefighter's boot (Casper & Murphy, 2003).

The Remote Perception Problem

What causes the remote perception problem? This question is brought to light by several studies. Reinhardt-Rutland (1996) addressed this issue by explaining how people directly perceive in natural environments. He states that in a natural environment observers use various sources of information, such as the actual object size in relation to other objects, in order to determine that object's distance from themselves. Under teleoperation conditions, it is much more difficult to determine distance due to the fact that actual object size is sometimes impossible to distinguish. In these remote environments, relative depth, or comparing one object's position to another, has been found to be much more useful.

Another issue to consider is size ambiguity within the remote environment. In a natural environment that is directly perceived, people immediately recognize the scale of the environment. In addition, since people have a strong sense of their own body size in relation to the environment, people are able to recognize their ability to move through that environment and around obstacles (Woods et al., 2004). However, when an operator is asked to maneuver a robot through a remote environment, this immediate perception is lost. The operator is no longer able to perceive relative size and is thus unable to effectively operate the robot. The operator cannot perceive whether a robot can pass through an opening or over an obstacle, causing problems in the search and rescue process (Casper, 2002).

Tittle et al. (2002) addressed the remote perception problem in another study. In natural environments, humans have the ability to perceive the passability of objects in relation to themselves. In a remote environment, however, there is a disconnection between the environment and the operator's perception of it. The operator no longer has a sense of his or her own body in relation to the visual cues in formations that support depth perception such as optic flow and motion parallax. In addition, when in a natural environment feedback about the rate of motion provided by the vestibular system can supply information that can be used in order to determine the scaling of objects within the environment (Tittle et al., 2002). When perceiving remote environments, the operator's perceptual system does not receive this information. In other words, as a person moves through a natural environment information from both their eyes and the rest of their body provide information about depth and distance. In the remote environment, the perception-action link is broken between the operator and the environment, and thus the ability to perceive size passability and distance is diminished (Tittle, et al., 2002).

Another problem arises from the point of view from which the operators see the environment. The operators are forced to see the remote environment from the point of view of the robot (Tittle, et al., 2002). Viewing the environment from the height of the robotic camera, which is typically very different from one's natural eye height, makes it difficult to scale objects and monitor the robot's rate of motion within the remote environment. As noted by Mark (1987), "Anthropometric variations in body size, mass, and proportions contribute to differences in people's action capabilities" (p. 361). In other words, as a person moves through an environment he or she must calibrate their perceived measurements of environmental properties in relation to their own body size, shape, height, etc. In order to support these claims, Mark conducted a series of experiments that looked at eye height (EH) and its effects on perceived maximum seat height (SH_{max}) and perceived maximum riser (step) height (R_{max}). In the first experiment participants were asked to make judgments based on their body size about the location of their eye height, SH_{max}, and R_{max} relative to a wall at five different distances. As the participants' distance from the wall increased, their perceived eye height decreased. Put simply, the further from the wall the participant stood, the shorter they perceived their eye height to be. From this it was noted that the change in perceived eye height accounted for 96% and 95% of the variance in the participant's judgments of SH_{max} and R_{max}, respectively.

In a second experiment Mark (1987) looked at the effect that changes in body size have on SH_{max} and R_{max}. Participants had 10 cm thick blocks attached to their feet and were then asked to make SH_{max} and R_{max} judgments. The results of this experiment were in accordance with the above assertions that people use eye height scaled information about surface height; initially, the participants' mean perceived SH_{max} while standing on the 10 cm thick blocks was an underestimation of the mean actual SH_{max}. In other words, participants were making their SH_{max} judgments as if they were still at their original height. More importantly, however, was that as the participants completed more trials, their judgments of SH_{max} steadily increased and approached their actual SH_{max}. This increase in perceived SH_{max} was potentially due to perceptual motor learning as participants were allowed to walk around with the blocks on their feet between trials. Looking at R_{max}, participants again initially made judgments as if they were at their original height. A different pattern was seen over the remaining trials, however.

Participant's judgments of R_{max} decreased as they completed more trials. The brief time that participants were given to walk around is a likely explanation for the change in R_{max} judgment.

Another related issue is that of ambiguity produced by perceived rate of motion due to a difference in viewing height. In teleoperation conditions the height of the robotic camera is usually very different from that of its operator's normal eye height. This relationship between optic flow and perceived rate of motion within an environment is affected by the observer's eye height (Woods et al., 2004). Thus, when an operator views a video stream from a remote robot, their visual system processes optic flow without motion feedback information that is normally provided by eye height. This discrepancy caused by the difference in viewing height introduces ambiguity and misperceptions of the remote environment.

An experiment by Fune, Moore, Gomer, and Pagano (2006) explored this issue further by investigating participants' ability to perceive robot passability while viewing the remote environment through cameras mounted at three different heights. Participants watched live feed from the camera, mounted low, medium, and high, as a robot approached an aperture and then responded "yes" or "no" as to whether or not the robot could pass through the opening without touching either side. On average, participants underestimated the passability boundary for all camera heights. Put simply, participants underestimated the size of the robot in comparison to the aperture, and thus they said that the robot could pass through the aperture when it could not. Additionally, the data revealed that the lowest camera height, a camera height commonly used on USAR vehicles, resulted in the worst passability estimates. The lowest camera produced means of 47.8 cm while the middle and high cameras produced means of 50.9 cm and 50.7 cm, respectively. In actuality, the robot required an aperture of 58.0 cm in order to pass through without touching either side. Furthermore, the difference between the lowest camera height and the other two camera heights was statistically significant. In other words, the low camera height produced the largest underestimation of passability. Thus, the middle and high camera heights, both of which were closer to a normal human perspective, resulted in more accurate passability judgments.

Radial Outflow

Several studies have looked at how head motion and moving influences perception. Gibson (1950, 1979) described that when an animal moves through its environment, objects in their line of sight either come into or out of view, and that images projected from these objects either enlarge or reduce in size. He explains how properties of objects are specified by invariants, or aspects of the optics that remain constant over transformations of the optic array. An example of these invariants is texture gradients (Gibson, 1950, 1979). An object, no matter how far away, will always obscure the same amount of a textured background. For example, a car in front of a brick wall will cover the same amount of the wall, proportionally, whether the viewer is 1 foot, 10 feet, or 100 feet from it. Despite the fact the image size of the car appears to become smaller as the viewer moves farther away, the ratio between the size of the car and the textured background remains invariant. Gibson stated that the optic flow produced by moving through the environment reveals invariants such as these. Thus, moving creates transformations of the optic array that reveal information about size and distance.

