MODELING HUMAN-ROBOT INTERACTION IN THREE DIMENSIONS

A Dissertation

by

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ABSTRACT

This dissertation answers the question: *Can a small autonomous UAV change a person's movements by emulating animal behaviors?* Human-robot interaction (HRI) has generally been limited to engagements with ground robots at human height or shorter, essentially working on the same two dimensional plane, but this ignores potential interactions where the robot may be above the human such as small unmanned aerial vehicles (sUAVs) for crowd control and evacuation or for underwater or space vehicles acting as assistants for divers or astronauts. The dissertation combines two approaches– behavioral robotics and HRI– to create a model of "Comfortable Distance" containing the information about human-human and human-ground robot interactions and extends it to three dimensions. Behavioral robotics guides the examination and transfer of relevant behaviors from animals, most notably mammals, birds, and flying insects, into a computational model that can be programmed in simulation and on a sUAV. The validated model of proxemics in three dimensions makes a fundamental contribution to human-robot interaction. The results also have significant benefit to the public safety community, leading to more effective evacuation and crowd control, and possibly saving lives. Three findings from this experiment were important in regards to sUAVs for evacuation: i) expressions focusing on the person, rather than the area, are good for decreasing time (by 7.5 seconds, $p < .0001$) and preference (by 17.4 %, $p < .0001$), ii) personal defense behaviors are best for decreasing time of interaction (by about 4 seconds, $p < .004$), while site defense behaviors are best for increasing distance of interaction (by about .5 m, $p < .003$), and iii) Hediger's animal zones may be more applicable than Hall's human social zones when considering interactions with animal behaviors in sUAVs.

DEDICATION

This dissertation would not have been possible without:

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1. INTRODUCTION

Small unmanned aerial vehicles (sUAVs) are becoming more common, which will likely lead to adoption by law enforcement [1] and other public safety entities [2], while also being proposed by companies such as Amazon for delivery interactions [3]. This accelerated adoption will necessitate an understanding of how humans will react by distancing themselves from these vehicles and require an autonomous capacity to interact in an appropriate manner. Other use cases which are being considered and which will be focused on close proximity, indoor interactions include: the Personal Satellite Assistant (PSA) project being developed by NASA and tested on the International Space Station, as well as the popular culture use of "helper" sUAVs on shows such as Marvel's Agents of S.H.I.E.L.D. in which they are used to augment crime scene technicians to gather laser scans of the environment. With the expectation that sUAVs are becoming more ubiquitous, as well as the applications to personal assistant robots, deep water robots for oil and gas rigs, and proposed delivery services, it is important to understand the nature of expected interactions and the impact of an sUAV on human movement.

When considering interactions with robots, it has been natural to map interactions from human-human interactions because the majority of robot interactions to this point have focused on ground robots, but when we begin to consider interactions with sUAVs it is natural to look to animal behaviors for insights into natural modes of interaction. Birds, insects, and ground based animals are able to communicate with other species in the cases of hunting, site defense, and personal defense. For this work, we are only considering site and personal defense, but these behaviors can be used to change the movement of other, much larger, animals; one example would be to consider a dog approaching a bird's nest, the bird will begin a site defense behavior which may be composed of individual expressions such as "feign injury" to draw the dog in another direction or "swoop and hit" to startle the dog and encourage the dog to withdrawal. Most humans have likely encountered these behaviors and have potentially even changed their movements in response to a bird or wasp displaying negative behaviors. It is expected that inspiration can be drawn from these behaviors, both site and personal defense, to create a model of how a sUAV can impact human movements and how these interactions are different from human-human or human-ground robot interactions.

This section begins with the primary and secondary research questions that guided the investigation of this dissertation work. Section 1.2 discusses the importance of an autonomous UAV and the need for ease of interaction. In Section 1.3, the use of animal behaviors will be explained. Section 1.5 provides the contributions of this dissertation work. Finally, Section 1.6 will outline the organization of this dissertation.

1.1 Research Question

The primary research question that this dissertation work addresses is:

Can a small autonomous UAV change a person's movements by emulating animal behaviors?

sUAVs interacting with people who are not controlling them is a novel research area and that the current understanding of human-human and human-ground robot interactions may not be applicable. This void is important when considering the safety implications of interactions with an uninformed public and will be necessary to prevent incidents which may negatively impact adoption. The main research question seeks to answer whether a sUAV can change a person's movements, which was tested in a simulation study. Animal behaviors were implemented to gain insights into how to change the movement of a larger animal and will result in two models of animal behavior: site and personal defense, which will be recommended for testing in a staged-world interaction. Finally, results from the experiments will provide feedback to a predictive model of human distancing.

This research question can be decomposed into the following four secondary research questions:

1. *What do we know about how humans and robots impact peoples' movements?* This question is addressed in Chapter 2 and results in a "Comfortable Distance" model which formalizes the factors that impact comfortable interaction distance, but are limited to two dimensional interactions and is later expanded using feedback from the experiments and insights from the animal models.

2. *How do animals influence others movement in interspecies interactions?* This question is addressed in Chapter 3 through a comprehensive review of animal literature, focused on site and personal defense interactions, and allows insight into the essential components for influencing movement which expanded the agent factors in the "Comfortable Distance" model. The results from this question are synthesized into two models of site defense and personal defense which were implemented in a simulation study for testing.

3. *Do approaches of an aerial vehicle cause peoples' movements to change in the same way as HHI or HRI interactions?* This question would lead to a simple mapping of the current "Comfortable Distance" model if true, but has been addressed by Duncan and Murphy [4] and the preliminary results indicate that the answer is "no," as shown in Section 2.2.

4. *Do approaches of an aerial vehicle cause peoples' movements to change in the same way as animal interactions?* This question would allow insights into perception of three dimensional interactions from a biological point of view and is addressed by the studies proposed in Chapter 6 through simulation interactions with human subjects. The results indicate that interactions with sUAVs displaying animal expressions might be better interpretted through the lens of Hediger's [5] animal social distancing than through Hall's [6] human social distancing, as discussed in Chapter 8.

This dissertation work is a comprehensive investigation of human movements generated by interactions with an autonomous sUAV using applied models of animal behaviors. The application domain used for this investigation is emergency evacuation, which led to an adoption of animal site defense behaviors. Results are fed into the "Comfortable Distance" model to better understand human distancing in interactions (and suggest future work) which is be applicable to domains outside of evacuation, and may include: entertainment robots, underwater and space assistants, and delivery robots.

1.2 Why an Autonomous sUAV?

Autonomous functionality is important when considering interactions with humans as a form of guarded motion, though this motion will be to guard the human or the interaction, rather than the vehicle itself. In order to ensure safe interactions and comfort for users, this functionality will need to be included as an option to be enabled, just like GPS lock or return to home. In this way, it removes the stress of interaction from both end users in public safety and the general public.

1.3 Why use Animal Behaviors?

Animal behaviors are being considered for the sUAV movements primarily because they provide an existence proof in the form that small birds and insects can cause movement change in larger animals, including humans. This proof allows for the consideration that their behaviors may be naturally understood by humans and that the behaviors when performed even by a sUAV will inspire a change in movement. The site defense behaviors have been selected because, as will be described further in Chapter 2, bottlenecks are the cause of the greatest loss of life in an evacuation and a rerouting of even 30% of people would result in a significant increase in survival rate at a fire [7]. Personal defense behaviors are also being used in order to allow the sUAV to display some self-protection instincts, as well as to decrease opportunities for humans to become injured due to inappropriate interactions or an assumption of safety.

Another reason to use animal behaviors is due to the work by Arkin [8] and Murphy [9], which indicates that behavior-based robotics paradigms can lead to natural mapping between sensing and reacting, and can also lead to shorter and easier to understand code. Throughout this document, perceptual schemas will be referred to as such or as what the agent is sensing and motor schemas will be referred to as expressions (because the animal literature discusses sub-schemas or sub-behaviors as behaviors and shifting terminology can become confusing).

1.4 Contributions

Five primary contributions are provided by this dissertation work to the fields of HRI, robotics, and public safety: i) the first work to suggest that sUAV interactions may not conform to the Computers are Social Actors model, ii) the first formal model of human distancing (the "Comfortable Distance" model), iii) the expansion of this model to incorporate findings from sUAV interactions, iv) a new set of recommended design guidelines for sUAV movements in close proximity to uninformed participants, and v) a better understanding of how these vehicles could be used in evacuations and other public safety applications.

Contribution 1: First Work to suggest that Interactions with sUAVs may not Conform to the Computers are Social Actors Model. This work presents the first formal study of human distancing with sUAVs (it is also the first for any size UAV), which suggests that humans do not distance themselves from sUAVs in the same way as humans or ground robots. This raises questions about safety in interactions between sUAVs and naive populations, which should be studied as a fundamental science question. This will impact the fields of HRI and the social sciences when approaching future studies on aerial vehicles, as well as the public safety community when considering how best to use these vehicles.

Contribution 2: First Predictive Model of Human Distancing. This work presents the first predictive model of human distancing which considers the attributes of the person interacting in addition to aspects of the environment and variables of the agent in the interaction. The experiments serve to validate this model with the personal factors being investigated as covariates, environmental factors being held constant, and agent factors being tested or controlled. This model was produced through a review of psychology, social science, and HRI literature and should be useful for all of these fields. An expansion of this model is also conducted through the addition of agent factors exhibited by animals in changing others' movements.

Contribution 3: First Formal Model of Human Movements and Distancing with sUAVs. This work presents the first formal study of human movement and distancing with sUAVs; it is also the first for any size UAV. The review of literature indicates a lack of research in the area of humans who are not controlling the UAV.

This will impact the field of HRI when approaching future studies on aerial vehicles.

Contribution 4: Recommended Design Guidelines for sUAV Movements in Close Proximity to Uninformed Participants. Due to the lack of research on interactions with sUAVs, there have been no recommended guidelines for interactions with sUAVs nor any guidelines for interactions with uninformed participants. With the increasing interest in these vehicles for public safety and corporate delivery, it will become more important to understand how bystanders will interact with these vehicles. These design guidelines will allow both fields to encourage safe interactions and discourage any potential injuries occurring from an assumption of vehicle safety.

Contribution 5: Understanding How sUAVs could be Used in Evacuations. It will be described in Chapter 2 why sUAVs are naturally suited to augment current evacuation capabilities, but this is unlikely to occur without being able to model how these vehicles would impact human movements. This technology could greatly improve the state-of-the practice in evacuation by removing ushers and public safety officers from harm's way while still informing crowds about potential exits through the use of animal behaviors.

1.5 Organization of the Dissertation

This dissertation is organized as follows. Chapter 2 serves as a review of the research literature for factors associated with human movement in evacuation, crowd control, sUAVs, human interactions, and ground robot interactions, as well as animal behaviors in human-robot interaction. Presented next in Chapter 3 is a review of animal behaviors for site and personal defense. In Chapter 4, the approach for this dissertation work is given. A comparison of human-human and human-ground robot interactions to human-aerial vehicle interactions is presented based on the work in Chapter 2.4 and it is recommended to perform a similar investigation for the animal interactions presented in Chapter 3. In order to accomplish this, the expression set of animal behaviors are be updated and guidelines for interaction experimentation and crowd interactions are presented. Chapter 5 describes the implementation of the animal behaviors on a sUAV in simulation, including the hardware and software specification. Chapter 6 presents the detailed experimental methods and design to assess the effects of these behaviors on human movements in simulation experiments. The results from the experiment are presented in Chapter 7, and are discussed further in Chapter 8. An overall summary, including a restatement of the main contributions and findings provided by this dissertation work, is given in Chapter 9.

2. RELATED WORK*

This literature review answers three questions: *How do small UAS interact with people who are not in control of the vehicle? Do other robots change a persons actions using animal behaviors? What do we know about how humans and robots impact peoples' movements?*. This dissertation examines evacuation as an example of the type of problem for which interactive sUAVs are naturally suited. Crowd control, crowd management, and human evacuation have all been thoroughly researched and contain insights into how to effectively use a robot in an evacuation. Evacuation robotics has only two interaction experiments, both with ground robots, and only one in a staged lab experiment. Interactive UAVs have not been used for real-world interactions, free-flying approach distance interactions, nor used with behavior-based architectures. The use of animal behaviors to impact human movement is relatively unexplored, with only one study suggesting future work in this area and having only performed robot-robot interactions currently. Approach distances are a common metric for human-human and human-robot interactions, so the experiments employing this metric are explored for insights into the factors that make people uncomfortable in an interaction.

Crowd control and crowd management were included for completeness and future work, but evacuation is the best fit for robot intervention due to the nature of the interaction and inherent danger to ushers and public safety officers. When reviewing papers in crowd management and evacuation, scientific technologies and survey papers over multiple disasters were included, but after-action reviews of single disasters were excluded due to the depth and lack of generality of the recommendations. For the robot evacuation papers, studies were included when they discussed agents aiding in an evacuation, but were excluded if they focused only on creating micro- or macroscopic crowd simulators. Interactive UAVs offer the ability to be dispatched to multiple floors, to see over crowds, and to augment closed-circuit television (CCTV) if necessary, but they might require a different set of interaction principles than ground robots. Papers were included if they discussed a small UAV interacting in the same room as a participant and were investigating the humans response to the shared location. The review of robots using animal behaviors to impact people's movements are included to determine whether there is a research gap in this area and what the results of other studies might suggest about the influence of animal behaviors. Research in this area is limited to a single paper and this lack of information establishes a research gap. A review of HHI and HRI studies is included to inform currently accepted rules of interaction in ground-based agents, and to suggest variables which should be controlled in experiments. Studies were only included if they involved an interaction where distance maintained was a measure, even if this was not the primary focus of the original study. Persuasive robotics is not included because this work is more concerned with blocking inappropriate paths than changing long-term beliefs and is traditionally focused on verbal interactions which are inappropriate for evacuations due to possible language barriers and loud noises.

First, a review of crowd management, crowd control, and evacuation is given in order to ground the necessary interactions and potential behaviors. Next, work in the area of interactive UAVs is presented. Then, a review of the use of animal behaviors to influence human movements is discussed. Finally, comfortable approach distance in both human-human and human-robot interactions is reviewed.

2.1 Crowd Management, Crowd Control, and Evacuation Methods

Crowd interactions are reviewed for general guidelines and completeness, but evacuation is the best fit for robot intervention. Recommendations for crowd management, crowd control, and evacuation both individually and collectively are presented to understand how crowds have been handled during emergency situations, the problems that may be encountered, and why evacuation is the area most ready for robot agents. Crowd management literature is reviewed for insights into how to control crowds before events happen in order to gain perspective on the most basic of tasks and as a direction for future work. As an event escalates past crowd management to crowd control, sources will be gathered from military and police guiding documents to inform crowd dynamics and interactions. Next, the four guidelines for evacuation were gathered from 6 papers examining after incident reviews of disasters in order to determine areas for improvement in human evacuations. Finally, 9 papers in robot evacuation research are reviewed with four findings presented while a gap is identified in behavior-based architectures and real world experiments.

From this review, it was determined that evacuation is naturally suited for UAVs because:

- They would allow ushers and officers to be removed from harm
- Could block bottlenecks to overcome the greatest impediment to a successful evacuation
- Provide additional views of the scene

Crowd control and crowd management have the potential for future development after successful testing with evacuation.

2.1.1 Crowd Management and Crowd Control

Abbott and Geddie [10] stated that "Crowd management and crowd control are two distinct but interrelated concepts. The former includes the facilitation, employment, and movement of crowds, while the latter comprises steps taken once a crowd (or sections of it) has begun to behave in a disorderly or dangerous manner." These are the working definitions that are used as the basis for the following reviews of crowd management and crowd control.

Before discussing the management and control of the crowd, crowds as a whole should be discussed. Kenny, McPhail, Waddington, Heal, Ijames, Farrer, Taylor, and Odenthal [11] sought to dispel rumors about crowds, they state that:

- "Crowds are not made up of isolated individuals, but a minority of individuals and a majority of small groups of people who are acquainted with one another."
- "Crowd participants seldom act in unison, and if they do, that action does not last long."
- "... research found that most people give as much effort and attention to others' well-being as they do to their own personal safety..."

2.1.1.1 Crowd Management

While this dissertation is primarily concerned with crowd control, or how to manage a crowd that is likely already disorderly, and evacuation, the principles of crowd management can still be used to inform understanding and communication with a crowd. These studies are also included for completeness in the hopes that this will be useful in future work with robots.

Abbott and Geddie [10] explored the significance of crowd management and crowd control as well as legal opinions of both adequate and inadequate crowd management techniques. As mentioned in the opening for this section, they defined the difference between crowd management and crowd control to help event designers to understand the legal expectations that they will need to fulfill. They also said that "effective crowd management plan entails adequate communication" and is "...concerned with effectively organizing the movement of crowds." The five objectives they defined for effective communication, which should be applicable to any type of crowd movement, were: i) to send a message, ii) to have a message received, iii) to insure understanding, iv) to achieve corrective action, and v) to exchange information. These are traditionally accomplished through signage, announcements, or direct interaction with ushers or security guards.

Disney theme parks are recognized as experts in crowd management, so no review of crowd management techniques would be complete without a discussion of their secrets. Calling the techniques employed by Disney "secret" would be no overstatement, and while the literature is limited, there were two pieces of information which seemed relevant. In [12], where Borrie discusses why Disney is the standard for recreational parks, Borrie states that "Disney is one of the experts at crowd management. Visual magnets, ('weinies' in Disney parlance), such as castles, are seen at the end of each thoroughfare to draw you on." Another interesting technique was presented by Barnes in [13], where he analyzed how Disney makes the park experience more enjoyable by trying to minimize lines and discussed that Disney will selectively dispatch parades to areas that are less crowded in order to encourage people to move to these areas.