In a 1979 study, Rogers and Graham examined motion parallax, or perspective transformations of the retinal image produced by the lateral movement of an observer or an object in the visual world. From their study the experimenters concluded that motion parallax provided sufficient information about depth and shape perception despite the absence of other sources of information. This study was then later generalized by several researchers to the case of radial outflow produced by forward and back head movements (see Bingham & Stassen, 1994; Bingham & Pagano, 1998; Pagano & Bingham, 1998).

Investigating Radial Outflow During Teleoperation

Bingham's work was extended by Dash (2004) in an experiment that examined whether radial outflow was an effective method for obtaining information for egocentric depth during teleoperation. In this study, participants were asked to remotely view white squares made of foam board in a black space under three different viewing conditions: passive, joystick, and head-coupled movement. In the passive condition, participants used keystrokes on a keyboard to move the camera forward and back in front of the target. In the joystick condition, participants were asked to do the same task; however, this time they moved the camera with a joystick input. Finally, in the head-coupled condition participants were able to move the camera back and forth via their own head movements. A visor with a lightweight electronic sensor attached allowed the participants to control the camera movement. The different targets produced 5, 11, and

14 degrees of visual angle measured from the camera lens which resulted in three different square sizes on the monitor: 7.6, 16.5, and 21.3 cm, respectively.

In his experiment, Dash (2004) hypothesized that his results would show that head-coupled movements would be superior to the other two conditions in providing egocentric depth information. After analysis of the data, however, it was found that the participants performed equally well in all three conditions. Best-fit lines for simple regressions predicting indicated distance from actual distance resulted in slopes of .61, .58, and .59, for the passive, joystick, and head-coupled movement conditions, respectively. Dash cited technology limitations in the apparatus as a limitation of the study and a possible explanation for the lack of difference in the three conditions. Dash also found that constant feedback regarding the actual distances of the objects was required in order for participants to successfully perform the task. The participants were able to perceive depth from radial outflow in all three conditions, indicating that forward and back camera movements provide important depth information.

A similar study was conducted by Pagano, Smart, Blanding, and Chitrakaran (2006) in which participants were presented with three passive viewing conditions presented in a fixed order: familiar objects with training and feedback, white squares in black space with training and feedback, and white squares with no feedback. Analysis of the data provided simple regressions that showed slopes of .96, .63, & .70, respectively. These results further indicate that constant and consistent radial outflow produced by an oscillating camera can provide effective information about depth perception in a remote environment. The results also indicate that once the subjects have been given training and feedback with familiar objects, they are then able to perform without continued feedback.

Following Pagano, Smart, Blanding, and Chitrakaran study, Gomer (2007) conducted an experiment that used an oscillating camera on top of a moving robot to create optic flow in hopes of improving operator depth perception. In this study, participants remotely observed white cubes in black space under two different separate sessions: dynamic (oscillating) camera and static (stationary) camera. In both conditions, participants were shown a white cube which they then drove 30 cm forward towards. Following this forward motion, participants were given a distance on a pulley device that they were then to replicate in the distance from the front of the camera to the front of the cube. Results from this experiment showed that participants reliably reproduced the instructed robot distances in both the static and dynamic viewing conditions. In other words, the participants did not utilize the additional information provided by the dynamic camera (radial outflow). These results suggest that the tank movement in the static camera condition provided enough information about depth so that the addition of camera movements in the dynamic camera condition did not add any information that the participants utilized.

A study conducted by Moore (2006) compared operator performance in both direct line of sight and teleoperation conditions. In this experiment, participants had to judge whether or not the robot could pass through apertures of various widths. Using the Method of Limits, three different robot widths were tested in both the direct line of sight and teleoperation conditions. Participants watched as the robot drove forward 2 m and stopped 1.5 m from the aperture. The results of this experiment revealed that participants slightly over estimated the passability boundary in the direct line of sight condition. Participants said that the robot could not pass through the aperture when it could. Additionally, results showed that participants underestimated the passability boundary in the teleoperation condition. In other words, they said that the robot could pass through the aperture when it could not.

Another study conducted by Moore, Gomer, Fune, Butler, and Pagano (2006) followed a similar procedure and obtained similar results. Apertures were presented to participants at random via the Method of Constant Stimuli. After giving passability judgments, participants then provided aperture width estimates by moving adjustable wooden blocks on a wooden track. Results showed that participants' size estimates were accurate in both direct line of sight and teleoperation, and did not differ between those two conditions.

In a follow up study, Moore et al. (2006) looked at operator performance on perception of robot passability when the remotely operated robot was not visible in the camera view. As in the previous experiment, subjects viewed the aperture from a camera mounted on the robot, but whereas in the previous experiment the camera was tilted downward so that the robot was in view, in this experiment the camera was angled in such a way so that none of the robot was in view. In this experiment, participants had to judge whether or not the robot they were operating could pass through apertures of various sizes without touching either side. Aperture sizes were adjusted via the Method of Limits. The results from this experiment compared to the results from the previous experiment showed that participants were better able to judge robot passability when the robot was in the camera view compared to when the robot was not in the camera view. In other words, participants more consistently and more accurately perceived robot passability under teleoperation conditions when they were able to see the front of the robot in the camera view. This reveals that the robot in view provides vital scale information to the operator and thus should be part of their line of sight. In addition to judging robot passability, subjects were asked to reproduce the size of the aperture using a reporting device. It was found that when the robot was not in view, subjects were unable to indicate the absolute size of the aperture.

Another follow up study conducted by Moore et al. (2006) removed optic flow from the information available to the participants during teleoperation. In order to do this, the screen was covered as the robot moved forward so that the participant could not see the robot movement. Apertures were presented to the subjects via the Method of Limits. Simple regressions predicting reproduced aperture width from actual aperture width were not significant. These results indicate that participants were not able to determine the aperture width when optic flow was not present.

The current study further examined the ability of participants to perceive aperture widths under teleoperation conditions. Instead of using the Method of Limits, however, this experiment used the Method of Constant Stimuli. The Method of Constant Stimuli provided the subjects with a larger range of aperture widths and thus allowed us to more accurately assess the statistical significance of the relationship between actual aperture width and subjects perceived aperture width. In other words, a larger range of perceptual freedom more accurately revealed the particpants' actual width perceptions. Participants were presented with two different viewing conditions: robot in view and robot not in view. Each of the participants also had two different motion conditions during the experiment: flow, where they watched the robot move forward, and no flow, where they did not watch the robot move forward. For each of the "Flow" conditions, the robot moved forward 2 m and stopped 1.0 m, 2.0 m, or 3.0 m from the aperture. In each of the no flow conditions, the robot remained stationary at the correct observation distance. The aperture sizes were determined so that the image width on the computer screen is constant for some of the combinations of robot distance and aperture width. After participants watched the video and saw any movement the robot made for the trial, they estimated the aperture width by using a pulley device to slide an indicator to demonstrate what they perceive the actual width of the aperture to be. These four different conditions at three different viewing distances allowed for the determination of what information operators rely on when perceiving aperture width during teleoperation. As a result, the following hypotheses were investigated:

> **Hypothesis 1:** Participants in the Robot in View condition will produce more accurate aperture width estimations than those participants in the Robot Not in View condition.
>
> **Hypothesis 2:** In both groups of participants, the Flow condition will produce more accurate aperture width estimations than the No Flow condition.

CHAPTER 2

METHODS

Participants

The participants for this study were 32 undergraduate students from Clemson University's Psychology Department Subject Pool. There were six male participants who ranged in age from 18-50 (m = 24.0) and 26 female participants who ranged in age from 18-27 (m = 19.3). Participants were divided into two groups of 16 for the duration of the study. All participants had normal, or corrected to normal (20/40), vision. In return for their participation, participants received course credit. Prior to the study, participants read and signed an informed consent document which informed the participants of the general purpose of the study, their rights as a participant, and experimenter contact information should they have any further questions.

Materials

For this study, a New Bright remote control H_2 Hummer 1:6 (24.5 x 28 x 64 cm) (Wixom, MI) was used. This RC truck was chosen because of its similarity in size to Urban Search and Rescue robots (USARs) currently in use in the field, its sturdy wheel base, and flat top. A white foam board box (20 x 31 x 70 cm) with a top (39.5 x 70 cm) was placed on the top of the H_2 Hummer to cover it, provide a flat surface to place the camera, and create a uniform size robot. The camera used was a Grandtec USA (Dallas, Texas) "Eye See All" security camera system that has wireless capability (See Figure 1). In order to maintain consistency across trials and participants, the camera was used to record each of the 30 different videos (videos are described in more detail in the next

Figure 1a Figure 1b Figure 1c

Figure 1: Eye See All camera from the side (Figure 1a), the front (Figure 1b), and angled (Figure 1c).

section). These recorded videos were then converted into 32 different playlists in the Windows Media Player application. Because the security camera recorded the videos at one-quarter of actual speed, the Media Player application's fast forward feature was used to present the images at real-time speed, and ranged in length from approximately 10-20 seconds. The recorded feed from the camera was displayed on a Dell PC with a 15" LCD monitor. The image from the robot appeared in a 3.5" x 2.5" window in the center of the Dell monitor using the Windows Media Player application (see Figure 2). The aperture apparatus consisted of several parts. Neutral curtains were hung on both sides and across the front of the aperture in order to create a uniform space that did not provide observers with any additional information. In addition, the two side curtains created a maximum aperture of 105.0 cm. The aperture itself was constructed as follows: four 2 x 4" pieces of wood were used as the vertical supports for the apparatus. Connected to the inside of those supports, two smaller (1 x 2") wooden pieces ran parallel to each other creating a track, or gap, for the aperture panels to slide in. The aperture panels were constructed using particle board that was covered in the same fabric that was used to create the area surrounding the aperture and measured 60 x 52 cm (See Figure 3). The aperture panels had wooden dowels running through the top left, top middle, and top right corners that acted as supports. These supports allowed the panels to hang in the gap created by the wooden track and slide left and right to create the different

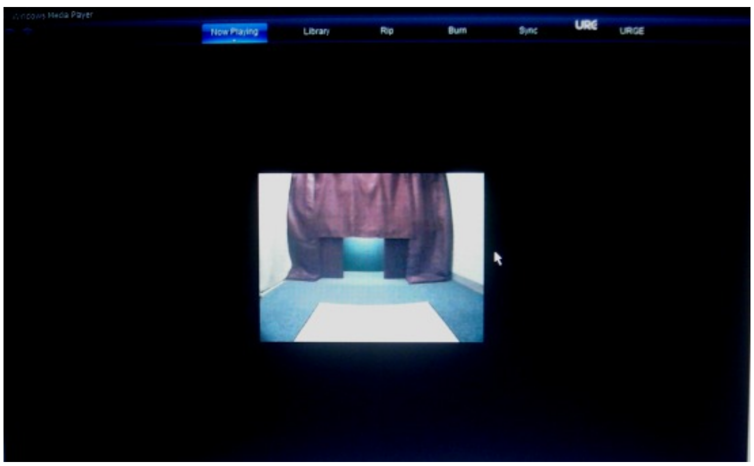

Figure 2: Participants video view using the Windows Media Player application.

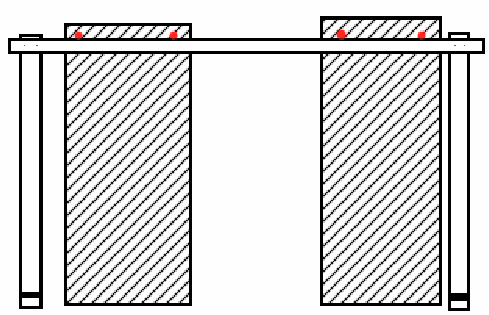

Figure 3: Computer generated image of the front view of the aperture apparatus.

gap sizes. The top of the aperture apparatus was marked at equidistant points from the center with the selected aperture widths. The edge of the panels lined up with these markings and both panels moved to create the aperture widths.

The apparatus was placed 2 feet in front of black foam board that spanned the width of the opening in order to create contrast between the aperture and the background and so that the background did not provide the participants with additional information. Additionally, a florescent light was attached to the top of the apparatus to ensure maximum light and contrast between the aperture and the background. The entire setup was placed on a 204" x 36" piece of Berber carpet. This carpet also functioned as the driving track. It covered up the floor and removed any additional information about the aperture that could be obtained by the 12" tiles on the floor (see Figure 4).

A pulley reporting device was used by participants in order to assess their perceived aperture width. This device consisted of one small, moveable, foam board indicator that was attached to the moveable string on the pulley device. Two additional foam board indicators were placed at either end of the device to act as width endpoints.

Figure 4: A picture of the aperture and carpet as described above.

The two end indicators had black lines on the inner edge and the moveable middle indicator had black lines along both edges to provide contrast between the indicator and its edge. A tape measure was connected to the experimenter's side of the track so that the participants' width estimates could be recorded to the nearest millimeter (See Figures 5a and 5b).