Ultimately, crowd management is concerned with passive control and is currently accomplished using ushers, signage, and PA systems, but could incorporate robots in the future.

2.1.1.2 Crowd Control

In order to determine how to effectively control a crowd, it is important to look at the ways in which crowd control has failed. As cited by Hopkins, Pountney, Hayes, and Sheppard [14], in their proposal of a crowd pressure monitoring system, the "principal cause of death at the Hillsborough disaster, in April 1989 was crush asphyxia," which was due to a lack of communication [15] to notify the crowd of the locked turnstiles that ultimately created a bottleneck.

Kenny, et. al [11] produced a set of recommendations and guidelines for crowd control using non-lethal weapons based on understood crowd behaviors. As mentioned previously, they started by dispelling commonly held beliefs about crowd behaviors. When trying to intervene in a crowd, a pyramid of potential points of intervention was created with motivation, confidence, stress, focus, and emotions in ascending order. Emotions change most rapidly and are sensitive to threats. Focus is the easiest to alter using ineffective focus, or active distractions, to encourage people to focus on personal needs.

Reicher, Stott, Cronin, and Adang [16] examine developments in crowd psychology to dispel the classical view that all crowd members should be treated as dangerous, but instead indicate that police should focus on collective identities within the crowd. This would allow them to more effectively advance the law-abiding agenda while calming or controlling the more hostile factions within a crowd. Further, they note the idea that crowd members will self-police in certain instances and that this can be more effective than an outsider actively intervening. This paper is more geared towards police at riots, but could be applicable in the context of robots at sporting matches and the idea that they might be more effective when viewed as a group member rather than agent of the police.

For insight into how to control a crowd, an examination into the way a crowd is perceived internally and externally is presented. It was noted by both Kenny, et al. [11] and Reicher, et. al that police should not treat all crowd members the same, but rather focus on the individuals causing problems; this is proposed because Reicher, et al. [16] argue that individuals do not lose personal identity, but shift to the social identity that has brought them into the group (e.g., my team versus theirs) and that an approach generalizing the crowd members can reinforce the idea that the police are the adversaries. Abbott and Geddie [10] point out that fans will act differently depending on the event, so security and evacuation procedures should be designed according to expected behaviors for a given group.

When agents are interacting with an unruly crowd, they should ensure that crowd members are treated as individuals to avoid encouraging an “us vs. them” attitude towards public safety officers.

2.1.2 Evacuation

Evacuation literature is presented to show that this area is best suited for the introduction of robotic agents and four guidelines for human evacuation are presented.

For the purposes of this document, evacuation is referred to by Rodriguez’s [17] first definition, ”withdrawal actions of persons from a specific area because of a real or anticipated threat or hazard”, rather than the second definition which considers the need for people to return after an evacuation from their home. In order to determine the likelihood of compliance with evacuation, Rodriguez identified the major factors that covary with evacuation compliance (in order based on level of empirical support): physical cues, social cues, personal warnings (versus impersonal), source credibility, being a female (versus male), and not owning a pet.

Sime [18] began with an investigation of 'affiliative' escape, where rather than being guided by panic, individuals are guided by the goal of rejoining their group before exit. The most common way for the group members to be located is by heading for the path from which the group entered. When examining the Summerland disaster, 72% of people who escaped and volunteered for interviews left by the main entrance and they were all members of groups. Of these participants, 73% left with one or more group members and these members were generally family group members. Most of the group members who exited alone were from mixed (not exclusively family) groups.

Sime [15] has identified a fundamental failure by the groups of engineering and psychology to acknowledge each other when considering the problem of evacuation, which necessitates a thorough review of both areas in this document. In his work, Sime summarized 3 fire disasters, 2 football stadium disasters, and 2 underground station evacuations. His findings were: delayed warning of the public was present throughout all; time to evacuate should not be only the time it takes for the crowd to move initially, but the time it takes to move to safety; and public address systems being used to give direction are more likely to be effective than alarm bells in getting people to move. This work also indicates that the two main impediments to evacuation are: leaving the way they entered and bottlenecks.

Hoskin and Spearpoint [19] present a study on emergency egress from stadia. Agreeing with Sime, they identify that people often attempt to leave the way they entered the stadium or attempt to exit near public transportation. They suggest that closed circuit television can be used with ushers to identify points of congestion and reroute the paths.

Graat [20] examined the factors that can effect the total egress time from a building or incident and determined that bottlenecks are created where the flow rate from one element in a path is greater than the flow rate of the next (e.g., from a foyer into a stairwell or hallway). Each bottleneck increases the risk that people can be crushed or trampled, due to increased motivation to move and resulting higher densities of people (greater than 2.5-3 persons per square meter), which causes a decrease in walking speed due to reduced personal space and feelings of crowding.

Pauls [21] examined environmental design and its impact on the movement of people at time of egress. This paper states that "... stair accidents pose a threat of injury that may be 2,000 times greater than that from structural failure..." Doorways and the edge effect that can be caused by them has been largely ignored in literature, but a preliminary study suggested that the effective width of a doorway of 910 mm is reduced to 560 mm in evacuation conditions.

From this literature, four main points should be considered in robot behavior design:

- Bottlenecks and crushing are the main impediment, but can be identified based on the density of people on CCTV (or robots).
- PA systems, rather than general alarms, should be used for direction when possible
- Group members should be allowed to exit together to avoid confusion when searching for their party.
- Edge effects can significantly decrease passageways, which results in a smaller area for the robot to guard.

2.1.3 Robot Evacuation

Current robotics research is lacking when considering the use of robots for large scale evacuation in a city or stadium, rather than single building fire evacuation, and the research has traditionally focused on multiple robot coverage, rather than single robot guidance or guarding. The use of behavioral robotics to guard dangerous areas is an open research area that has not been considered.

Robot evacuation has focused on two areas: assistive robots and modeling human behavior. Examples of assistive robotics include: coverage [22], robot-assisted discovery of evacuation routes [7, 23, 24], and robot design [24–26]. Modeling human behavior has considered how agents may guide evacuees or change their behavior [22, 27] and how human panic behavior escalates [28].

Models of microscopic and macroscopic evacuation, as well as space syntax models, are beyond the scope of this work since it is expected that the robot will be directed to an area by the event staff or incident commander based on the identification of a bottleneck or expectation of overcrowding.

2.1.3.1 Robot Assistance

Kim, Kim, Lee, Kang, and An [26] designed a robot for fire evacuation which was designed to be thrown into a fire site to gather environmental information, search for displaced people, and evacuate them from the fire site. This paper focused on the design of the robot rather than user testing or human interactions, so will not be described further.

Robinette and Howard have the most comprehensive studies on robot evacuation, starting with two multi-robot simulations in two dimensions [7, 28] and progressing to a full human study with a 3D simulation in [24]. The first study [28] worked on creating the rules for a human panic model and they using these rules to create evacuation robot behaviors. The robot would initially attract as much attention as possible, then head towards the exit and continue to oscillate between people and the exit in order to continue guiding any stragglers. This took place in simulation and indicated that trials with robots would help evacuate more people than trials without robots. In the next study [7], the number of people who would trust their memories over other people, "true believers," was varied and then the number of people who would trust the robots, "robot believers," was also varied. It was determined that between 30% and 70% of people in The Station Nightclub fire (the incident being modeled) were true believers and that with 30% of true believers, four robots provided a significant impact on survival with robot believers between 10% and 90%. Finally, in [24] two robot designs were compared in a 3D simulation by having users wander around in a mall environment, then introducing one of two evacuation robots. Neither robot was preferred significantly, so the designs will be considered, but the evacuation times were shorter with the robot half the time and the robots were followed 1/3 of the time, which is greater than the lower bound of 30% needed from [7].

Moshkina [25] designed a framework for affective robotic behavior and one of the dissertation experiments sought to identify the effect of negative mood and fear emotions by a humanoid robot on participants' perception of the robot and their compliance with a request to evacuate. The NAO robot was used by standing on a table and giving a tour, when the lights were shut off and the robot gave both an indirect and then a direct request to evacuate. The indirect request was "We need to evacuate immediately" and the direct request was "Please proceed to the exit." The combined negative mood and fear emotions conditions were the most effective, and the robot was identified as more compelling, convincing, and conscious with the participants complying more quickly. Additionally, no participants in the control condition complied with the indirect request while 29% and 31% complied in the mood and combined respectively. The downside was that there was a higher level of negative affect and a higher level of nervousness in the combined vs. control conditions.

Shell and Matarić [22] examined the use of a multi-robot system to deploy auditory beacons in an office building. The basis for the use of auditory beacons was that visibility rapidly deteriorates with smoke accumulation and the experiments by Withington [29] that showed people were between 40-90% faster at evacuating with directional beacons in a smoke filled room than when trying to exit without the beacons. Other points made in this paper were that robotics solutions allow for selective traffic monitoring and reports to emergency personnel and that HRI in evacuation is an interesting and open problem. This approach was tested both in simulation and with a robot deployment in a university building.

The majority of the work in robot assistance during an evacuation has been done in simulation, with only two studies having human interaction studies. When using robots for evacuation, 30% of people need to follow the robot to increase the survival rate and two interaction studies found that approximately 30% of people will follow a robot usher or listen to a robots directions.

2.1.3.2 Crowd Modeling

Three papers on crowd modeling are examined and two findings on agent-based evacuation are be presented.

Ferranti and Trigoni [23] proposed two "Evacuation Route Discovery mechanisms" and tested them in a 2D simulation to assess the impact of both exploration algorithms and area topology on the quality of discovered evacuation paths. This paper is included for completeness, but is not relevant to the current work.

Luh, Wilkie, Chang, March, and Olderman [30] sought to help guide people more efficiently by dividing them into groups and modeling evacuation as a network flow problem to overcome bottlenecks. This paper was only run in a 2D simulation, but the authors planned fire drills and virtual reality experiments to test their findings.

Rodriguez and Amato [27] investigate the interaction between agents and the influence this has on evacuation plans. Two main mechanisms were used to direct the agents: local barriers to an exit (physical or agent) and global direction with more complete information. The result was that giving only local information can increase evacuation time greatly, so global information should also be used to aid in the understanding of the local barriers.

When using robots as local barriers, their presence should be combined with global directions (e.g., the PA system) to avoid increasing evacuation time. As presented in the section on human evacuation, it was confirmed in simulations that groups will continue to move together.

2.2 Interactive Small UAVs

Interactive UAVs is a concept that has only been established in the last four years, but is likely to experience a rapid expansion in the near future. The 6 studies are varied and have attempted to replicate studies in HHI or HRI, but initial results suggest that UAVs may not follow established rules for ground-based interactions with humans or robots.

Duncan and Murphy [31] conducted the first study on social behavior in small UAVs to determine how the general public would interact with a sUAV both before and after observing an appropriate interaction. It was found that people would mimic others when they were unsure how to interact with UAVs, confirming the idea of "social proof".

Ng and Sharlin [32], studied social behavior in small UAVs using a Parrot AR.Drone to test the use of control gestures for collocated interactions with 5 users. This work sought to replace current UAV interfaces and future work was planned with the Kinect sensor.

Sharma, Hildebrandt, Newman, Young, and Eskicioglu [33] were the first to investigate the use of UAVs for communication. Eighteen participants observed 16 motions by the Parrot AR.Drone and then rated their perception using the Self-Assessment Manikin. They found that to increase the valence or arousal of a participant, space should be used more indirectly or the motion should be performed more quickly.

Liew and Yairi [34] considered the effects of noise and appearance on interactions with robots using a blimp and Parrot AR.Drone. This was tested by measuring the distance the participants maintained both when retrieving a box and rolling in a chair. The results indicate that the blimp might be a better social platform.

Duncan and Murphy [4] conducted the first collocated experiment in which a UAV approached a person to determine the appropriate height for interaction and to test whether UAVs conform to the norms established for human-human and human-ground robot interactions. The results suggested no difference in preference for height and that human-UAV interactions may not conform to established interaction differences.

Szafir, Mutlu, and Fong [35] investigated the ability for humans to gauge "intent", in the form of inferring the robot's path, through the use of both 3d simulation and interaction studies between a Parrot AR.Drone and a participant seated behind a table. When the robot used animation principles such as arcing, easing, and anticipation behaviors, the participants liked the operator more and felt safer in the interaction.

The main gaps in research with social UAVs are: the lack of research in natural interactions and in the use behavior-based robotics.

2.3 Robots using Animal Behaviors to Influence Movement

Animal behaviors have been used extensively in multi-robot interactions, internal drives for various robots, and as the basis for "pet" robots, such as Sony Aibo or Paro Seal, but none of these have been implemented with the sole purpose of influencing human movements or actions in the world. The closest study that exists proposes an extension of animal deception behaviors from robot-robot interactions to human-robot interactions.

Shim and Arkin [36] proposed the idea of using deceptive behavior adapted from animals for robot interactions and human-robot interactions, as well as potential uses, but have not completed HRI studies.

This dearth of research leads to a sizable gap which is examined extensively throughout this dissertation.

2.4 Factors in Approach Distance

The purpose of this section is to examine the relevant works from psychology and human-robot interaction in order to determine the factors that might affect a general model of comfortable distance, or how to influence human movements based on proxemic distancing. Papers were included in this review only if they used approach distance as a measure. This work is based on the CASA (computers are social actors) model by Nass, Steuer, and Tauber [37], which considers human studies to be directly applicable to human-computer and human-robot interactions; therefore the rest of this section presents both sets of findings together. Psychologists have studied environmental conditions extensively, but HRI researchers have not examined these conditions. Agent and personal factors have been examined by both psychologists and HRI researchers. It is important to isolate the factors by environment, agent, and human so that experimenters know the conditions they will try to isolate in an experiment versus the conditions they can change. As HRI experiments continue in this area, the model can be expanded in order to include new findings. For a more thorough review of these ideas, see Duncan and Murphy [38].

2.4.1 Environmental Conditions

Environmental conditions are those features of the environment that are readily identifiable and can be measured. The conditions that have been studied include: lighting, ceiling height, room size, barrier height, and location (indoor/outdoor).

Adams and Zuckerman [39] studied how lighting and room size impact personal space between for human-human interactions. Their findings demonstrated that a reduction in lighting has a similar effect on interpersonal space as a decrease in room size.

Cochran and Urbanczyk [40] examined how different ceiling height conditions impact personal space for human-human interactions. This study determined that a lower ceilinged room resulted in a larger interpersonal distance being required.

Cochran, Hale, and Hassim [41] investigated how indoor and outdoor locations impact personal space for human-human interactions. The indoor space had a significantly larger interpersonal distance than the outdoor space. In this study, the ceiling height was unbounded in the outdoor condition.

Room size is centrally related to all environmental condition findings.

1. Room size is inversely related to personal space [39].
2. Lighting is directly related to room size [39].
3. Ceiling height is directly related to room size and outdoor locations are considered to have a ceiling of infinite height [40, 41].

2.4.2 Personal Factors

Personal factors are those features of the human that are identifiable and whose impact can be measured. The factors that have been studied include: gender, age, mood, personality, pet ownership, robot experience, and position (sitting/standing).

Kinzel [42] studied the impact of the angle of approach on interpersonal distance in violent prisoners for human- human interactions. This was the first study to use the stop distance technique and was the only study found to take mood into account. This study showed that the average rear personal zone was larger for violent prisoners and that the average front zone was larger for non-violent prisoners. The total zone was over four times larger for violent prisoners.

Mumm and Mutlu [43] examined the four models of interpersonal distancing (Reciprocity, Compensation, Attraction-Mediation, and Attraction-Transformation) for human-robot interactions. To do this, they studied the impacts of pet ownership, and gender on human-robot distancing with the Wakamaru robot. This study found that males distanced themselves further than females and pet owners distanced themselves further than non-pet owners.

Takayama and Pantofaru [44] investigated human-robot distancing based on pet ownership and robot experience. This study showed that pet owners and people with at least a year of robot experience maintain a smaller distance from the PR2 robot and that gaze combined with gender has a significant impact on distance.

Syrdal, Dautenhahn, et al [45] examined the effects of subject personality and the impact of the position of the subject, sitting or standing, on the preferred approach direction of the Peoplebot robot. The effects in this study were too small to be considered significant for the sample size used in the experiments, but suggest that higher extraversion scores led to a better tolerance of inappropriate robot behavior.

Syrdal, Koay, et al [46] studied the role of individual differences on spatial preferences, but focused on the impact of personality on human-robot distancing with the Peoplebot robot and the impact of gender on approach angle. As part of this study, the authors identified a set of external (cultural norms, situational/interactional context, degree of acquaintance between actors, and relative social status between actors) and internal factors (gender, personality, physical attributes, health and medical factors, and other individual differences). This study showed that gender impacts approach angle preference, and that extroversion and conscientiousness impact distance.

Walters, Dautenhahn, et al [47] examined the impact of personality on human-robot distancing with the Peoplebot robot. This study showed that proactive subjects allowed the robot to approach closer.