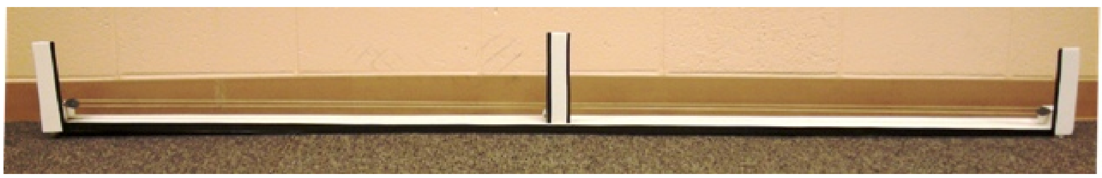

Figure 5a

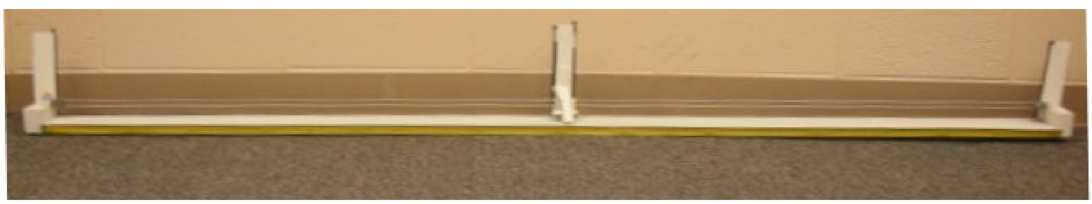

Figure 5b

Figures 5a and 5b: Aperture width estimation apparatus participant side (Figure 5a) and experimenter side with measuring tape for recording participant aperture estimates (Figure 5b).

Design

The experiment was a mixed repeated measures design. The participants were divided into two groups. For half of the participants the robot was in the camera view throughout the experiment. For the other half of the participants the robot was not in the camera view throughout the experiment. For the robot in view conditions, the camera was placed at the back of the robot so that the front end of the robot was in the participants' camera view (see Figure 6a). For the robot not in view conditions, the camera was placed at the front of the robot so that the front end of the robot was not in the participants' camera view (see Figure 6b). For all viewing conditions, a second model of the robot was placed on the floor next to the participant to act as a reference. Both groups had two viewing conditions: optic flow and no optic flow. In the flow conditions, participants viewed the robot moving on the monitor as the robot drove

Figures 6a and 6b: Camera placement at the rear of the robot for the in view condition (6a) and camera placement at the front of the robot for the not in view condition (6b).

forward 2 m to its viewing destination. In the no flow conditions, participants viewed a static image of the robot at its viewing destination. Additionally, there were three viewing distances at which the front of the camera stopped for all four conditions: 1.0 m from the aperture, 2.0 m from the aperture, and 3.0 m from the aperture. For these three different distances there were 5 viewing angles (see Table 1) that were held constant in order to make aperture sizes at the three distances appear the same width on the viewing screen. The participants received each of the 15 distance x viewing angle combinations

Table 1: Aperture widths at the five viewing angles in degrees (VA) and three distances (D).

	VA1: 8.578	**VA2: 11.421**	**VA3: 14.250**	**VA4: 17.062**	**VA5: 19.852**
D1: 1.0 m	15.0 cm	20.0 cm	25.0 cm	30.0 cm	35.0 cm
D2: 2.0 m	30.0 cm	40.0 cm	50.0 cm	60.0 cm	70.0 cm
D3: 3.0 m	45.0 cm	60.0 cm	75.0 cm	90.0 cm	105.0 cm

twice within both flow conditions for a total of 30 trials per flow condition and 60 trials overall per participant. The order of presentation for the 30 trials with each flow condition was randomized.

Procedure

Upon completion of the informed consent document, participants were tested for normal or corrected to normal (20/40) vision using a LogMAR chart at 6 meters to determine their ability to accurately see what was presented to them and to ensure that any differences in performance were not due to differences in acuity. After the participant's vision was assessed, they were shown the robot, the camera placement on top of the robot, and the aperture apparatus. They were then taken to the computer and shown three separate static images taken at the three different distances. These images all had the same visual angle and demonstrated that apertures of different sizes may appear to be the same size on the screen.

Following the width familiarization task, the participant began the experiment. The experimenter loaded the appropriate playlist into the Media player and played the video using the fast forward feature. Once the video reached the end, the experimenter paused it so that the participant had as much viewing time as they needed to make their width estimations, and so that there was a clear separation between trials. The participants were presented with two different conditions: optic flow and no optic flow. In the flow condition, participants watched the video on the screen as the robot moved 2 m forward so that the camera was located either 1.0 m, 2.0 m, or 3.0 m from the aperture (see Figure 7). In the no flow condition, participants did not observe as the robot moved forward. Instead, they watched a stationary video of the aperture from the robot's viewing point, either 1.0 m, 2.0 m, or 3.0 m from the aperture. While the duration of the flow videos was slightly longer than the no flow videos, participants were allowed to view the paused image of the aperture at the viewing destination in both conditions for as long as they wanted in order to make their width estimation.

In both of the flow conditions, immediately following their viewing of the video or static image the participant turned around and moved the center indicator on the pulley so that the width from the end of the device to the corresponding side of the indicator reflected their perceived width of the aperture. Once the participant was content with their aperture width, it was recorded, the experimenter selected the next trial's video, the pulley was reset, and the next trial began.

The study took approximately 1 hour to complete. Upon completion, the participants were debriefed, thanked for their participation, and their course credit was awarded.

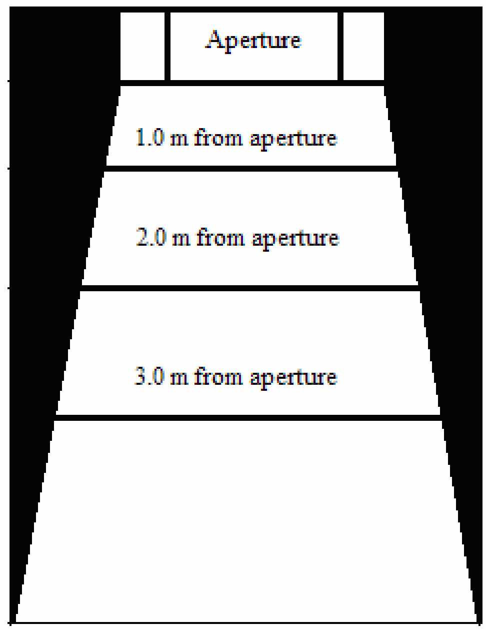

Figure 7: Teleoperation set-up. Shown is the aperture location as well as the three observation lines.

CHAPTER 3

RESULTS

Width Perception

The original data contained a number of outliers. The data was screened with simple regressions in which casewise diagnostics were used to locate outliers. In a regression, these diagnostics simply identify those cases that are more than 3 standard deviations away from the mean of indicated widths for each actual aperture width. Put simply, it identifies those cases that are more than 3 standard deviations away from the best fit line for the regression. After running the regressions three separate times, a total of 56 cases out of 1920 cases were removed. This resulted in a removal of approximately 3% of the data points, and the remaining data was used in the following analyses.

Four Simple regressions predicting indicated aperture width from actual aperture width for each of the two viewing conditions (robot in view and robot not in view) and each of the two flow conditions (optic flow and no optic flow) are depicted in Figures 8 and 9, respectively. Each of the data points shown in Figures 8 and 9 are a single width estimate made by a participant for a particular width. For each condition, perceived width varied as a function of actual width; however, the slopes of these functions ranged from 0.762 to 0.780. The r^2 values for all conditions tended to be similar and the slopes of the functions were consistent over variations in both viewing condition and flow condition. Similar results were obtained from four simple regressions predicting indicated aperture width from actual aperture width for each of the four combined conditions (Flow, In View; Flow, Not in View; No Flow, In View; No Flow, Not in

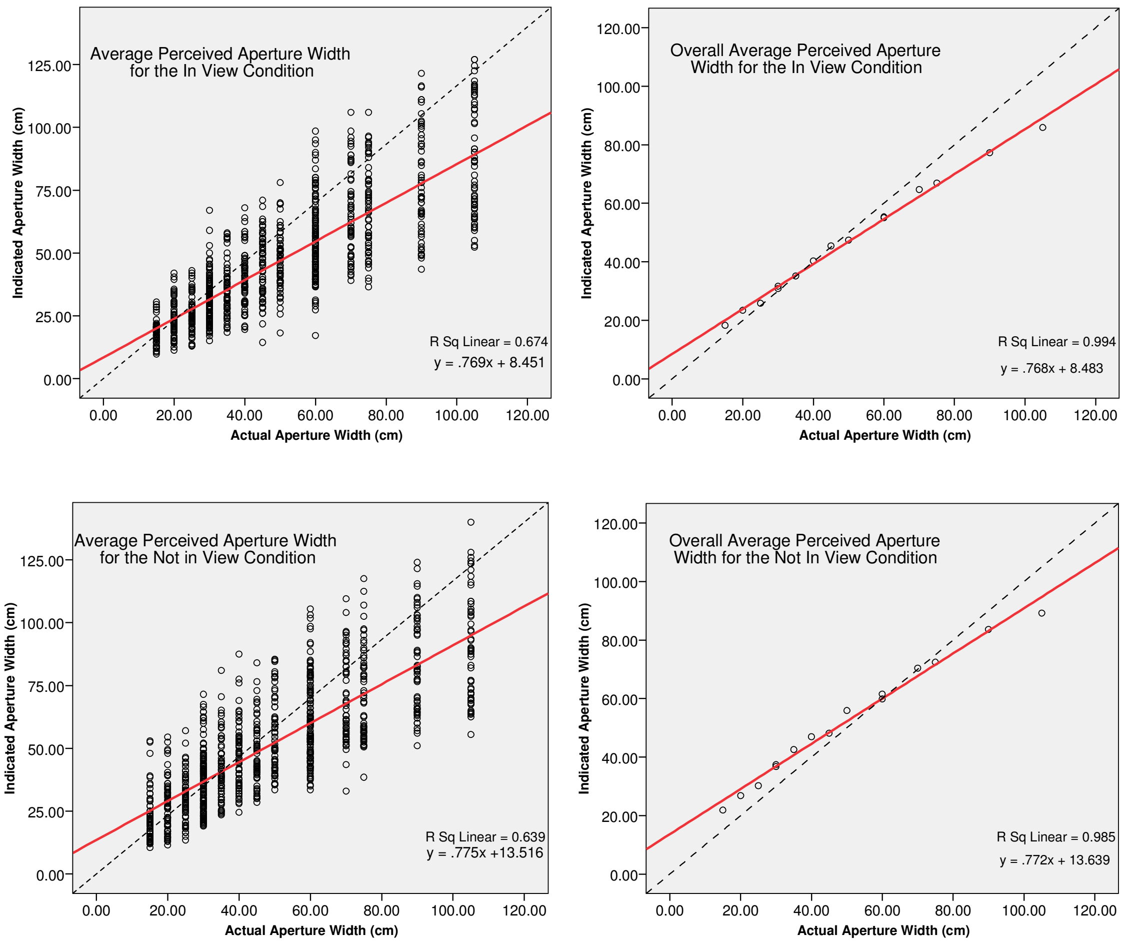

Figure 8: Average perceived aperture width as a function of actual aperture width for viewing condition. The red line is the line of best fit for the actual data and the dotted black line is the ideal line of perfect performance with a slope equal to 1 and a Y-intercept equal to 0, in which perceived performance would equal actual performance.

View) and from 12 simple regressions predicting indicated aperture width from actual aperture width for each of the four conditions at each of the 3 distances (Flow, In View at 1m, 2m, and 3m; Flow, Not in View at 1m, 2m, and 3m; No Flow, In View at 1m, 2m, and 3m; No Flow, Not in View at 1m, 2m, and 3m). The results from all 20 simple regressions are given in Table 2.