Pacchierotti, Christensen, and Jensfelt [48] investigated hallway passing behaviors for human-robot interactions with the Peoplebot using robotics students as subjects with the goal of embodying social intelligence. This study was used to test parameters of the robot and found that users preferred a robot to move fast (between 0.25 to 0.39 meters per second), but this might be explained by the participants comfort level with the robot. Another finding is that there were two types of users: those who treated the robot as a person and those who treated the robot as a machine.

Oosterhout and Visser [49] studied the impact of person age on likeability and approach distance for human-robot interactions with Mobi, Sr. and Mobi, Jr. Children were 3.5 times more likely to interact with the short robot, while young adults were 7 times more likely and adults are 2.8 times more likely to interact with the taller robot. There was a 0.63 meter difference between the two robots.

Personal factors were varied and sometimes conflicting based on their reporting in the literature.

1. The main gender finding was that males distanced themselves further than women from robots [43, 46].

2. Age was only examined in one study with the participants grouped into children, young adult, and adult. Young adults showed the most sensitivity to robot height and were 7 times more likely to interact with a tall robot than a short robot [49].

3. Mood has only been studied with regard to violent prisoners, and this study showed that violent prisoners had a total personal space zone that was four times larger than other prisoners [42].

4. Different personality dimensions were explored, and it was suggested that: extroverts had a better tolerance of inappropriate robot behavior and proactive subjects allowed the robot to approach closer [45–47].

5. Pet ownership findings were conflicting, with one study suggesting that pet owners distance themselves further from a robot [43], and the other suggesting the opposite [44].

6. Experience with robots led to users who maintained a smaller distance from the robot [44] and preferred a faster moving robot [48].

2.4.3 Agent Factors

Agent factors are those features of the agent that can be changed based on the situation. The factors that have been studied include: angle of approach, height of agent, speed of approach, and gaze.

Adams and Zuckerman [39] studied the impact of the angle of approach on interpersonal distance for human-human interactions. Only females were included in this study, and the experimenter who approached them was also a female. Their study showed that as the direction of approach moved from front to rear, the distance requirements increased.

Kinzel [42] examined the effect the angle of approach on interpersonal distance in violent prisoners for human-human interactions. This study showed that the average rear personal zone was larger for violent prisoners and that the average front zone was larger for non-violent prisoners.

Caplan and Goldman [50] investigated personal space violations as a function of height in human-human interactions. This study showed that people were more likely to invade the personal space of a short person over a tall person, regardless of gender.

Hartnett [51] reported on how interpersonal distances changed based on whether the participants were approaching someone who was sitting versus standing, and whether standing height had any effect on this distance in human-human interactions. People maintained twice as much distance from a tall person than a short person. Females approached more closely to someone who was sitting and males approached more closely to someone who was standing.

Mumm and Mutlu [43] examined the four models of interpersonal distancing (Reciprocity, Compensation, Attraction-Mediation, and Attraction-Transformation). To do this, they studied the impacts of gaze behavior on human- robot distancing with the Wakamaru robot. This study found that as gaze increased, so did the distance between the human and the robot.

Takayama and Pantofaru [44] studied human-robot distancing based on gaze behaviors with the PR2 robot. This study showed that gaze combined with gender has a significant impact on distance.

Oosterhout and Visser [49] investigated the impact of height on likeability and approach distance for human-robot interaction with Mobi, Sr. and Mobi, Jr. Children were 3.5 times more likely to interact with the short robot, while young adults were 7 times more likely and adults are 2.8 times more likely to interact with the taller robot. There was a 0.63 meter difference between the two robots.

Agent factors have not been very well studied in the literature.

1. Angle of approach was found to increase comfortable approach distance as the angle moved from front to back [39, 42].

2. Height had an effect in that the taller an agent is, the less likely people are to invade its space [49, 50].

3. The suggested approach speed for comfortable distance trials is approximately 0.15 to 0.20 meters per second to minimize measurement error [51].

4. An increase in gaze usually results in a larger personal space being necessary [43, 44].

2.5 Summary

This review has established four major research gaps and made an argument for both the use of interaction distancing as an experimental measure and the necessity to overcome bottlenecks in evacuation. The four research gaps identified are:

- Using robots for site defense rather than as guides in an evacuation

- Staged-world interaction studies for robot evacuations without verbal communication

- Distance studies with small UAVs and how distances change based on display behaviors
- Animal behaviors by robots for influencing human movements

Based on these four gaps, this dissertation seeks to advance fundamental knowledge in robotics research and will have broad applications in the real world.

Crowd management and crowd control are more involved concepts and are left for future work. Human evacuation literature identifies bottlenecks as the greatest failure point, which is naturally suited for the use of robots in order to remove humans from harm while still providing guidance. Robotic evacuation has shown that robots will be followed around 30% of the time when used as ushers and that global information should be provided at local barriers such as robots. Factors in approach distance established distancing as a measure and suggests environmental conditions and personal factors to measure in an interaction, but may not be applicable to UAVs based on the findings from social UAVs. Social behavior in UAVs has shown a gap in the area of real-world interactions and behavior-based approaches.

3. BACKGROUND: ANIMAL BEHAVIORS

This section answers the question: *How do animals influence others movement in interspecies interactions?* Interspecies interactions were the focus due to communication limitations and animals were studied due to their ability to influence the interaction distances of both humans and other large mammals. This review focused on books covering ethologies of multiple animals and animals displaying defensive or aggressive behaviors. Individual studies were excluded to encourage the synthesis of behaviors across animals.

A survey of both group and individual behaviors from nine books about insects, mammals, birds, and animals in general resulted in a set of three classifications of behaviors that are used to change other animals, including humans', movements: site defense, personal defense, and hunting. The behaviors in the area of hunting are excluded from discussion here as they are not appropriate for human-robot interactions. Thirty-four site defense behaviors are presented to contend with the most common problem in evacuation: bottlenecks. Fourty-four personal defense behaviors are presented as a mechanism to allow the robot to cope with a violent crowd.

3.1 Site Defense

Site defense behaviors were studied for their insight into how a mammal, bird, or insect would behave when their territory or nest was threatened by a predator. These behaviors were divided into mobbing and distraction display. Mobbing was further divided into approaching and threatening. Distraction display was composed of many individual behaviors. A depiction of this categorization can be found in Figure 3.1, with bird behaviors in bold, insect behaviors italicized, and mammalian behaviors underlined.

Armstrong [52] investigated bird displays and inferred reasons for them from short stories of interactions of other researchers in the wild. The concepts of injury feigning and startling predators as site defense mechanisms are presented with evidential stories to support their effectiveness.

Wittenberger [53] examined animal social behaviors, including those from chimpanzees, baboons, ungulates, big cats, and birds. Mobbing is one such behavior which occurs in all of these animals, but specific manifestations are not introduced until the next section.

Ruxton, Sherratt, and Speed [54] summarized work on methods animals use to avoid attack, which included behaviors from insects, birds, and mammals. This work contributed many of the expressions in the distraction display section.

Caro [55] discussed antipredator defenses for birds and mammals including extensive discussion of both nest and personal defense, which are discussed further in future sections.

When considering how the identified behaviors are triggered or transitioned, the perceived state of the predator should be considered at any given time. A predator's perceived state consists of states: detected, approaching, passing, and close.

As depicted in Figure 3.2, the first behavior executed by the agent is to stay nearby and monitor for approaching predators. When a predator is detected, the agent should consider whether the predator will pass the site without collision or if not whether they are too close to the site to draw their attention elsewhere. If they are far enough away and seem to be passing the site, then the agent can perform a distraction display to lead them in another direction. If they are far enough away and do not seem to be passing the site, the agent can approach them and try to intimidate them. Finally, if they are close to the site and do not appear to be passing, the agent can threaten them to convince them that they are not welcome in the area.

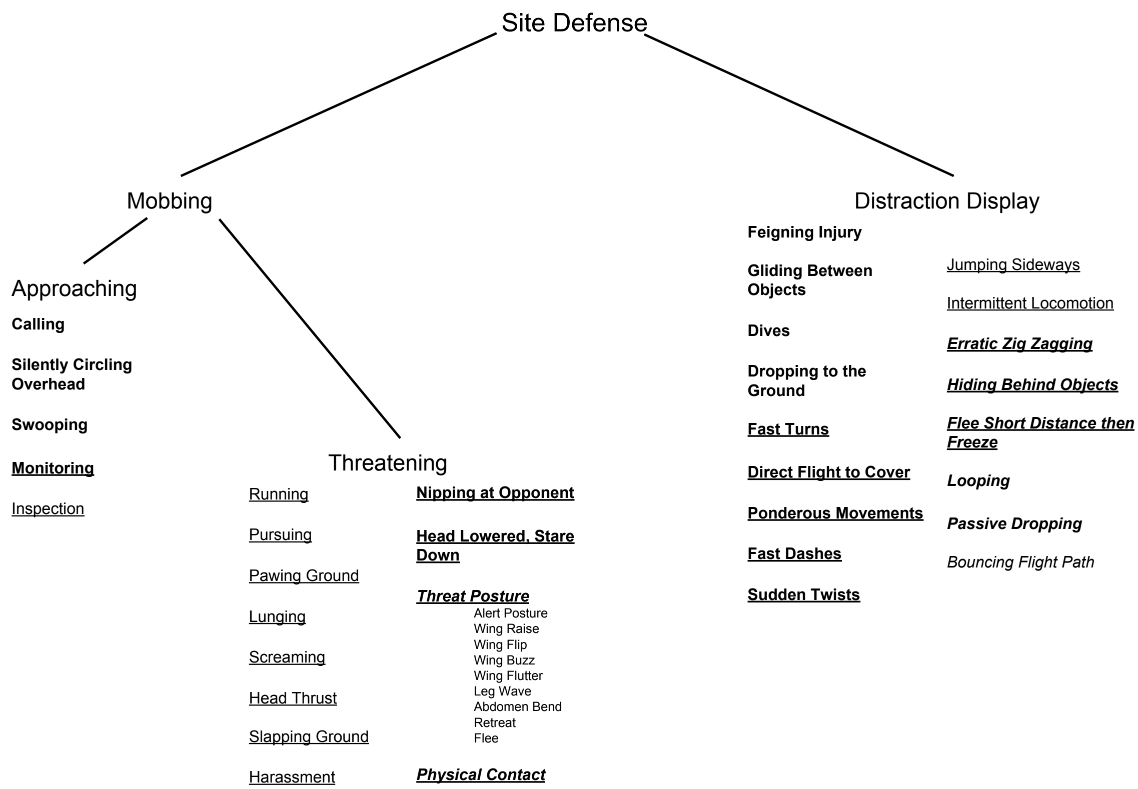

Figure 3.1: A tree depicting the Site Defense behaviors discovered through a review of literature.

3.1.1 Mobbing

Mobbing is defined as "an approach towards a potentially dangerous predator (whether it is actively hunting or not), followed by frequent position changes with most movements centered on the predator " [55] and is composed of both Approaching and Threatening behaviors with intensity increasing as the distance to a protected site decreases. These behaviors are used to indicate detection to predators, defend territory, and discourage predators from returning when they are hunting [53]. This summary focuses on mobbing from an individual, rather than group mobbing.

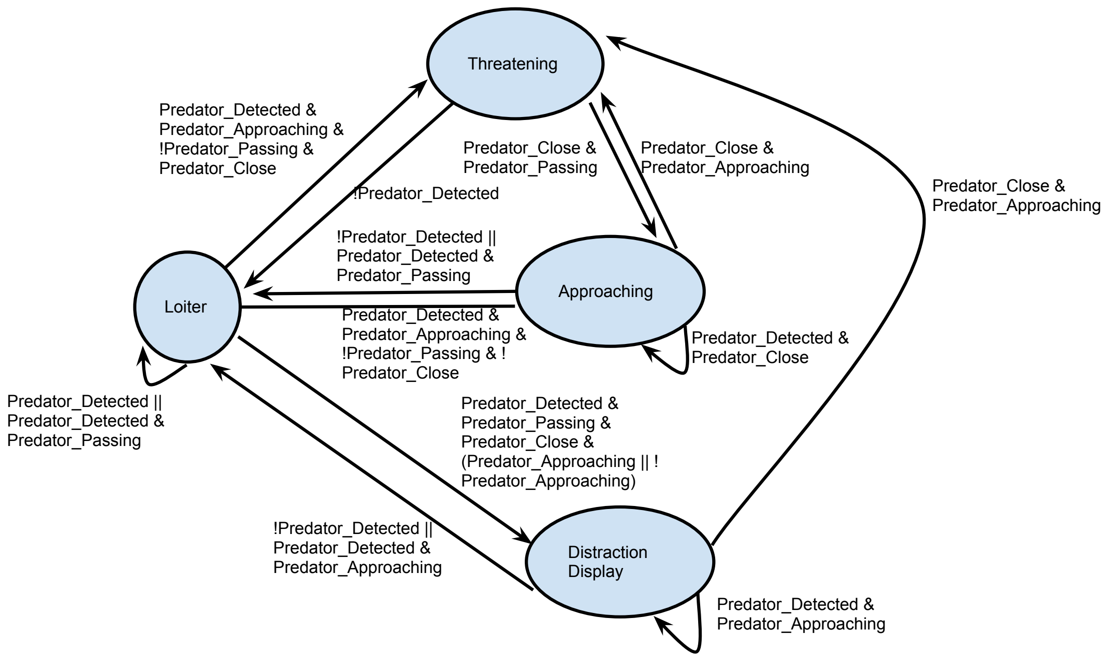

Figure 3.2: A finite state machine depicting the triggering of Site Defense behaviors discovered through a review of literature.

Approaching behaviors are used to convey fitness and to let a predator know that they have been seen and will no longer have the element of surprise. These behaviors consist of:

- Calling, occurs in birds
- Silently Circling Overhead, occurs in birds
- Swooping, occurs in birds
- Monitoring, occurs in birds and mammals
- Inspection, occurs in mammals

Threatening behaviors are used to directly intimidate the predator by displaying weapons or other dominant displays. These behaviors consist of:

- Running, occurs in mammals
- Pursuing, occurs in mammals
- Pawing Ground, occurs in mammals
- Lunging, occurs in mammals
- Screaming, occurs in mammals
- Head Thrust, occurs in mammals
- Slapping Ground, occurs in mammals
- Harassment, occurs in mammals
- Nipping at Opponent, occurs in birds and mammals
- Head Lowered Stare Down, occurs in birds and mammals
- Threat Posture, occurs in birds, mammals, and insects
- Physical Contact, occurs in birds, mammals, and insects

3.1.2 Distraction Display

Distraction display behaviors are also known as “Protean Display” and are used to entice a predator to follow an agent away from a site or territory [54]. Some of these behaviors involve looking weak or easy to catch, while others involve a disorienting flight path to confuse the predator.

Many of the distraction display behaviors are designed to cause the predator to attack in the wrong place, or to lead it away from an easier target [52], and consist of:

- Feigning Injury, occurs in birds
- Gliding Between Objects, occurs in birds
- Dives, occurs in birds
- Dropping to the Ground, occurs in birds
- Fast Turns, occurs in mammals and birds
- Direct Flight to Cover, occurs in mammals and birds
- Ponderous Movements, occurs in mammals and birds
- Fast Dashes, occurs in mammals and birds
- Sudden Twists, occurs in mammals and birds
- Jumping Sideways, occurs in mammals
- Intermittent Locomotion, occurs in mammals
- Erratic Zig Zagging, occurs in insects, mammals, and birds
- Hiding Behind Objects, occurs in insects, mammals, and birds
- Flee Short Distance then Freeze, occurs in insects, mammals, and birds
- Looping, occurs in insects and birds
- Passive Dropping, occurs in insects and birds
- Bouncing Flight Path, occurs in insects

3.2 Personal Defense

Personal defense behaviors were studied for their insight into how a mammal, bird, or insect would behave when threatened or approached by a predator. These behaviors were divided into active and passive, with active denoting an escalation towards fighting and passive denoting a non-confrontational approach. Active was further divided into standing ground and physical attack, with physical attack composed of both fighting and bunting. Passive was further divided into advertising perception, withdrawal, or protean display. A depiction of this categorization can be found in Figure 3.3, with bird behaviors in bold, insect behaviors italicized, and mammalian behaviors underlined.

Ewer [56] described behaviors in mammals, including threats, communication, and fighting. These expressions are detailed further in both active and passive personal defense.

Hafez [57] examined the behavior of domestic animals, including ungulates, dogs, cats, and birds. This book covers signaling behaviors, body postures, and defense of self.

Curio [58] studied predation in birds, fish, and mammals, and was most informative in the area of personal defense mechanisms when faced with a predatory attack. This includes mainly passive responses such as advertising perception and protean displays.

Ruxton, Sherratt, and Speed [54] summarized work on methods animals use to avoid attack, which included behaviors from insects, birds, and mammals. This work contributed many of the expressions in the advertising perception and protean display sections.

Caro [55] discussed antipredator defenses for birds and mammals including extensive discussion of both nest and personal defense, which are discussed in future sections.