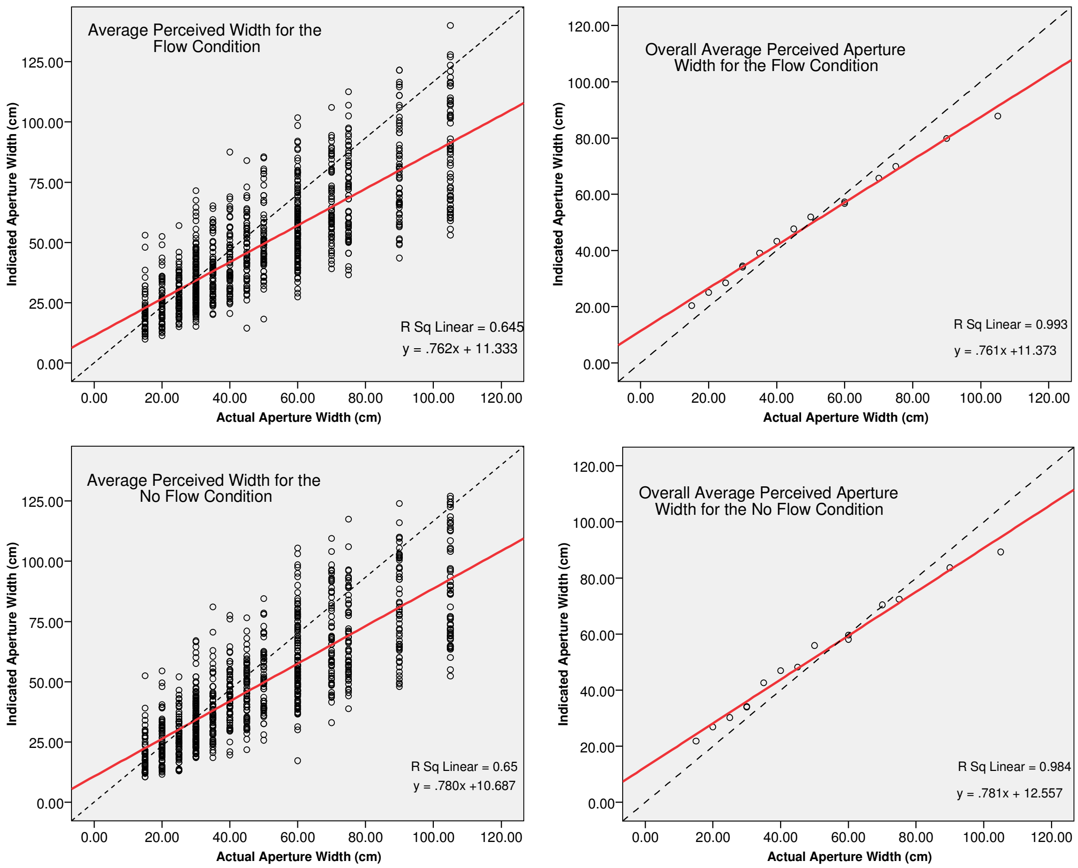

Figure 9: Average perceived aperture width as a function of actual aperture width. The red line is the line of best fit for the actual data and the dotted black line is the ideal line of perfect performance with a slope equal to 1 and a Y-intercept equal to 0, in which perceived performance would equal actual performance.

A multiple regression was conducted to determine if the slopes and intercepts differed as a function of viewing condition (in view or not in view). The multiple regression was conducted using actual width, viewing condition (coded orthogonally), and a term that used a viewing condition by actual width condition interaction to predict indicated width. The regression resulted in an $r^2 = .660$ ($n = 1863$) with a partial F of 3547.16 ($p<.001$) for the actual width, a partial F of 12.48 ($p<.001$) for the viewing condition, and a partial F of 0.05 ($p>.80$) for the interaction term. Partial Fs for actual width assess how much the actual gap width predicts the variation in the responses after accounting for the variation due to the other terms. The partial *F* for viewing condition assesses the degree to which the intercepts for the two viewing conditions differ from each other and tests for a main effect of viewing condition. The partial *F* for the interaction term assesses the degree to which the slopes for the two conditions differ from each other. When the multiple regression was conducted again without the interaction term, the partial *F* for the actual width became 3549.30 ($p<.001$) and the partial *F* for the viewing condition became 66.73 ($p<.001$). As the r^2 did not change after the interaction term was removed, it can be concluded that the interaction accounted for less than 1% of the variance in indicated width. When the multiple regression was conducted again without the viewing condition, the partial *F* for the actual width became 3419.21 ($p<.001$) and the $r^2 = .647$. This indicates that the viewing condition accounted for 1.3% of the variance in the indicated width. This shows a small but statistically reliable tendency to perceive the gap as being larger while the robot is not in view than when it is in view (see Table 3). Specifically, the intercepts and regression lines show that the participants perceived the gap width to be, on average, 5cm larger in the not in view condition in comparison to the in view condition. This 5cm overestimation accounts for 12.7% of the total width of the robot.

A multiple regression was conducted to determine if the slopes and intercepts differed as a function of flow condition. The multiple regression was conducted using actual width, flow condition (coded orthogonally), and a term that used a flow condition by actual width condition interaction to predict indicated width. The regression resulted

Table 2: Simple regressions predicting perceived width from actual width as a function of view, flow, and distance conditions.

Condition	R^2	N	Slope	Intercept
In View	.67*	940	0.77	8.45
Not in View	.64*	922	0.78	13.52
Flow	.65*	929	0.76	11.33
No Flow	.65*	933	0.78	10.69
Flow, In View	.67*	468	0.76	8.81
Flow, Not in View	.64*	460	0.77	13.77
No Flow, In View	.68*	471	0.78	8.81
No Flow, Not in View	.64*	461	0.78	13.26
Flow, In View				
1m	.41*	158	0.86	5.50
2m	.41*	157	0.78	8.22
3m	.41*	151	0.68	14.62
Flow, Not in View				
1m	.30*	159	0.99	6.86
2m	.35*	153	0.74	16.41
3m	.40*	146	0.69	19.42
No Flow, In View				
1m	.37*	159	0.79	6.58
2m	.45*	158	0.83	6.71
3m	.39*	152	0.69	14.82
No Flow, Not in View				
1m	.33*	159	1.09	4.69
2m	.41*	153	0.86	11.36
3m	.42*	147	0.70	18.12

* $p \leq .001$

in an $r^2 = .65$ ($n = 1863$) with a partial F of 3416.75 (p<.001) for the actual width, a partial F of 0.20 (p>.60) for the flow condition, and a partial F of 0.47 (p>.40) for the interaction term. When the multiple regression was conducted again without the interaction term, the partial F for the actual width became 3417.69 (p<.001) and the partial F for the flow condition became 0.13 (p>.70). The r^2 value remained .65. From this it can be concluded that the interaction accounted for less than 1% of the variance in indicated width. When the multiple regression was conducted again without the flow condition, the partial F for the actual width became 3419.21 (p<.001) and the r^2 again remained 0.65. This indicates that the flow condition accounted for less than 1% of the variance in the indicated width. The difference between indicated widths for the two flow conditions was not substantially different, which indicates that there was no effect for flow condition. These multiple regressions confirm that participants perceive width in a similar manner for both flow conditions (see Table 3).

In order to asses if the participants were basing their width estimates on visual angle, multiple regressions were conducted to predict indicated aperture width from actual gap width and the visual angle created by the gap when the robot was positioned at the corresponding distance (which represents the size of the image width on the viewing screen). The visual angle equates to the different width images and their corresponding size on the monitor. Therefore, all widths with the same visual angle appeared to be the same width on the monitor. The first multiple regression using visual angle as a predictor was conducted for the no flow condition. The multiple regression resulted in an $r^2 = .65$ ($p < .001$, $n = 933$), with a partial F of 1189.85 ($p < .001$) for actual width and a partial F of 0.07 ($p > .70$) for visual angle. This regression was repeated without the visual angle, resulting in an $r^2 = .65$ and a partial F of 1731.06 ($p < .001$) for actual width, indicating that the participants were not basing their size judgments on the visual angle of the gap. Similar multiple regressions were conducted for the flow condition, as well as for the two viewing conditions (in view and not in view). The results obtained were similar to those in the no flow condition and can be seen in Table 4.