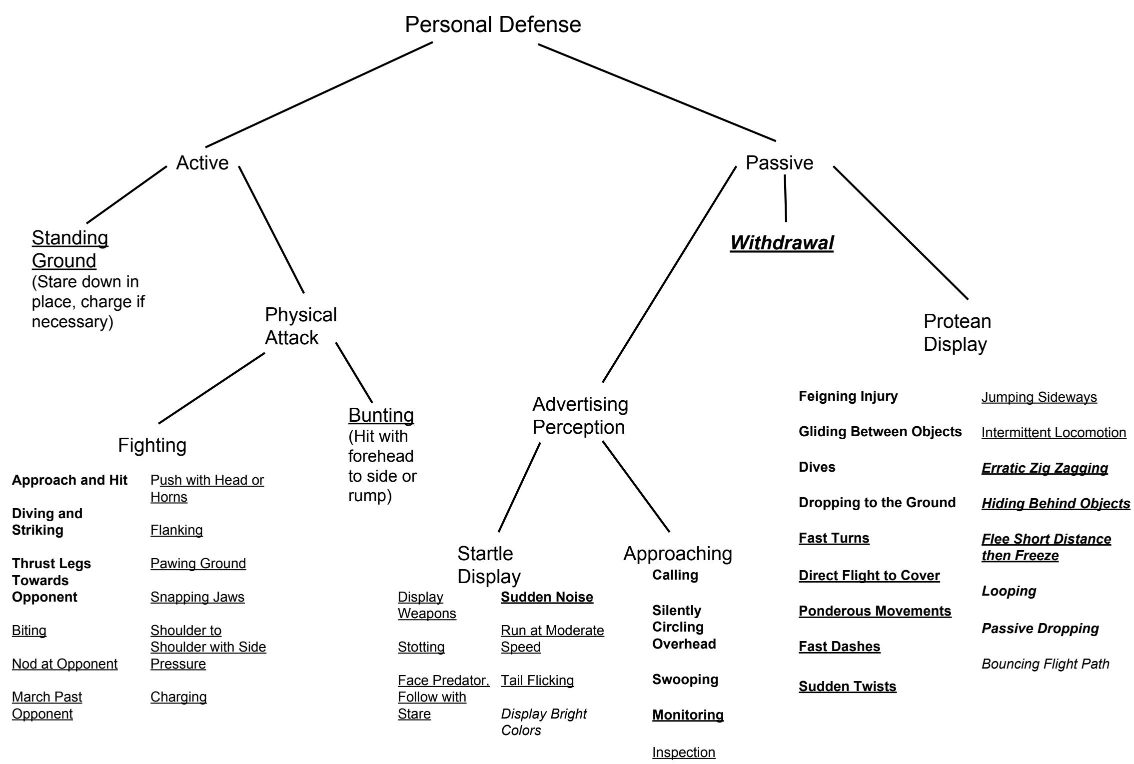

Figure 3.3: A tree depicting the Personal Defense behaviors discovered through a review of literature.

When considering how the identified behaviors are triggered or transitioned, the passing of time should be considered along with the perceived state of both the predator and the agent. A predator's perceived state consists of states: detected, submissive, standing ground, threatening, approaching, passing, and close. The agent's perceived state consists of states: encircled and healthy.

As depicted in Figure 3.4, the first behavior executed by the agent when itself is to wait to determine the most appropriate behavior once a predator is detected.

When a predator is detected, the agent should give a startle display to alert the predator that they are detected and the element of surprise is lost. If the agent is encircled, the standing ground behavior would be initiated; otherwise if the predator is close and approaching then the approaching behavior would be selected, or if the predator is not close but is approaching the fighting behavior would be selected, or if the predator is not approaching but is submissive the bunting behavior would be selected. From the stranding ground behavior, the agent would transition to fighting if approached or to bunting if not. From approaching, the agent would transition to fighting if threatened or protean display if not. From bunting, the agent would transition to fighting if approached. Finally, if the predator is still not submissive, withdrawal behaviors would be selected.

3.2.1 Active Personal Defense

Active personal defense is composed of two groups of behaviors, standing ground and physical attack, with physical attack composed of both bunting and fighting. Standing ground is a method of personal defense in which the prey stands in place, staring at the predator, and charges if necessary. This defense is activated by a predator being detected, the prey being healthy, and the prey being encircled by predators [58]. Physical attack is composed of both fighting and bunting, and is activated only as a last resort. Fighting is composed of many individual behaviors with a goal towards establishing dominance rather than causing the injury or death of an opponent [56]. Bunting is accomplished by hitting with the forehead to the side or rump and also has a goal of establishing dominance, but this time by moving an opponent.

Standing ground is a behavior, used by mammals, in which the agent stares down the predator and charges if necessary. This behavior is triggered by a predator

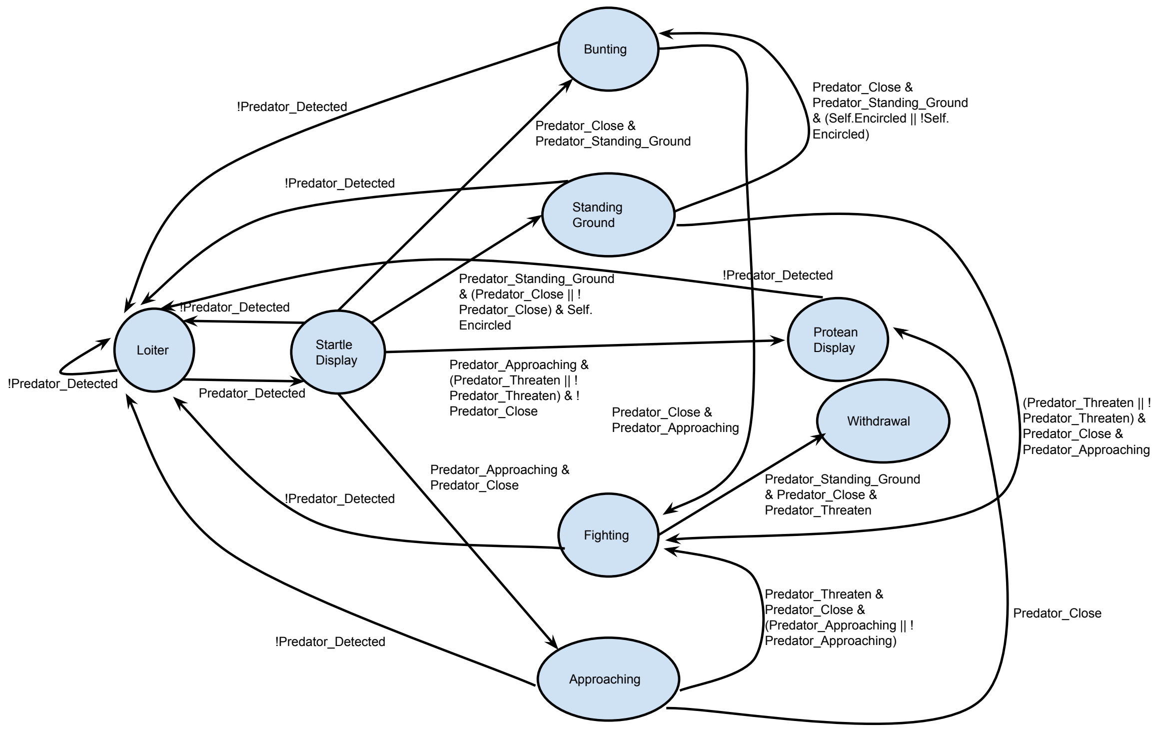

Figure 3.4: A finite state machine depicting the triggering of Personal Defense behaviors discovered through a review of literature.

dashing at or otherwise "testing" an agent, and is a display of fitness because a weak agent would attempt to flee in this situation [58].

Physical attack is a set of behaviors composed of both bunting and fighting. Bunting (or butting) is "a blow with the forehead directed at the opponent's side or rump" and is used by mammals when an adversary is slow to submit [57]. Fighting is meant to "decide who is the stronger, not to kill off the weaker" [56] and consists of:

- Approach and Hit, occurs in birds
- Diving and Striking, occurs in birds

- Thrust Legs towards Opponent, occurs in birds
- Biting, occurs in mammals
- Nod at Opponent, occurs in mammals
- March Past Opponent, occurs in mammals
- Push with Head or Horns, occurs in mammals
- Flanking, occurs in mammals
- Pawing Ground, occurs in mammals
- Snapping Jaws, occurs in mammals
- Shoulder to Shoulder with Side Pressure, occurs in mammals
- Charging, occurs in mammals

3.2.2 Passive Personal Defense

Passive personal defense is composed of three sets of behaviors: advertising perception, protean display, or withdrawal. Advertising perception is composed of two further sets of behaviors: approaching and startle display. Approaching is manifested through individual behaviors to convey both perception and a lack of fear. Startle display is composed of individual behaviors meant to intimidate predators and convey fitness to allow the prey time to escape. Protean display is composed of individual behaviors and meant to confuse or disorient the predator after a primary defense has failed. Withdrawal is used as a final resort when the predator is standing ground and the prey has exhausted all other personal defense options.

Advertising perception is a set of behaviors contained in two subsets, startle display and approaching; they are triggered when a predator is detected to convey a loss of surprise and the fitness of the agent [54]. Startle display behaviors consist of:

- Sudden Noise, occurs in birds and mammals
- Display Weapons, occurs in mammals
- Stotting, occurs in mammals
- Face Predator and Follow with Stare, occurs in mammals
- Run at Moderate Speed, occurs in mammals
- Tail Flicking, occurs in mammals
- Display Bright Colors, occurs in insects

Approaching behaviors consist of:

- Calling, occurs in birds
- Silently Circling Overhead, occurs in birds
- Swooping, occurs in birds
- Monitoring, occurs in birds and mammals
- Inspection, occurs in mammals

Protean display is meant to increase the predators' reaction time or reduce speed of pursuit [55] and display excessive cost of pursuit to predators [54], and consists of:

- Gliding Between Objects, occurs in birds
- Dives, occurs in birds

- Dropping to the Ground, occurs in birds
- Fast Turns, occurs in mammals and birds
- Direct Flight to Cover, occurs in mammals and birds
- Ponderous Movements, occurs in mammals and birds
- Fast Dashes, occurs in mammals and birds
- Sudden Twists, occurs in mammals and birds
- Jumping Sideways, occurs in mammals
- Intermittent Locomotion, occurs in mammals
- Erratic Zig Zagging, occurs in insects, mammals, and birds
- Hiding Behind Objects, occurs in insects, mammals, and birds
- Flee Short Distance then Freeze, occurs in insects, mammals, and birds
- Looping, occurs in insects and birds
- Passive Dropping, occurs in insects and birds
- Bouncing Flight Path, occurs in insects

The final passive personal defense behavior is to withdrawal when no other behavior has been successful at dissuading the predator by causing its withdrawal or submission. Withdrawal behavior is generally accompanied by a lowered head and looking away from the opponent in submission [57].

3.3 Summary of Animal Behaviors

The focus of this background chapter was to introduce animal behaviors for influencing interspecies movement and the focus was on site and personal defense behaviors. This background is useful in guiding the creation of a behavior-based framework for robots to influence human movement. Finite state machines were presented to demonstrate how the individual behaviors may be triggered in animals and are expanded in the next section to show how they may be used by a robot.

4. APPROACH

This dissertation produced two major deliverables: i) the *Comfortable Distance (CD) model*, which represents the current knowledge of human-human and human-ground robot interactions and was extended to include human-aerial vehicle interactions, ii) a behavioral model of personal defense to inform this model regarding three-dimensional interactions, and iii) a behavioral model of site defense to inform interactions outside the "personal" zone defined by Hall in [6] and supported by the other works in the *CD model*. These behavioral models were tested using human subjects experiments to establish baseline interaction distances for the human-sUAV interactions and to inform the expected distances from the CD model. When considering previous work on interaction principles, the question: *Do approaches of an aerial vehicle cause peoples' movements to change in the same way as HHI or HRI interactions?* The answer to this question appears to be no based on the work by Duncan and Murphy in [4] and described further in Section 2.2. A follow up question is: *Do approaches of an aerial vehicle cause peoples' movements to change in the same way as animal interactions?*

The rationale behind this project is to expand the knowledge of human-UAS interaction to include humans who are not in control of the robot by leveraging information gained from behaviors exhibited by animals and insects to influence the movements of much larger animals. Guidelines are presented from the behaviors to design more generalizable interactions through incorporation into the model developed from the literature review, but the focus in this work is to have the robot guard a space. Additionally, guidelines are presented from HHI and HRI to situate the aerial robot movements in the current state of the research and to ensure that confounds in the experiments are anticipated and controlled when possible.

As previously explained, robots are naturally suited to assume the task of guarding bottlenecks in an evacuation scenario and aerial vehicles have distinct advantages over ground robots due to their ability to change altitude in order to see or maneuver over crowds, transition to a different floor, or remove themselves from danger. Aerial vehicles' paths should be intuitively adapted from behavioral studies of birds and insects due to their operation in the same planes and the natural ability of these behaviors to communicate ideas about movement to other, larger species. These paths were tested using human interaction studies and focusing on the metrics of social interaction distancing, interaction timing, and preference to inform the potential uses of specific behaviors and the general interpretation of movement rules in naive interactions with aerial vehicles.

The behavior-based implementation is reactive in nature, relying on a sense-act mapping between percepts in the environment (e.g. perceptual schemas such as person detected, person approaching, and person threatening) to natural behaviors (site defense and personal defense) adapted from the literature presented previously. This mapping is presented later in this section and has been simplified based on the fact that the experiment produced expressions (or motor schemas) which naturally escalate. Some of the expressions defined previously have been excluded because physical contact is an inappropriate interaction and the removal of the contact resulted in some duplicate behaviors.

Ultimately, the behavioral approach to sUAV interaction was adopted based on the fact that many birds or insects are able to make animals, including humans, move when necessary. In order to best create a behavior set which increases or decreases in impact, it is necessary to quantify the distances at which people will interact with a vehicle exhibiting different behaviors by populating the CD model and to determine the amount of time that is added to their hesitation when these behaviors are encountered. By establishing these numbers, this work seeks to draw conclusions about which types of movement (e.g. speed or height changes) make people more or less comfortable in interactions.

4.1 Guidelines from Human-Human and Human-Robot Interactions

In this section, a preliminary model is provided based on the analysis of the findings in approach distance across the social sciences and HRI which were reviewed in Section 2.4. While it is unclear that a sUAV will be treated as a human or ground-robot, the lessons learned through those experimental processes should inform the experimental design process and are presented here for that purpose. When compared to the model in [38], there have been two additional findings from the animal behavior literature review added to this model (updated model shown in Figure 4.1), which are: the predictability of the motions and the dimensionality of the motion, whether 2D or 3D (neither of which had not been previously studied). Here, the three findings that suggest areas to be documented, tracked, and controlled during HRI experiments are presented.

4.1.1 Finding 1: Document Environmental Conditions

Finding 1: Document Environmental Conditions. The most important finding from the literature is that environmental conditions can have a large impact on the amount of space which people feel comfortable maintaining, and thus should be documented as completely as possible. This can take the form of photographing all areas of experimentation, ensuring replicable lighting conditions, and drawing a diagram of the interaction area with distances measured accurately.

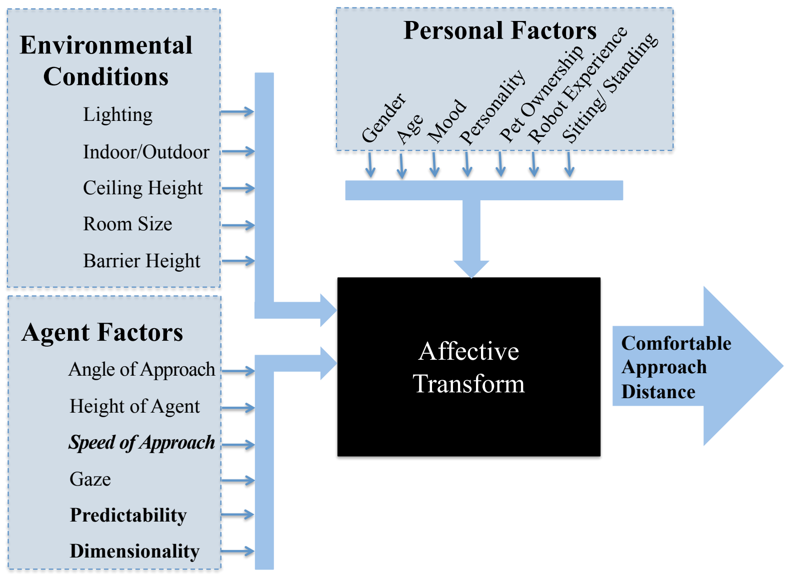

Figure 4.1: "Comfortable Distance" Model, incorporating the environmental conditions, agent factors, and personal factors identified from the literature. The transform black box represents the interactions between the factors, which can be partially gathered from the literature. The output is the distance that a human would feel comfortable being distanced from a robot or another human.

4.1.2 Finding 2: Track Personal Factors

Finding 2: Track Personal Factors. When designing the experimental surveys, the 6 previously described personal factors should be tracked for all participants in order to determine any covariates. These factors are: gender, age, mood, personality, pet ownership, and robot experience.

4.1.3 Finding 3: Control for Agent Factors

Finding 3: Control for Agent Factors. Agent factors were varied with based on the specific animal behaviors that will be described, but when possible were controlled for and held constant. These factors include: the angle of approach, height of the agent, approach speed, amount of gaze, predictability of motions, and size or volume of space occupied by the vehicle.

4.2 Methodology

The question: *Can a small autonomous UAS change a person's movements by emulating animal behaviors?* was decomposed into two sub-questions:

1. *Do approaches of an aerial vehicle cause peoples' movements to change in the same way as human or ground robot interactions?*

2. *Do approaches of an aerial vehicle cause peoples' movements to change in the same way as animal interactions?*

4.2.1 Aerial Vehicle Interaction versus Human-Human or Human-Ground Robot Interactions

When considering the question of aerial vehicles impacting human movements, the first question was whether they would conform to the current understanding of interactions. Previous interactions have been limited to human interactions with humans or ground robots and the findings have been consistent between the two fields resulting in the application of the CASA model to understand interactions in general. In order to test whether this understanding would transfer to aerial vehicles as well, an experiment was conducted which replicated the HHI and HRI studies previously identified. This experiment had a sUAV approach a person directly with a constant speed, mimicking a human approach, and the result was that humans did not maintain the same amount of space as they would with a human or ground robot, thus the comfort was not the same and movements would not be impacted in the same way. Further details on this study can be found in Section 2.2 or [4].

4.2.2 Aerial Vehicle Interaction versus Animal Interactions

When considering the question of aerial vehicles impacting human movements, the second question was whether they conform to the understanding of interspecies interactions of animals. The previous chapter introduced the expressions of the identified behaviors from animal literature. In order to test whether this understanding will transfer to aerial vehicles, an experiment was conducted which replicates the animal expressions previously identified. This experiment is described briefly here and more thoroughly in the next chapter. The study was conducted in simulation and displayed in a cave automatic virtual environment (CAVE) with a realistically sized sUAV model to determine expected interaction distances, interaction times, and preference for each expression. These measures were used to develop the escalation strategy for implementation in future studies and findings which were fed into the CD model.

4.3 Models of Animal Behaviors

From the animal behaviors presented in Section 3, an appropriate set of behaviors was synthesized into two models which were fed into the larger CD model: i) a model of site defense and ii) a model of personal defense. These models were tested for their applicability to two different zones of interaction, the personal and the social where the site defense behaviors were expected to discourage personal zone interactions and the personal defense behaviors would take over in this space. Due to the different spatial zones they inhabit, these selected behaviors are presented as a single escalation Finite State Automata (FSA), depicted in Figure 4.2, rather than two separate FSAs. In the escalation strategy figure, the circle is a single state and the boxes represent individual behavior paths that can be interrupted by the behavior of the person(s) detected. The two behavior paths are described further later in this section.

Incorporation of the behavioral models into the CD model came in the form of determining the difference in interaction distancing based on the varying of the agent

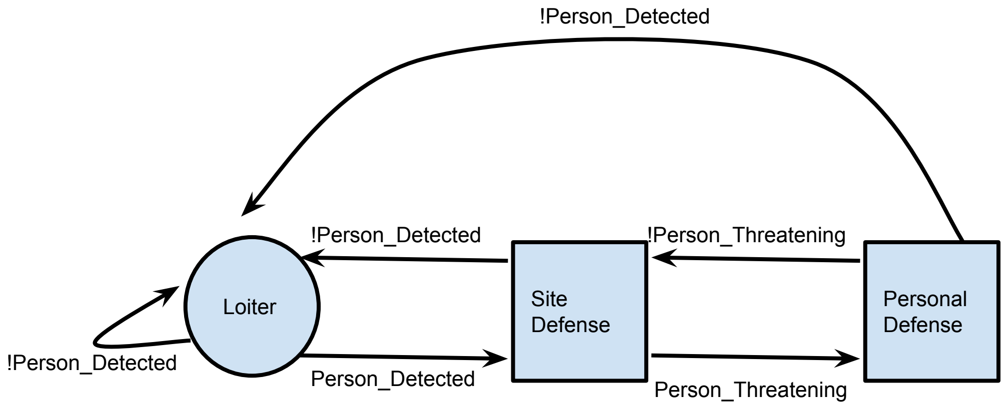

Figure 4.2: Basic escalation strategy FSA based on identified behaviors.

factors. An example of the varying of agent factors is shown in the difference between the expressions ponderous movement and erratic zigzagging, ponderous movement has low predictability and also low speed while erratic zigzagging has low predictability and high speed.

The "Site Defense" block can be expanded into the escalation strategy shown in Figure 4.3. Site Defense is composed of two types of behaviors: approach and threaten; distraction displays were excluded because they encourage the animal to leave the area of interest and would not contribute to the goal of using a robot to guard a bottleneck or to redirect traffic. The specific component behaviors for approach and threaten have been selected from the ones presented in the previous section by excluding physical contact and behaviors that are essentially repeats when considered in the context of an aerial vehicle (see Figure 4.4). If the robot is threatened during the interaction, the robot could exit the site defense behavior and enter the personal defense behavior.

The "Personal Defense" block can be expanded into the escalation strategy shown

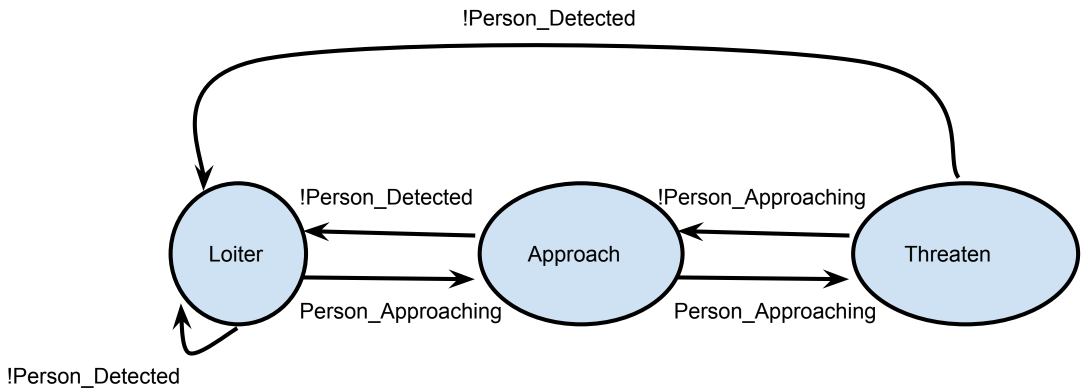

Figure 4.3: Site Defense escalation strategy for robots based on identified behaviors.

in Figure 4.5. Personal Defense is composed of five types of behaviors: startle display, stand ground, approach, protean display, and withdrawal. The specific component behaviors have been selected from the ones presented in the previous section by excluding physical contact and behaviors that are essentially repeats when considered in the context of an aerial vehicle (see Figure 4.6). This behavior would be exited if the person is no longer a threat, or is not detected.

These escalation strategies are composed of individual "expressions" of a larger behavior type. The efficacy and clarity of the individual expressions was tested for incorporation into the escalation strategy and informed the CD model through the human-subjects experiments described in later chapters, so will not be described further here.

4.4 Recommended Crowd Interaction Guidelines

From the crowd management, crowd control, and evacuation literature, pre-

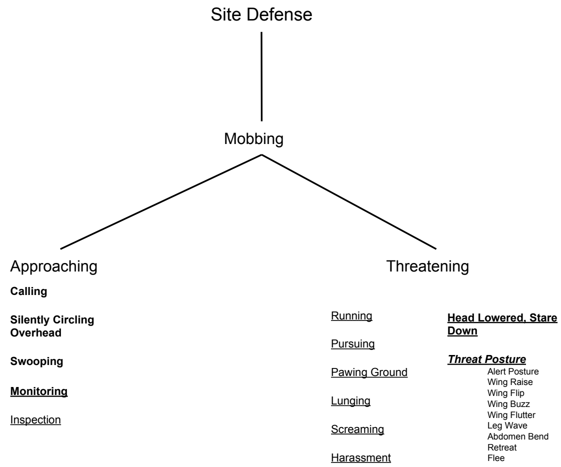

Figure 4.4: Site Defense expressions for aerial vehicles based on identified behaviors, but excluding physical contact and repeat behaviors.

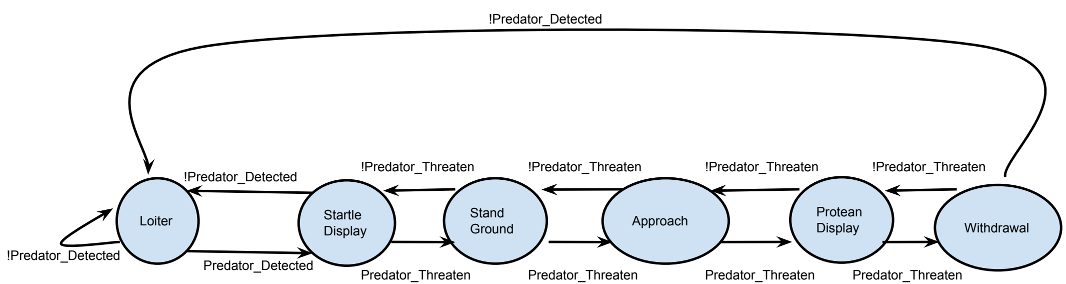

Figure 4.5: Personal Defense escalation strategy for robots based on identified behaviors.

sented in Section 2.1, two major guidelines were adopted and will be described below.

4.4.1 Guideline 1: Guide at Potential Bottlenecks

Bottlenecks are a main source of both injuries and death in evacuation scenarios; to overcome this point of failure, agents should be used to guide people to a less crowded area. Natural bottlenecks occur in areas where groups of people move into an area of less space (e.g., from a concourse to a tunnel) or a more challenging

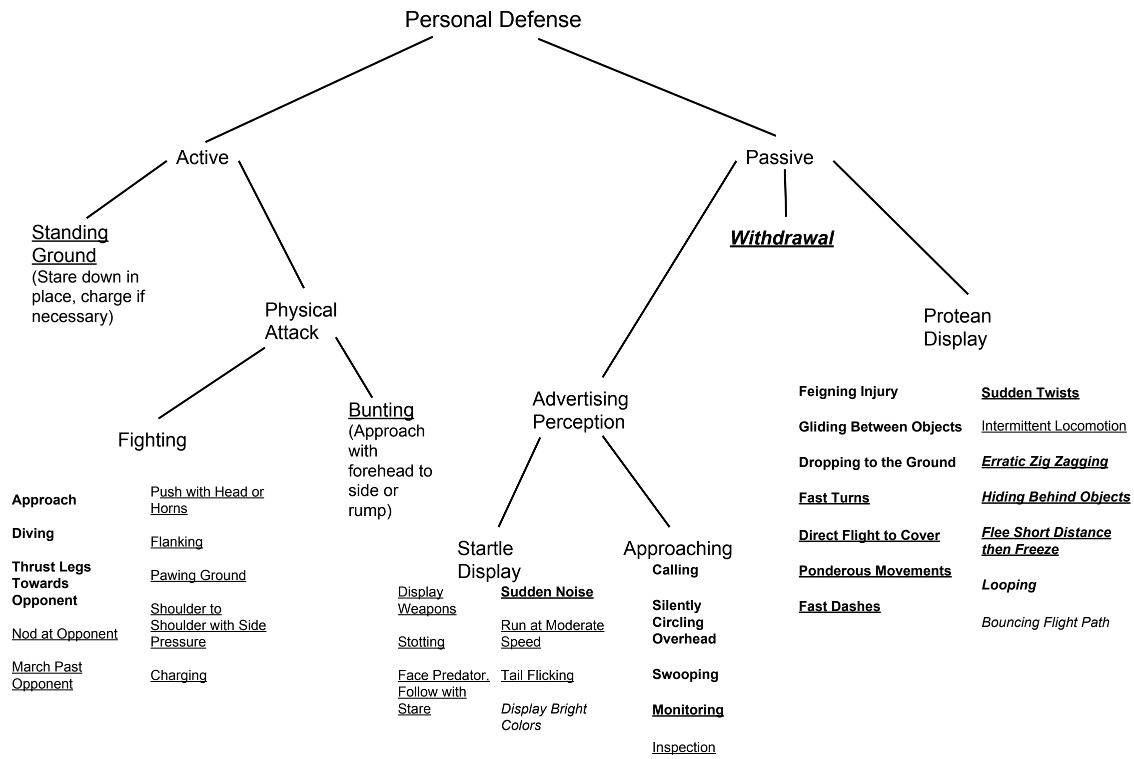

Figure 4.6: Personal Defense expressions for aerial vehicles based on identified behaviors, but excluding physical contact and repeat behaviors.

exit path (e.g., from a flat area to stairs). For more information, see Section 2.1.2.

4.4.2 Guideline 2: Encourage Appropriate Routes

Another common point of confusion in evacuation is when people attempt to exit the same way they entered, which would allow robots to be placed in this area to guide people to other, safer or less congested, exits. Entry is generally based on ease of access (e.g., close to public transportation) rather than an equal distribution of crowd between entry points, so exit should be based on safest or fastest exit.

4.5 Summary

The generated models of animal behaviors could be used to impact human movements through the use of a sUAV and the experimental design was guided by the findings from the areas of HHI, HRI, crowd control, and evacuation to improve the CD model. This approach was driven by two fundamental questions: 1) whether the change human movements conforms to the current understanding of human-human and human-ground robot interactions, which seems to be no; and 2) whether they conform to the understanding of interspecies interactions of animals. These behaviors are appropriate for this use because the animals who employ these behaviors are smaller than the robot and can impact movements in animals as large as a human with these expressions. The expression set was selected from those presented in the previous chapter and the selection process is elaborated upon in the experimental methods and design chapter, but will ultimately be tested using human-subjects experimentation. Finally, this work will expand the knowledge of human-UAS interactions to include humans who are not in control of the robot and will create guidelines for more generalizable interactions through a formalization of the CD model.

5. IMPLEMENTATION

The implementation details of a subset of the expressions, identified in Section 4.3, on a sUAV in simulation will be described here along with any assumptions or simplifications this causes. This implementation is necessary to test the additions to the CD model through human subjects experiments and to inform future research on interactions in both two- and three-dimensions. The robot depicted was the AirRobot AR100B and software was written specifically for the the simulation, but wwas based on the Behavior Based Robotics principles presented in Section 5.2. The simulation used for the experiment was the Unity framework. Additional details regarding the language used for implementation is provided later in this chapter.

5.1 Platform Description

The platform implementation was based on a vertical take-off and landing (VTOL) platform due to the expected flight patterns and the necessity of such a platform in public safety applications which include indoor and outdoor components. Fixed-wing platforms can provide longer flight times, but less maneuverability especially when considering interactions in limited spaces. There are several sUAV platforms with the VTOL capabilities that are assumed in this experiment, such as the Draganflyer X4 or X6, the AeroVironment Qube, or the Aeryon SkyRanger. The AirRobot AR100B (see Figure 5.1) is currently used by the U.S. military, Germany military, and U.K. police forces, so is representative of the platforms used and has a safety hoop to protect itself from light collisions into infrastructure. The AirRobot AR100B is already owned and programmable by the Center for Robot-Assisted Search and Rescue, so was used for this study as an exemplar platform.

Figure 5.1: AirRobot AR100B platform from AirRobot.

5.2 Behavior Implementation

Behavior implementation is left for future work, but here will be suggested as described in Arkin's Behavior-Based Robotics textbook [8] and Section 3.5 of Murphy's Introduction to AI Robotics textbook on Schema Theory [9]. As defined in the previous two references, a behavior is composed of both a motor schema and a perceptual schema. The individual behavioral expressions presented in Chapter 3 are the motor schemas, but are referred to as expressions throughout the text.

Specific meta-behaviors are described in Tables 5.1 and 5.2, but all were released by affordances in direct perception. Both Site and Personal Defense behaviors in this work could be triggered by observation of a human in the field of view (from the onboard camera feed of the robot), but in practice would be instantiated by an end user. Triggering can either be defined by an approximation using a person's "blob" size in vision or through external perception for simplification in the experimental environment with the understanding that small distance sensors are likely to be common place on sUAVs in the near future. All behaviors were centered on the person and necessitated fixing the "gaze" attribute of the agent factor from the CD model to a full gaze condition.

Site Defense Behavior Table				
Releaser	Behavior	Motor Schema	Percept	Perceptual Schema
always on	avoid_obstacles()	avoid(plane)	plane_broken	scan_plane()
not person_detected	loiter()	hover()	person_detected	identify_person()
person_detected	approach()	next.approach _expression()	person_distance	size_person()
person_detected and next.approach _expression() = NULL	threaten()	next.threaten _expression()	person_distance	size_person()

Table 5.1: Site Defense behavior table

5.3 Expression Implementation

The expressions presented in Section 4.3 were again examined for their applicability to the platform selected earlier in this chapter, with no modifications being made (such as the addition of lights and speakers). Final trees for Site and Personal Defense are shown in Figures 5.2 and 5.3. In these trees, with 9 Site Defense expressions and 15 Personal Defense expressions, those drawn from insects have a red dot, birds have a blue dot, and ground animals have a green dot. More information about the differences between expressions are provided in tables in Chapter 6.