A multiple regression was conducted to predict indicated aperture width from actual gap width and the visual angle in the flow, in view condition. The multiple regression resulted in an $r^2 = .67$ ($p < .001$, $n = 468$), with a partial F of 667.19 ($p < .001$) for actual size and a partial F of 0.12 ($p > .70$) for visual angle. This regression was repeated without the visual angle, resulting in an $r^2 = .67$ and a partial F of 958.03 ($p < .001$) for actual width, indicating that the participants were not basing their size judgments on the visual angle of the gap. Similar multiple regressions were conducted for the flow, not in view condition, the no flow, in view condition, and the no flow, not in view condition. The results obtained were similar to those in the flow, in view condition and can be seen in Table 4.

Table 3: Multiple regressions determining if the slopes and intercepts differed as of function of viewing condition or flow condition.

		Partial F Value		
Condition	R^2	**Actual Width**	**Condition**	**Interaction**
View	.66	3547.16*	12.48*	0.048
	.66	3549.30*	66.73*	--
Flow	.65	3416.75*	0.20	0.47
	.65	3417.69*	0.13	--

n = 1864
* p ≤ .001

Table 4: Multiple regressions predicting indicated aperture width from actual gap width and the visual angle.

			Partial F Values	
Condition	R^2	**N**	**Actual Width**	**Visual Angle**
In View	.67	940	1366.63*	0.52
	.67	940	1940.40*	--
Not in View	.64	922	1113.22*	0.32
	.64	922	1629.33*	--
Flow	.65	929	1180.40*	0.70
	.65	929	1685.76*	--
No Flow	.65	933	1189.84*	0.05
	.65	933	1731.06*	--
Flow, In View	.67	468	667.19*	0.12
	.67	468	958.03*	--
Flow, Not in View	.64	460	562.54*	0.04
	.64	460	801.51*	--
No Flow, In View	.68	471	695.80*	0.44
	.68	471	979.19*	--
No Flow, Not in View	.64	461	548.31*	0.97
	.64	461	824.67*	--

* $p \leq .001$

CHAPTER 4

GENERAL DISCUSSION

The current study was an investigation of gap width estimations by a teleoperator in a remote environment. Participants were divided into two groups, robot in view and robot not in view. Each group viewed the aperture under two different conditions; an optic flow condition where the robot moved 2m forward toward the aperture so as to provide additional flow information and a no optic flow condition where the robot was stationary. For each condition, the participants watched as a pre-recorded video of the aperture played. Once they had watched the entire video, participants reported their aperture width estimations using manual, direct line of sight reporting device.

Overall, participants were able to determine aperture width accurately for either viewing condition or optic flow condition; however, it does not appear as though participants were relying on the visual angle to determine their width estimations. Thus while it appears that radial flow produced by the robot movement did not provide participants with any additional useful perceptual information about the width of the aperture, participants were using some information other than visual angle within the environment to perceive the aperture width.

Simple regressions were conducted to predict indicated aperture width from actual aperture width for each of the two viewing conditions (robot in view and robot not in view) and each of the two flow conditions (optic flow and no optic flow). The data showed that the r^2 values for all conditions tended to be similar, ranging from .64-.67, and the slopes of the functions were consistent over variations in both viewing condition and flow condition and ranged from .76-.78.

Similar simple regressions were conducted for each of the four combined conditions (Flow, In View; Flow, Not in View; No Flow, In View; No Flow, Not in View) and for each of the four combined conditions at each of the 3 distances (Flow, In View at 1m, 2m, and 3m; Flow, Not in View at 1m, 2m, and 3m; No Flow, In View at 1m, 2m, and 3m; No Flow, Not in View at 1m, 2m, and 3m). The r^2 for these regressions were still consistent, but were much smaller than for the flow or viewing condition regressions. The r^2 for the four combined conditions ranged from .64-.68 with slopes ranging from 0.76-0.78. The r^2 for the twelve distance conditions ranged from .30-.45 with slopes ranging from 0.69-1.09.

In conducting these simple regressions, two trends were revealed. The first of these showed that variability in perceived width changes as a function of aperture width. Secondly, as viewing distance increases the slopes decrease and the intercepts increase. Specifically, the range of responses increases with the distance from the aperture, indicating that accuracy is diminished. This finding is consistent with previous research (Moore et al., 2006).

Several multiple regressions were conducted in order to predict indicated aperture width from actual gap width and a variety of other variables. The first of these was a multiple regression conducted to determine if the slopes and intercepts differed as a function of viewing condition. The multiple regression used actual width, viewing condition (coded orthogonally), and the viewing condition by actual width condition interaction to predict indicated width. Overall, actual width was a good predictor of indicated width [$r^2 = .66$, partial F = 3547.16 ($p<.001$)]. Running the regression again without the interaction term revealed that it accounted for less than 1% of the variance. Running the regression a third time without the viewing condition revealed that it accounted for 1.3% of the variance. Thus, there was a small, yet statistically reliable, tendency to perceive the gap as being larger while the robot is not in view compared to when the robot is in view. While a 1.3% contribution to variability in aperture size estimation may seem small, in the context of the present research it is very meaningful. Because we used a large range of aperture widths (90 cm range between the smallest and largest apertures), and a large possible range for estimation (215 cm range on the reporting device), the large variance in actual aperture widths accounted for a very large proportion of the variance in the participants' judgments. If we had used a smaller range of aperture widths then the viewing condition would have accounted for a larger percentage of the variance in the participants' judgments. Additionally, this 1.3% was found under ideal conditions where participants had the opportunity to use additional information from the clean, well-lit environment to make their width estimations. In a highly deconstructed environment, like that of the September 11 aftermath, operators would have to rely more on information such as having the robot in view in order to be able to make their judgments. Consequently, the 1.3% contribution would increase. This finding could have serious implications for field operators. It is known that operators have difficulty determining if the robot they are controlling can fit through an opening (Casper & Murphy, 2003; Moore et al., 2006). This consistent 5 cm (or 12.7 % of the total robot width) overestimation could mean the difference between fitting through an opening or not. Knowing the tendency to overestimate the size of the robot should it not be in view, operators could be trained to calibrate their width estimations while working with these types of robots.