Each expression was implemented in the Unity game engine, using MonoDevelop and the Unity version of JavaScript. Expressions escalated based on the participant's distance from the robot, where the robot changed speed, height, predictability,

Personal Defense Behavior Table				
Releaser	Behavior	Motor Schema	Percept	Perceptual Schema
always on	avoid_obstacles()	avoid(plane)	plane_broken	scan_plane()
not person_too_close	loiter()	hover()	person _distance	identify_person()
person_too_close	startle_display()	next.startle _expression()	person _distance	size_person()
person_too_close and next.startle _expression() = NULL	fighting()	next.fighting _expression()	person _distance	size_person()
person_too_close and next.fighting _expression() = NULL	protean_display()	next.protean _expression()	person _distance	size_person()
person_too_close and next.protean _expression() = NULL	withdrawal()	altitude_up()	person _distance	size_person()

Table 5.2: Personal Defense behavior table

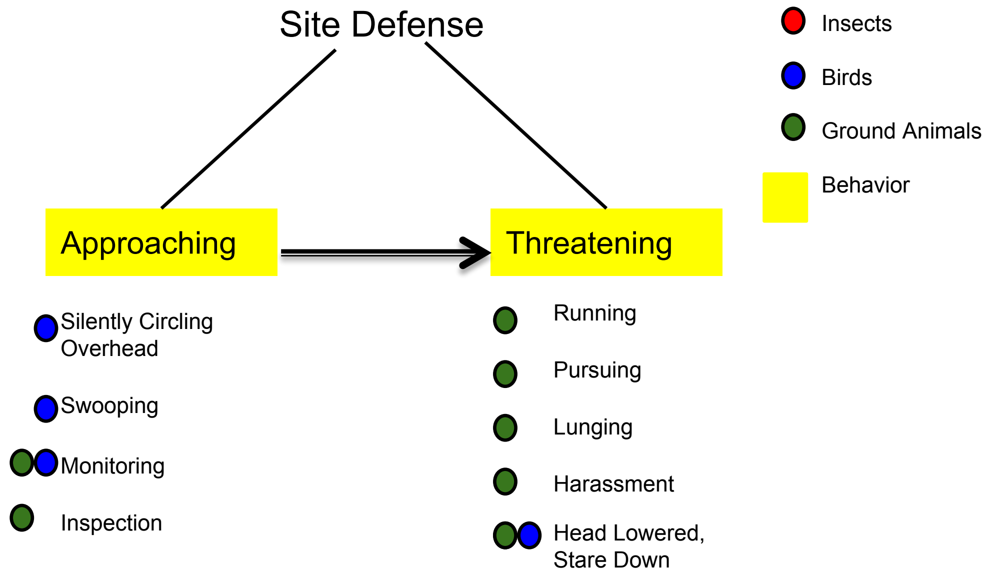

Figure 5.2: Final Site Defense tree for implementation in simulation on the AirRobot AR100B. Biological inspiration for the expression is reflected in the dots beside each expression with red for insects, blue for birds, and green for ground animals. Additionally, the highlighted words are for the names of the behavior represented by those expressions.

or maximum distance from the participant at 6.5 m, 4.5 m, and 2.5 m. These escalation distances were chosen to give maximum visibility of the changes before entering the Social zone defined by Hall in [6]. The high speed condition increases from 1.5 to 3.0 to 5.0 meters per second and the low speed condition increases from 1.5 to 2.0 to 2.0 meters per second. Low predictability conditions would increase the likelihood of a direction or distance change as distance decreased, but high predictability expressions would not change with regards to randomness since all conditions are cyclical. The maximum distance from the robot to the avatar (referred to as follow distance) decreased from 2.0 to 1.0 to 0.5 meters for robots centered on a person, but did not change for robots centered on an area.

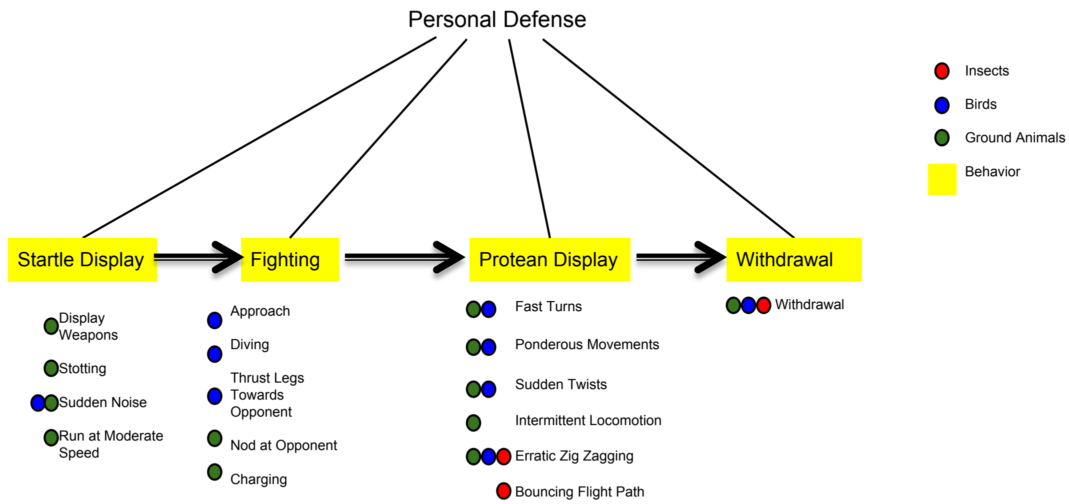

Figure 5.3: Final Personal Defense tree for implementation in simulation on the AirRobot AR100B. Biological inspiration for the expression is reflected in the dots beside each expression with red for insects, blue for birds, and green for ground animals. Additionally, the highlighted words are for the names of the behavior represented by those expressions.

5.4 Software Description

Software was developed in a JavaScript variant for the Unity game engine. This section describes the metrics tracked in the game and the behavior of the avatar controlled by participants.

The simulation was developed to understand human interaction with a sUAV, so the following metrics were tracked: distance, time, and preference. As the participants approach a robot, their distance was tracked whenever they were within 10m of the robot and the minimum distance was maintained based on the specific robot. Additionally, time was tracked for the same distance in order to track the total time of interaction. Finally, a graphical depiction of the entire path taken by the participant was created from a text file of all points encountered by the participant, which was used to determine which robots were preferred.

The avatar that was controlled by participants was not able to be killed, but would take "damage" when it hit, or was hit, by a robot and this damage would be represented by a red flash on the screen as well as a negative counter. This avatar had a maximum speed on 1.4 meters per second, which is referenced in the Oculus Rift Best Practices guide as the suggested human walking speed for video games (compare to 3.0 meters per second for jogging).

5.5 Hardware Description

The simulation was run on a custom gaming PC running an Intel Core i5-3570K Ivy Bridge 3.4GHz (3.8GHz Turbo) processor, 8GB (2 x 4GB) DDR3 SDRAM, and a VisionTek Products 7750 Eye 6 2GB DDR5 graphics card. The graphics card was chosen for its ability to support six outputs, of which five were used for this experiment.

5.6 Summary

This section described the suggested implementation of the two behavioral models (Site and Personal Defense) for an sUAV, as well as the actual implementation of all parts of the simulation experiment. The implementation was based on behavioral schema theory and the behavioral models established in the previous section, along with the handling of the implementation of the Agent Factors as established by the CD model. Detailed descriptions of the proposed platform and software programming languages were given.

6. EXPERIMENTAL METHODS AND DESIGN

This experiment compared 24 expressions of 5 behaviors identified from animal literature, as explained in Chapter 3, in order to determine their effectiveness in changing a person's path. These expressions were tested based on varying 3 independent variables, or factors, (speed, predictability, and dimensionality) with 3 dependent variables being measured in each interaction (distance, time, and preference). Previous studies have tested a single or multiple factors in a single set of approaches, but this study tested a range of expressions and how these factors may impact their ability to increase distance. This was the first study to test the effect of predictability and dimensionality on interaction distancing, and resulted in the addition of these factors to the Comfortable Distance (CD) model. A result of this study is the ability to understand which expressions are not effective in redirecting a person's movement, whether due to an inability to increase distance, an increase in time, or a demonstrated preference. Nine hypotheses were tested (one for each dependent variable per factor) with a set of 64 participants.

Nine hypotheses are outlined (with expected findings) which were used to answer the primary research question given in Section 1.1. Details of the experiment are given, including those for participants, facilities, equipment, and personnel. Assessment of the participants is discussed, including a pre- and post-trial survey, as well as the metrics for measuring individual interactions. The study protocol for this investigation is also provided in this section.

6.1 Research Hypotheses and Expected Findings

There are nine hypotheses and expected findings for the formal evaluation of the use of an sUAV using animal expressions to impact human movements, shown

Hypothesis	Independent Variable	Dependent Variable	Levels	Predicted Effect	Controlled Variables
Hypothesis 1	Speed	Distance	Low High	Decrease Increase	Agent & Personal
Hypothesis 2		Time	Low High	Increase Decrease	
Hypothesis 3		Preference	Low High	Increase Decrease	
Hypothesis 4	Predictability	Distance	Low High	Increase Decrease	Agent & Personal
Hypothesis 5		Time	Low High	Increase Decrease	
Hypothesis 6		Preference	Low High	Decrease Increase	
Hypothesis 7	Dimensionality	Distance	Two Three	Decrease Increase	Agent & Personal
Hypothesis 8		Time	Two Three	Increase Decrease	
Hypothesis 9		Preference	Two Three	Increase Decrease	

Table 6.1: Nine hypotheses for three independent variables

in Table 6.1. These nine hypotheses can be divided into three factors: the impact of the already defined factor of speed, as well as informing the addition of predictability and dimensionality of interaction to the CD model. The levels of these factors are shown in Tables 6.2 and 6.3.

The factor of speed has been defined elsewhere; for a thorough review of the factor of speed in human-agent distancing, see [38]. Pacchierotti, Christensen, and Jensfelt [48] identified a preferential speed of 0.25-0.39 meters per second for robot passing behaviors. Butler and Agah [59] identified comfortable speeds of 0.254 and 0.381 meters per second in robot approach experiments. This would lead to a conclusion that speeds should be between 0.25 and 0.39 meters per second for interactions, but Hayduk [60] in a synthesis of human-human studies suggests a speed of 0.15

Site Defense Expressions		Agent Factors		
Expression	Parent Behavior	Speed	Predictability	Dimensionality
Silently Circle Overhead	Approaching	Low	High	2
Swooping		High	High	3
Monitoring		Low	High	2
Inspection		Low	High	2
Running	Threatening	High	High	2
Pursuing		High	High	2
Lunging		High	High	3
Harassment		Low	Low	3
Head Lowered, Stare Down		Low	High	2

Table 6.2: Nine site defense expressions with agent factor values

Personal Defense Expressions		Agent Factors		
Expression	Parent Behavior	Speed	Predictability	Dimensionality
Display Weapons	Startle Display	Low	Low	2
Stotting		Low	Low	2
Sudden Noise		Low	Low	2
Run at Moderate Speed		Low	High	2
Approach	Physical Attack	Low	High	3
Diving		High	High	3
Thrust Legs to Opponent		High	Low	2
Nod at Opponent		Low	High	2
Charging		High	High	3
Fast Turns	Protean Display	High	Low	3
Ponderous Movements		Low	Low	3
Sudden Twists		High	Low	3
Intermittent Locomotion		High	Low	2
Erratic Zigzag		High	Low	3
Bouncing Flight Path		High	Low	2

Table 6.3: Fifteen personal defense expressions with agent factor values

to 0.2 meters per second is recommended to reduce overshoot by the experimenter. These speeds were suggested for robots directly approaching the person when trying to find a comfortable distance, but may not translate to an interpretation of animal behaviors, where the robot may be moving in multiple directions. For this study, low speed was 2 meters per second and high speed was 5 meters per second. This is based on the speeds identified by Caro [61], citing Lind, Kaby, and Jakobsson [62] on page 421 when discussing low speed versus high speed attacks by birds.

Predictability in this context is meant to be a judgment of whether the expression is cyclic or random in nature. This judgment was made from the descriptions of the expression, as well as the goal of the parent behavior, as found in the review of animal literature in Chapter 3. This factor has not been previously examined in human distancing literature, but animal literature would lead to the expectation that unpredictable behaviors are used to display fitness [54], confuse predators [63] (likely increasing time of interaction), and startle them (potentially causing them to move away) [54, 64].

As with predictability, the number of dimensions of robot movement (referred to as dimensionality throughout this chapter) have not been previously studied in human distancing because humans and ground robots can only move in two dimensions. Several studies in psychology have examined the perception of the size of objects based on their distance from the horizon, for example [65, 66]. Tozawa and Oyama [65] found that motion parallax (change in angular velocity as an object is moved closer to a subject) was a more effective cue than perspective cues (change in height with respect to the horizon) when estimating size, but that both were equally effective for distance cues. Bertamini, Yang, and Proffitt [66] found that relative size perception is best at eye level and sharply decreased above and below eye level. Based on these two findings, it was believed that the addition of a third dimension of movement (x, y, and z) rather than only (x, y or x, z) would result in a perception of a larger-size and thus more intimidating robot. The addition of a third dimension was predicted to be seen as display flight, which in animals is closely correlated with territory [52]. Due to the findings and associations in this paragraph, it was expected that these interactions would increase distance, decrease preference, and decrease time of interaction.

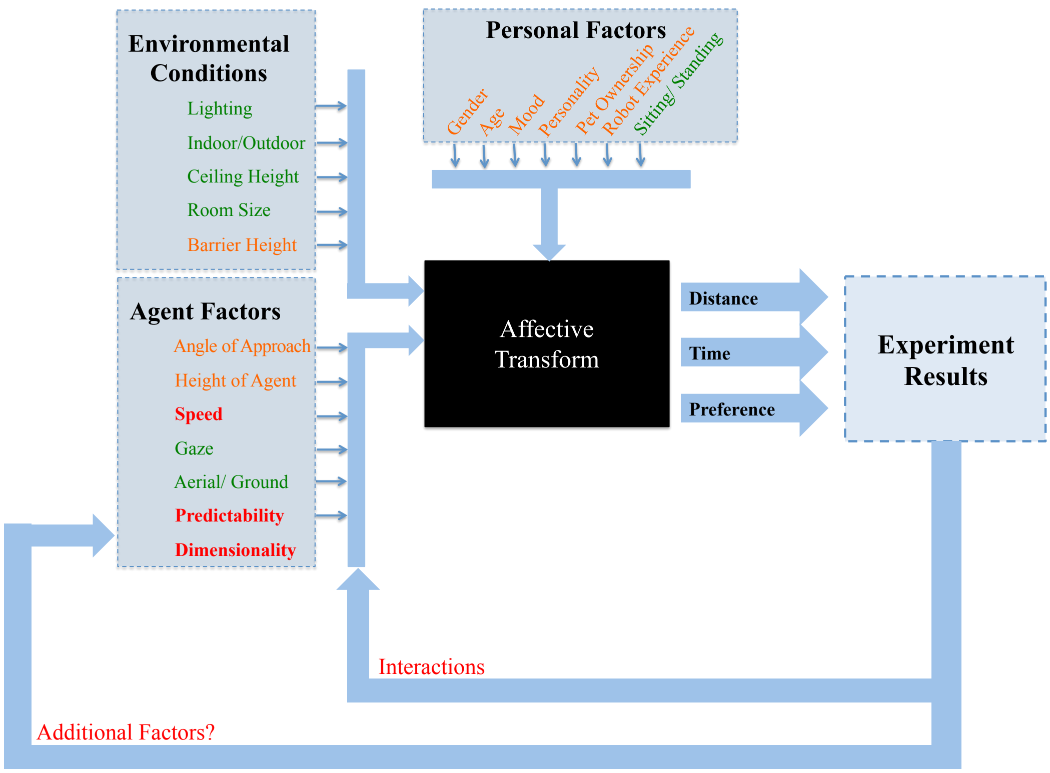

Figure 6.1: "Comfortable Distance" Model, adjusted to show what the Independent Variables (in red), the Measured Covariates (in orange), and the Controlled Variables held constant (in green) are for the proposed experiments. The output is the distance that a human would feel comfortable being distanced from a robot or another human, as well as the other Dependent Variables (time of interaction and preference), which were used to understand the affect generated by the expression. Finally, the results feed back to the model in the form of additional factors and possible interactions between the Independent Variables.

As shown in Figure 6.1, the components of the CD model were either varied in this study (Independent Variables), measured in this study (Measured Covariates), or held constant in this study (Controlled Variables). The Dependent Variables are: distance, time, and preference. Distance was presented as a measure in Chapter 2 to understand how people interact with agents, while time and preference were added to understand affect generated by an expression. For each independent variable, the others were held constant and each dependent variable was assessed separately. Distance was the primary dependent variable to inform the CD model, but increased time of interaction was counter to the goal of evacuation so led to reassessment. Preference was also seen as counter to the goal of evacuation because it indicates that the robot is seen as more "passable" and would not be as good at guarding an area. The Measured Covariates are the Personal Factors from the CD model (gender, age, mood, personality, pet ownership, robot experience, sitting/standing), as well as the angle of approach. These were measured in order to test them against significant findings, for more information on testing see Section 6.3.

Nine site defense expressions, shown in Table 6.2, were tested in interactions with varied amounts of speed, predictability, and dimensionality. All behaviors have been described in Chapter 3, but will be briefly described here. The two behaviors (approaching and threatening) each have component expressions which were tested here for applicability in an evacuation scenario. Approaching is made up of four expressions: silently circle overhead, swooping, monitoring, and inspection. Threatening is made up of five expressions: running, pursuing, lunging, harassment, and head lowered, stare down.

Fifteen personal defense expressions, shown in Table 6.3 were tested with varying levels of speed, predictability, and dimensionality. All behaviors have been described in Chapter 3, but will be briefly described here. Personal defense includes three behaviors: startle display, physical attack, and protean display. Startle display includes four expressions: display weapons, stotting, sudden noise, and run at moderate speed. Physical attack includes five expressions: approach, diving, thrust legs to opponent, nod at opponent, and charging. Protean display includes six expressions: fast turns, ponderous movements, sudden twists, intermittent locomotion, erratic zigzag, and bouncing flight path.

Nine hypotheses will be presented starting in Section 6.1.1 through Section 6.1.9, but these are also summarized in Table 6.1. There are three hypotheses for each independent variable (speed, predictability, and dimensionality), one for each dependent variable (distance, time, and preference). Hypotheses 1-3 concern speed and expectations for each level of speed is predicted for each dependent variable, which leads to six predicted effects. Hypotheses 4-6 concern predictability and 7-9 concern dimensionality.

6.1.1 Hypothesis 1: Increased Robot Speed Will Increase Interaction Distances

Hypothesis 1: Participants will be more likely to maintain a larger distance when encountering a faster moving robot rather than a slower robot.

Low speed robot expressions are drawn mainly from the approaching and startle display behaviors, while high speed expressions are from threatening, physical attack, and protean display. Based on human-robot interaction studies by Pacchierotti, Christensen, and Jensfelt [48] and Butler and Agah [59], participants prefer a robot moving around 0.4 meters per second, which is significantly less than our low speed of 2 meters per second. Both this and the fact that the high speed of 5 meters per second is considered a fast attack in birds [62] lead to a belief that participants will stay further away from a fast robot. This will be measured by the average approach distance to "high speed" robot expressions when compared to "low speed" robots.

6.1.2 Hypothesis 2: Increased Robot Speed Will Decrease Interaction Times

Hypothesis 2: Participants will be more likely to maintain a shorter time in the guarded area when encountering a faster moving robot rather than a slower robot.

Low speed robot expressions are drawn mainly from the approaching and startle display behaviors, while high speed expressions are from threatening, physical attack, and protean display. Based on human-robot interaction studies by Pacchierotti, Christensen, and Jensfelt [48] and Butler and Agah [59], participants prefer a robot moving around 0.4 meters per second, which is significantly less than our low speed of 2 meters per second. Both this and the fact that the high speed of 5 meters per second is considered a fast attack in birds [62] lead to a belief that participants will leave the area faster when encountering a fast robot. This will be measured by the average amount of time spent close to "high speed" robot expressions when compared to "low speed" robots.

6.1.3 Hypothesis 3: Increased Robot Speed Will Decrease Preference

Hypothesis 3: Participants will be less likely to choose to pass that robot when encountering a faster moving robot rather than a slower robot.

Low speed robot expressions are drawn mainly from the approaching and startle display behaviors, while high speed expressions are from threatening, physical attack, and protean display. Based on human-robot interaction studies by Pacchierotti, Christensen, and Jensfelt [48] and Butler and Agah [59], participants prefer a robot moving around 0.4 meters per second, which is significantly less than our low speed of 2 meters per second. Both this and the fact that the high speed of 5 meters per second is considered a fast attack in birds [62] lead to a belief that participants will choose to pass a slow robot rather than a fast robot. This will be measured by the average number of attempts to pass “high speed” robot expressions when compared to “low speed” robots.

6.1.4 Hypothesis 4: More Predictability Will Decrease Interaction Distances

Hypothesis 4: Participants will be more likely to maintain a larger distance when encountering a less predictable robot rather than a predictable robot.

High predictability expressions are drawn mainly from the approaching, threatening, and physical attack behaviors, while low predictability expressions are from protean and startle display behaviors. This factor has not been previously examined in human distancing literature, but animal literature would lead to the expectation that unpredictable behaviors are used to display fitness [54] and startle predators (potentially causing them to move away) [54, 64]. Based on this research, it is predicted that interaction distance will increase with less predictable robots. This will be measured by the average approach distance to “high predictability” robot expressions when compared to “low predictability” robots.

6.1.5 Hypothesis 5: Less Predictability Will Increase Interaction Times

Hypothesis 5: Participants will be more likely to maintain a shorter time when encountering a more predictable robot rather than a less predictable robot.

High predictability expressions are drawn mainly from the approaching, threatening, and physical attack behaviors, while low predictability expressions are from protean and startle display behaviors. This factor has not been previously examined in human distancing literature, but animal literature would lead to the expectation that unpredictable behaviors are used to display fitness [54] and confuse predators [63] (likely increasing time of interaction). Based on this research, it is expected that time of interaction will increase with less predictable robots. This will be measured by the average amount of time spent close to “high predictability” robot expressions when compared to "low predictability" robots.

6.1.6 Hypothesis 6: More Predictability Will Increase Preference

Hypothesis 6: Participants will be less likely to choose to pass that robot when encountering a less predictable robot rather than a predictable robot.

High predictability expressions are drawn mainly from the approaching, threatening, and physical attack behaviors, while low predictability expressions are from protean and startle display behaviors. This factor has not been previously examined in human distancing literature, but animal literature would lead to the expectation that unpredictable behaviors are used to display fitness [54], confuse predators [63] (likely increasing time of interaction), and startle them (potentially causing them to move away) [54, 64]. Due to this application in nature, it would be expected that humans will show a preference for more predictable behaviors. This will be measured by the average number of attempts to pass "high predictability" robot expressions when compared to "low predictability" robots.

6.1.7 Hypothesis 7: Increased Number of Dimensions Used by the Robot will Increase Interaction Distances

Hypothesis 7: Participants will be more likely to maintain a larger distance when encountering a robot encompassing three dimensions rather than a robot acting in a plane.

Tozawa and Oyama [65] found that motion parallax (change in angular velocity as an object is moved closer to a subject) was a more effective cue than perspective cues (change in height with respect to the horizon) when estimating size, but that both were equally effective for distance cues. Bertamini, Yang, and Proffitt [66] found that relative size perception is best at eye level and sharply decreased above and below eye level. Based on these two findings, it is believed that the addition of a third dimension of movement (x, y, and z) rather than only (x, y or x, z) will result in a perception of a larger-size and thus more intimidating robot. The addition of a third dimension is predicted to be seen as display flight, which in animals is closely correlated with territory [52]. Drawing from both the human interaction and animal literature, it is expected that participants will maintain a larger distance from a three dimensional robot. This will be measured by the average approach distance to "three dimensional" robot expressions when compared to "two dimensional" robots.

6.1.8 Hypothesis 8: Increased Number of Dimensions Used by the Robot will Decrease Interaction Times

Hypothesis 8: Participants will be more likely to maintain a shorter time in the guarded area when encountering a robot encompassing three dimensions rather than a robot acting in a plane.

Tozawa and Oyama [65] found that motion parallax (change in angular velocity as an object is moved closer to a subject) was a more effective cue than perspective cues (change in height with respect to the horizon) when estimating size, but that both were equally effective for distance cues. Bertamini, Yang, and Proffitt [66] found that relative size perception is best at eye level and sharply decreased above and below eye level. Based on these two findings, it is believed that the addition of a third dimension of movement (x, y, and z) rather than only (x, y or x, z) will result in a perception of a larger-size and thus more intimidating robot. The addition of a third dimension is predicted to be seen as display flight, which in animals is closely correlated with territory [52]. Drawing from both the human interaction and animal literature, it is expected that participants will maintain a shorter time with a three dimensional robot. This will be measured by the average amount of time spent close to "three dimensional" robot expressions when compared to "two dimensional" robots

6.1.9 Hypothesis 9: Increased Number of Dimensions Used by the Robot will Decrease Preference

Hypothesis 9: Participants will be more likely to avoid a robot encompassing three dimensions rather than a robot acting in a plane.

Tozawa and Oyama [65] found that motion parallax (change in angular velocity as an object is moved closer to a subject) was a more effective cue than perspective cues (change in height with respect to the horizon) when estimating size, but that both were equally effective for distance cues. Bertamini, Yang, and Proffitt [66] found that relative size perception is best at eye level and sharply decreased above and below eye level. Based on these two findings, it is believed that the addition of a third dimension of movement (x, y, and z) rather than only (x, y or x, z) will result in a perception of a larger-size and thus more intimidating robot. The addition of a third dimension is predicted to be seen as display flight, which in animals is closely correlated with territory [52]. Drawing from both the human interaction and animal literature, it is expected that participants will choose to avoid a three dimensional robot. This will be measured by the average number of attempts to pass "three dimensional" robot expressions when compared to "two dimensional" robots.

6.2 Participants

A total of 68 participants were recruited for the study, with 4 participants unable to complete the study due to equipment failure or an insufficient amount of time to complete all required parts of the study. Detailed demographic information was collected through the use of a pre-interaction survey, this data included: culture, video game experience, personality, mood, and robot opinions/ experiences. These participants were recruited from the Texas A&M Campus mailing lists, which has been successfully used to recruit participants in previous HRI studies.

Participants included both 37 males and 27 females, with an average age of 36 years old and a standard deviation of 16 years. Of these participants, 19 played video games yearly or never, 13 played monthly, 17 played weekly, and 15 played daily. Forty-three of the participants had previous experience with robots in either a consumer, industrial, educational, or entertainment setting, while the other twenty-one participants reported no prior robot experience.

6.3 Experimental Design

This simulation study which was conducted in a CAVE environment and used to evaluate the effectiveness of the expressions of the animal behaviors, described in Chapter 3, for impacting human movements. Participants were asked to guide a first person avatar through a series of rooms (an example is shown in Figure 6.2) with an incentive to reach the end as quickly as possible without incurring any injuries to their avatar. Each room will have the same space of interaction, with the robots being placed on a line and the room split with a wall behind them. At the entry to each room, the participants will encounter pairs of robot platforms performing the identified expressions.

The design of the sets of robot encounters, which were split based on factor with a total of three, and were based on the two-alternative forced-choice (2AFC) technique, which has been used in psychology to study sensory thresholds for vision [67], acoustic cues [68], taste [69]. Roboticists have used this method to understand human decision making in human-robot teaming [70, 71], though in this case they sought to influence the decision making with rewards. The 2AFC method has also been used to test preferences, for example in masculinity [72] whose methods were used in this experiment to determine preference for predictability, dimensionality, and speed in

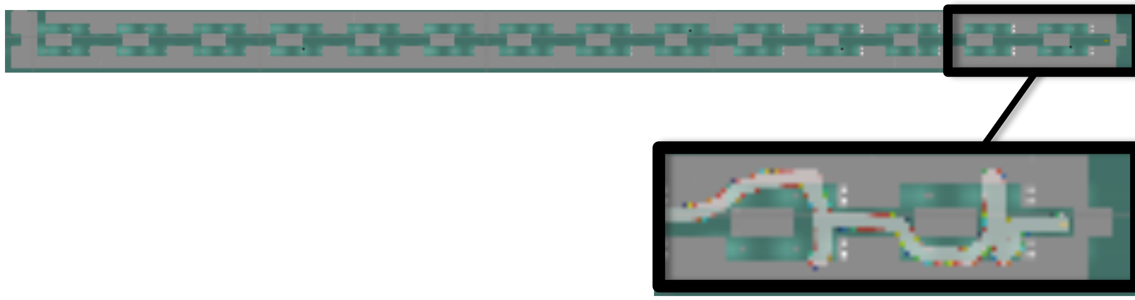

Figure 6.2: Maze navigated by participants. A different set of robots was positioned with one on either side of the center wall, and one set in each room. The faint line on the exploded view is the path taken by a given participant to display the path taken.

robot behaviors. The primary statistical measure for each set of encounters was a one-sample t-test. Each set of encounters was designed (as much as possible) to hold other factors constant while comparing for the factor of interest. For example, when comparing high versus low speed expressions the predictability and dimensionality were held constant when possible.

Psychophysiological measurements, more specifically heart rate data, were recorded along with audio and video during each experiment. The pre-trial survey was given to measure the personal factors in anticipation of them being covariates with the main effect based on the previous literature. A post-trial survey was given to measure feelings about the interaction and feedback about speed, predictability, and dimensionality. Data from this experiment was evaluated to provide results for the nine hypotheses, be fed back into the CD model to update the expected results, and select the best expressions to inform future work.

6.4 Facilities

Study 1 took place in building 8007 at Texas A&M University's Riverside Campus in order to use the established CAVE environment (see Figure 6.3) for life sized interactions.

Figure 6.3: CAVE environment used in Study 1. Simulation projected on 5 screens (3600x1080) with participant interacting while seated at table.

6.5 Equipment

Seven different pieces of equipment were used for this experiment Video cameras, 2 GoPro Hero, were used to capture video of the CAVE and the participants in Study 1. For psychophysiological sensing, wearable Biopack BioNomadix sensors were used. Finally, all surveys were conducted using a paper form approved by IRB. All listed equipment has a minimum of 1 backup, and additional equipment was used as needed. Participant information is stored in locked cabinets and encrypted files as required by IRB.

6.6 Personnel

The investigator of this work has been responsible for setting up experimental protocols and gaining IRB approval, and ran all of the trials and statistical analysis of the results.

6.7 Pre-Trial Survey

A pre-trial assessment survey of individual background knowledge and experience was given to each participant (e.g., experiences with robots, pets, etc.) to ensure that any confounds can be identified in data analysis (shown in Appendix A). The pretrial survey used the Positive and Negative Affect Schedule (PANAS) [73] examining feelings for the past few days and current day and the International Personality Item Pool [74] to test for dominant personality characteristics.

6.8 Post-Trial Survey

An IRB-approved post-trial assessment survey (shown in Appendix B) was used to evaluate participant attitudes, feelings about the interaction, and any changes in affective state.

6.9 Study Protocol

For each potential participant in the experiment, an IRB-approved announcement for the study was first read aloud by the investigator. The verbal announcement presented an overview of the study for individuals who wished to participate. Potential participants were able to withdraw from the study at any time. Finally, the potential participant completed the Consent Form. Upon consent, the potential participant will become a participant.

After consent, a preparatory statement was read to the participant to describe what they were to expect (this contained only necessary information). Participants were instructed on interactions in the simulation and a practice run of a similar space took place. After the participants were briefed on the study, questions were solicited and the trial began.

6.10 Discussion of Design

One limitation of the current design is that this experiment only tested a single robot, rather than multiple robots of different sizes and designs. As with much of the previous literature, covered in [38], a single robot (or agent) was being tested in order to test the impact of individual factors. Future refinements can include the testing of open- versus closed-rotor systems, large versus small systems, and even the effectiveness of multiple versus single robot displays.

6.11 Summary

This section described the details for designing understandable behaviors and assessing the impact of their application by an sUAV on peoples' movements in order to incorporate the findings into the CD model. Nine hypotheses with expected findings were outlined to answer the primary research question. Participant, facility, equipment, and personnel details were given for this study. Descriptions of the surveys and the experimental design to assess the behaviors appear.

7. DATA ANALYSIS AND RESULTS

This section presents the analysis for the data collected during the interactive simulation study to evaluate the addition of speed, predictability, and dimensionality of robot motion as factors in the "Comfortable Distance" model (CD model). Only a subset of the data collected were analyzed for this dissertation, as the focus was restricted to distance, time, and preference of participants from the robots demonstrating the site and personal defense expressions defined in Section 3. The analyses performed for the study data included three categories for each of the three factors: i) interaction distance (both split by factor, and with the interactions between factors), ii) interaction time (both split by factor, and with the interactions between factors), and iii) preference (only split by factor). For each of the nine analyses (3 categories x 3 factors), inferential statistics will be presented. All statistical tests were performed at a significance level (α) of 0.05.

Two three-way (2 x 2 x 2) repeated measures analysis of variance (ANOVA) were run for each distance (in meters) and time (in seconds). Resulting in information about Speed (low vs. high), Predictability (low vs. high), and Size (2D vs. 3D) of robot motions, as well as interactions between these factors. The results from these ANOVAs will be presented in Sections 7.1.1, 7.1.2, 7.2.1, 7.2.2, 7.3.1, and 7.3.2. Additionally, a one-sample t-test (compared to 50%) was run for each of the three factors to determine whether the mean preference (in percentage) was statistically different from the expectation of a random choice (50%). The results from these t-tests will be presented in Sections 7.1.3, 7.2.3, and 7.3.3.

An additional set of three hypotheses were developed after running the experiment to test the factor of motion-centeredness, which is whether an expression is centered on the person interacting with the robot or the space the robot is guarding. Three within-subject t-tests were run to determine whether each of the three categories of measurement (based on the difference between the two being different from 0). The results from these t-tests will be presented in Sections 7.4.1, 7.4.2, and 7.4.3.

7.1 Robot Speed Impact on Interaction Distance, Interaction Time, and Expression Preference

The results from the two three-way repeated measures ANOVAs and the one-sample t-test for speed of robot motion will be presented in this section and compared to Hypotheses 1-3, which were presented in Section 6.1.

7.1.1 Increased Robot Speed Decreased Interaction Distance

Hypothesis 1, as presented in Section 6.1.1, was: *Participants will be more likely to maintain a larger distance when encountering a faster moving robot rather than a slower robot.* The participants' interaction distance with each robot were recorded to the nearest hundredth of a meter (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a 2 (low speed vs. high speed) by 2 (low predictability vs. high predictability) by 2 (2D vs. 3D) repeated measures ANOVA. Table 7.1 contains both the descriptive (mean, standard deviation, and number of participants or N) and inferential (degrees of freedom or df, value of F, and significance or p-value).

Overall, subjects tended to decrease their interaction distances as robot speed increased, $\text{Mean}_{\text{LowSpeedRobot}} = 2.33$ m versus $\text{Mean}_{\text{HighSpeedRobot}} = 2.06$ m, $F(1,63) = 5.49$, $p = 0.02$. This finding was in contrast to the prediction based on the classification of the animal behaviors (fast speed are more likely to be attack behaviors, while low speed are more about distraction), but in keeping with the findings from other researchers from human-robot interaction [48, 59].