A second multiple regression was conducted to determine whether the slopes and intercepts differed as a function of flow condition. The multiple regression used actual width, flow condition (coded orthogonally), and a term that used a flow condition by actual width condition interaction to predict indicated width. Overall, actual width was a good predictor of indicated width [$r^2 = .65$, partial F = 3416.75 ($p<.001$)]. Again, actual width was a good predictor of indicated width. When the regression was run a second time without the interaction term, it was determined that the interaction accounted for less than 1% of the variance. Similarly, when the regression was run a third time, it was determined that the flow condition did not account for a significant portion of variance in the indicated width. There is a possible explanation for this finding that can be seen in the method for this experiment. While both viewing condition and flow condition were randomized, the two variables were never completely separated from one another. Trials were randomly mixed together in order to create a play list of 60 videos. These play lists included both the flow and no flow videos, which resulted in participants potentially seeing a flow video first, thus biasing their perception of any subsequent videos. In other words, there was no pure no-flow condition for participants to experience. In order to control this condition better and to be able to conclusively determine if flow has an effect, future experiments should block and then counterbalance the presentation of flow and no flow. For example, some participants would view no flow first and others would view flow first. Conducting the experiment in this way would allow experimenters to analyze the information by conducting regressions comparing those who received flow first vs. those who received no flow first. The difference in performance between the two conditions would clearly show the affect of flow on performance.

Another series of multiple regressions was run to predict indicated aperture width from actual gap width and the visual angle (which represents the size of the image width on the viewing screen) created by the gap when the robot was positioned at the corresponding distance. These were run for both of the flow and no flow conditions, both viewing conditions, as well as combinations of the two (e.g. flow, in view). For all of these regressions it was determined that participants were not basing their width estimations on the visual angle on the screen. This begs the question, then, what were the participants basing their estimates on? There could be several explanations for these findings. First, it was already mentioned that participants used the actual width of the gap to make their estimations. Participants were able to use the actual size of the aperture instead of the size on the screen, and thus their retina, to determine how wide a gap was. Second, while optic flow did not return any significant results in this study, it is quite possible that it had an effect that is unseen. As mentioned previously there was a lack of a completely static (no-flow) condition. It is possible that participants received information from the flow condition that they were then able to translate to the no flow condition in order to make their width estimations. This transferal would explain why participants were able to complete the task in both conditions as well as for the lack of difference in results between the two conditions. A third explanation requires there to be some other information within the environment that participants perceived in order to determine their estimates. Due to the limitations of this study, however, it is impossible to determine conclusively what this additional information was.

Recalling previous research (Casper & Murphy, 2003; Murphy, 2004), operators had difficulty performing in remote environments such that they had difficulty determining if the robots they were operating could pass through various apertures or maneuver around obstacles. The question arises, then, why were participants in this experiment able to perform well in all conditions? The answer lies in several other potential sources of information from which participants could have obtained information that made it possible for them to do the task in all conditions. The first of these is texture gradients (Gibson, 1950). The right wall of the driving track was a cinderblock wall that had equidistant block spacing. As the participant viewed the environment, it is possible that the spacing between the blocks as well as the consistent size of the blocks themselves provided them with enough information to base their width estimations off of. In order to control for this potential source of information, further studies should take measures to ensure that both track walls as well as other elements of the visual environment lack additional information.

Another source of possible information lies in the aperture construction. The horizontal panel of fabric that created the top of the aperture also provided the participants with a basis for visual comparison between widths. While the visual angles remained constant and, if measured, were the same width on the screen (see Figure 10), the difference of where the panels hit on the top curtain was visually dissimilar. In fact, several participants commented that they used the panels' position or characteristics of the hanging curtain (e.g. wrinkles or proportion open vs. covered) instead of the gap width to make their width estimates. In order to control for this, future studies would have to be much more basic instead of applied. Put simply, the environment would have to be more controlled and there should be no defined top or bottom to the opening.

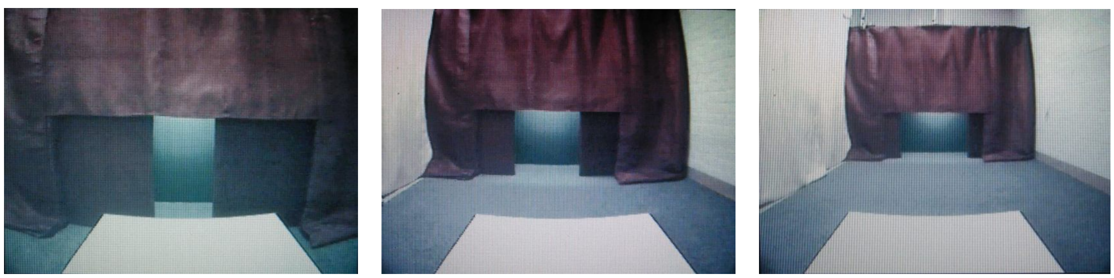

Figure 10: Three images from the familiarization videos. The aperture in each has the same measured size on the monitor (1.3 cm when viewed at the appropriate size) yet they each have a different visual appearance.

A third potential area of information was in the familiarization task. While viewing the static images, participants were told that even though gaps may appear the same on the screen, it was possible for them to be different sizes. This information could have primed them to expect different widths and made them more prone to a larger range of estimations. One participant in particular commented that they focused on the robot's distance from the gap. Because of the priming information, the participant assumed that when the robot was further away the openings were larger. In order to control for this, further studies would have to test participants with and without the additional information. In other words, prime one group and leave one group to attempt the task without the familiarization information.

The question arises of why the results from this study were so different from those of the Moore et al. (2006) study on which this experiment was based. The differences were due in part to the fact that the Moore et al. study was designed to look at passability and not width estimates. The method of limits was used for Moore et al.'s study to assess passability boundaries. With this method the width of the aperture was progressively widened or narrowed until it reached the size that the participant judged the robot could just pass through. The participant then judged the size of the resulting aperture. This method did not provide a large enough range to assess the statistical significance of the relationship between actual aperture width and indicated aperture width. Because the participants perceived the robot size the same every time, and were simply identifying when the aperture width reached that perceived width, the aperture range was considered small. The current study utilized the method of constant stimuli, which provided the participants with a larger range of aperture widths by providing participants with widths that were clearly bigger and smaller than the width of the robot. This is what created the larger range, and thus allowed for the more accurate representation of the relationship between actual and indicated aperture widths.

As there were several potential areas for interference with the effects of optic flow, it is important that further research in this area of study be conducted. Future studies should ensure that there are no sources of interference that detract from the benefits of optic flow. Doing so will help determine what makes performing well in a remote environment so difficult for trained operators in the field and less difficult for untrained students in an experimental setting.

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