Most central to this work is the main effect of speed, however the interaction effects will now be presented for further exploration in the discussion section with regards to animal behaviors, evacuation, and future work. The main effect of Speed was qualified by an interaction (p <0.0001) with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased distance in the low speed condition and increased distance in the high speed condition (see Figure 7.1).

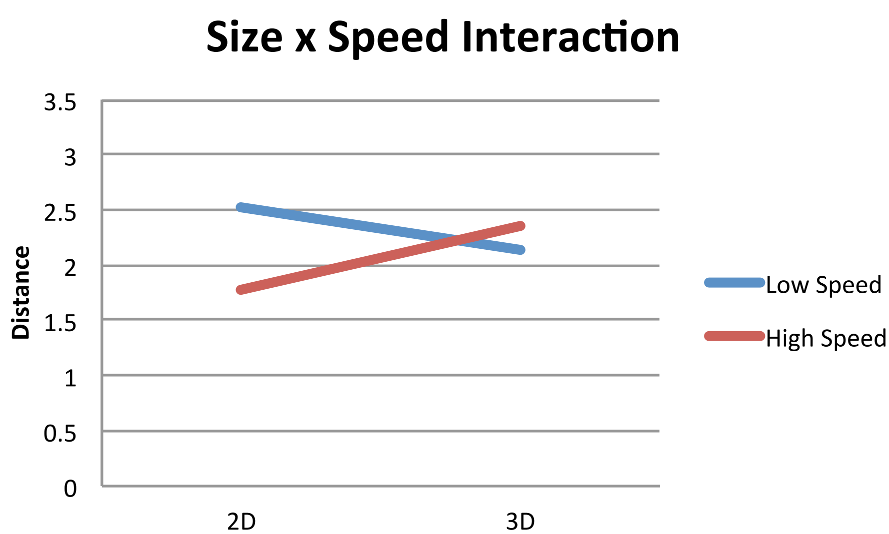

Figure 7.1: Interaction (p <0.0001) of Speed with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased distance in the low speed condition and increased distance in the high speed condition

7.1.2 Increased Robot Speed Increased Interaction Time

Hypothesis 2, as presented in Section 6.1.2, was: *Participants will be more likely to maintain a shorter time in the guarded area when encountering a faster moving robot rather than a slower robot.* The participants' interaction time with each

Independent Variable	Mean	Standard Deviation	N	df	F	Significance
Low Speed	2.33 m	0.77	64	1	5.49	p <0.02
High Speed	2.06 m	0.75	64	1	5.49	p <0.02
Low Predictability	2.06 m	0.75	64	1	6.82	p <0.01
High Predictability	2.34 m	0.75	64	1	6.82	p <0.01
2D	2.15 m	0.70	64	1	1	p >0.05
3D	2.24 m	0.74	64	1	1	p >0.05
Size x Speed	See Graph	See Graph	64	1	22.39	p <0.0001
Predictability x Speed	N/A	N/A	64	1	3.14	p >0.08
Predictability x Size	See Graph	See Graph	64	1	7.49	p <0.008
Predictability x Speed x Size	See Graph	See Graph	64	1	9.86	p <0.003

Table 7.1: Mean distances for interactions based on speed, predictability, and size

robot were recorded to the nearest tenth of a second (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a 2 (low speed vs. high speed) by 2 (low predictability vs. high predictability) by 2 (2D vs. 3D) repeated measures ANOVA. Table 7.2 contains both the descriptive (mean, standard deviation, and number of participants or N) and inferential (degrees of freedom or df, value of F, and significance or p-value).

Overall, subjects tended to increase their interaction time as robot speed increased, $\text{Mean}_{\text{LowSpeedRobot}} = 40.2$ seconds versus $\text{Mean}_{\text{HighSpeedRobot}} = 44.6$ seconds, F(1,63) = 15.9, p = 0.0002. This finding was in contrast to the prediction based on the classification of the animal behaviors where fast speed are more likely to be attack behaviors, while low speed are more about distraction and thus would be confusing which would lead to increased time.

Most central to this work is the main effect of speed, however the interaction effects will now be presented for further exploration in the discussion section with regards to animal behaviors, evacuation, and future work. The main effect of Speed was qualified by an interaction (p <0.003) with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased time in the high speed condition and increased time in the low speed condition (see Figure 7.2).

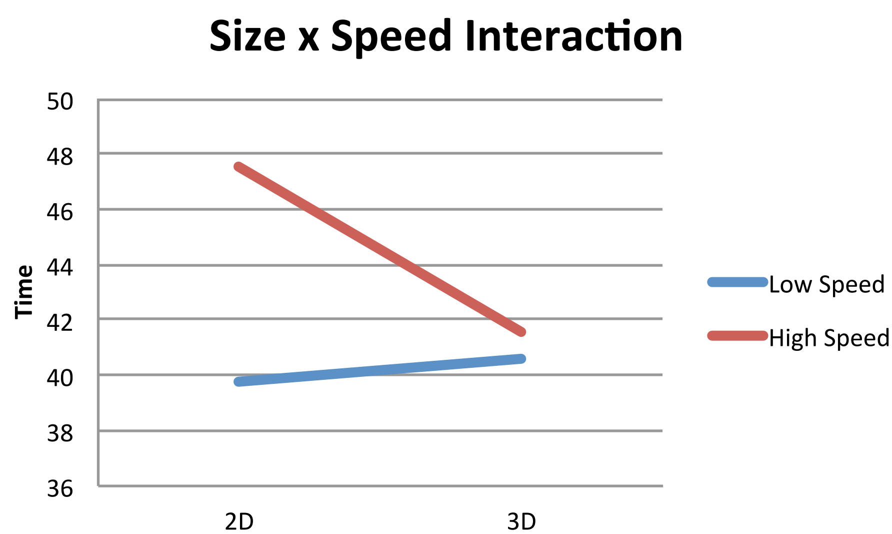

Figure 7.2: Interaction (p <0.003) of Speed with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased time in the high speed condition and increased time in the low speed condition

7.1.3 Increased Robot Speed Increased Preference

Hypothesis 3, as presented in Section 6.1.3, was: *Participants will be less likely to choose to pass that robot when encountering a faster moving robot rather than a slower robot.* The participants' preference for each robot were recorded based on their choice to pass (or not) robots displaying an expression with the high or low level of a factor (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a a one-sample t-test (compared to 50%) based on whether their choice was seemingly random.

Independent Variable	Mean	Standard Deviation	N	df	F	Significance
Low Speed	40.2 seconds	10.1	64	1	15.9	p <0.0002
High Speed	44.6 seconds	14.5	64	1	15.9	p <0.0002
Low Predictability	42.8 seconds	13.3	64	1	0.49	p >0.05
High Predictability	42 seconds	11.8	64	1	0.49	p >0.05
2D	43.7 seconds	11.6	64	1	5.09	p <0.03
3D	41.1 seconds	13.5	64	1	5.09	p <0.03
Size x Speed	See Graph	See Graph	64	1	9.77	p <0.003
Predictability x Speed	N/A	N/A	64	1	0.00	p >0.99
Predictability x Size	See Graph	See Graph	64	1	8.94	p <0.004
Predictability x Speed x Size	N/A	N/A	64	1	0.03	p >0.86

Table 7.2: Mean times for interactions based on speed, predictability, and size

Overall, subjects tended to prefer to pass robots as robot speed increased, $\text{Mean}_{\text{LowSpeedRobot}}$ = 44.8% versus $\text{Mean}_{\text{HighSpeedRobot}}$ = 55.2% (SD = 12.6%) was significantly different from $t(63)$ = -3.3, p = 0.002. The 95% confidence interval for mean preference ranged from 44.9 to 55.1% This finding was in contrast to the prediction based on the classification of the animal behaviors, where fast speed are more likely to be attack behaviors and low speed are more about distraction and thus would be confusing which would lead to increased time. This finding is supported by the HRI literature indicating a preference towards fast robot speeds [48, 59].

7.2 Robot Predictability Impact on Interaction Distance, Interaction Time, and Expression Preference

The results from the two three-way repeated measures ANOVAs and the one-sample t-test for speed of robot motion will be presented in this section and compared to Hypotheses 4-6, which were presented in Section 6.1.

7.2.1 Increased Robot Predictability Increased Interaction Distance

Hypothesis 4, as presented in Section 6.1.4, was: *Participants will be more likely to maintain a larger distance when encountering a less predictable robot rather than a predictable robot.* The participants' interaction distance with each robot were recorded to the nearest hundredth of a meter (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a 2 (low speed vs. high speed) by 2 (low predictability vs. high predictability) by 2 (2D vs. 3D) repeated measures ANOVA. Table 7.1 contains both the descriptive (mean, standard deviation, and number of participants or N) and inferential (degrees of freedom or df, value of F, and significance or p-value).

High predictability robots were those without any randomness in the code (leading to cyclic motions), while low predictability robots had variables with either random distances, turns, or height changes. Overall, subjects tended to increase their interaction distances as robot predictability increased, $\text{Mean}_{\text{LowPredictabilityRobot}} = 2.06$ m versus $\text{Mean}_{\text{HighPredictabilityRobot}} = 2.34$ m, $F(1,63) = 6.82$, $p = 0.01$. This finding was in contrast to the prediction based on the classification of the animal behaviors, where low predictability are more likely to display fitness or startle predators while high predictability are more about site defense or physical attack, [54, 63].

Most central to this work is the main effect of predictability, however the interaction effects will now be presented for further exploration in the discussion section with regards to animal behaviors, evacuation, and future work. The main effect of Predictability was qualified by an interaction ($p < 0.008$) with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased distance in the high predictability condition and increased distance in the low predictability condition (see Figure 7.3).

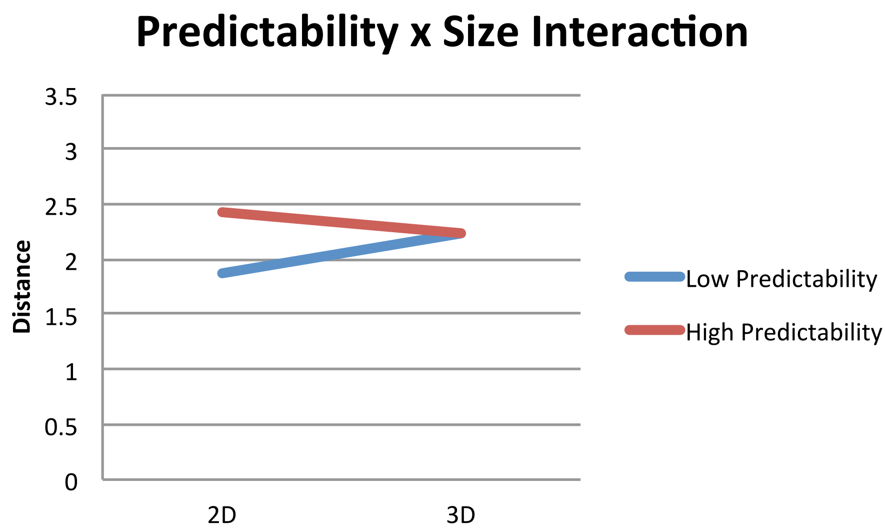

Figure 7.3: Interaction (p <0.008) of Predictability with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased distance in the high predictability condition and increased distance in the low predictability condition

7.2.2 Robot Predictability Impact on Interaction Time

Hypothesis 5, as presented in Section 6.1.5, was: *Participants will be more likely to maintain a shorter time when encountering a more predictable robot rather than a less predictable robot.* The participants' interaction time with each robot were recorded to the nearest tenth of a second (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a 2 (low speed vs. high speed) by 2 (low predictability vs. high predictability) by 2 (2D vs. 3D) repeated measures ANOVA. Table 7.2 contains both the descriptive (mean, standard deviation, and number of participants or N) and inferential (degrees of freedom or df, value of F, and significance or p-value).

High predictability robots were those without any randomness in the code (leading to cyclic motions), while low predictability robots had variables with either random distances, turns, or height changes. There was no statistical difference in time of interaction based on the predictability of the robot, $\text{Mean}_{\text{LowPredictabilityRobot}} = 42.8$ seconds versus $\text{Mean}_{\text{HighPredictabilityRobot}} = 42$ seconds, $F(1,63) = 0.49$, $p > 0.05$.

However there was an interaction effect, which will now be presented for further exploration in the discussion section with regards to animal behaviors, evacuation, and future work. The interaction ($p < 0.004$) of Predictability with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased time in the high predictability condition and increased time in the low predictability condition (see Figure 7.4).

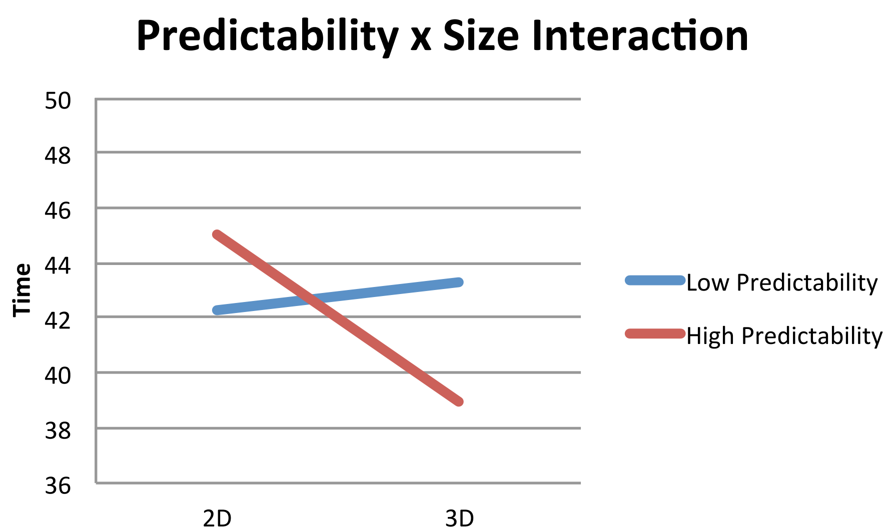

Figure 7.4: Interaction ($p < 0.004$) of Predictability with Dimensionality of the robots motion, where an increase in Dimensionality resulted in decreased time in the high predictability condition and increased time in the low predictability condition.

7.2.3 Robot Predictability Impact on Preference

Hypothesis 6, as presented in Section 6.1.6, was: *Participants will be less likely to choose to pass that robot when encountering a less predictable robot rather than a predictable robot.* The participants' preference for each robot were recorded based on their choice to pass (or not) robots displaying an expression with the high or low level of a factor (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a a one-sample t-test (compared to 50%) based on whether their choice was seemingly random.

There was no statistical difference in preference of interaction based on the predictability of the robot, $\text{Mean}_{\text{LowPredictabilityRobot}} = 49.9\%$ versus $\text{Mean}_{\text{HighPredictabilityRobot}} = 50.1\%$ (SD = 13.6%) was not significantly different from $t(63) = 0.1$, $p > 0.05$. The 95% confidence interval for mean preference ranged from 46.6 to 53.4%.

7.3 Dimensionality of Robot Motion Impact on Interaction Distance, Interaction Time, and Expression Preference

The results from the two three-way repeated measures ANOVAs and the one-sample t-test for speed of robot motion will be presented in this section and compared to Hypotheses 7-9, which were presented in Section 6.1.

7.3.1 Dimensionality of Robot Motion Impact on Interaction Distance

Hypothesis 7, as presented in Section 6.1.7, was: *Participants will be more likely to maintain a larger distance when encountering a robot encompassing three dimensions rather than a robot acting in a plane.* The participants' interaction distance with each robot were recorded to the nearest hundredth of a meter (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a 2 (low speed vs. high speed) by 2 (low predictability vs.

high predictability) by 2 (2D vs. 3D) repeated measures ANOVA. Table 7.1 contains both the descriptive (mean, standard deviation, and number of participants or N) and inferential (degrees of freedom or df, value of F, and significance or p-value).

High dimensionality robots were those that moved in 3 dimensions, while low dimensionality robots only moved in two (with either height or distance from the plane of the line fixed). There was no statistical difference in preference of interaction based on the dimensionality of the robot, $Mean_{2DRobot} = 2.15$ m versus $Mean_{3DRobot} = 2.24$ m, $F(1,63) = 1$, $p > 0.05$. This lack of a finding was in contrast to the prediction based on the classification of the animal behaviors, where high dimensionality is closely related to territory, [52].

However there was an interaction effect, which will now be presented for further exploration in the discussion section with regards to animal behaviors, evacuation, and future work. The interaction ($p < 0.008$, $p < 0.0001$) of Dimensionality with both Speed and Predictability of the robots motion,where an increase in Dimensionality resulted in increased distance in all conditions except those robots with both high predictability and low speed (see Figure 7.5).

7.3.2 Increased Dimensionality of Robot Motion Decreased Interaction Time

Hypothesis 8, as presented in Section 6.1.8, was: *Participants will be more likely to maintain a shorter time in the guarded area when encountering a robot encompassing three dimensions rather than a robot acting in a plane.* The participants' interaction time with each robot were recorded to the nearest tenth of a second (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a 2 (low speed vs. high speed) by 2 (low predictability vs. high predictability) by 2 (2D vs. 3D) repeated measures ANOVA. Table 7.2 contains both the descriptive (mean, standard deviation, and

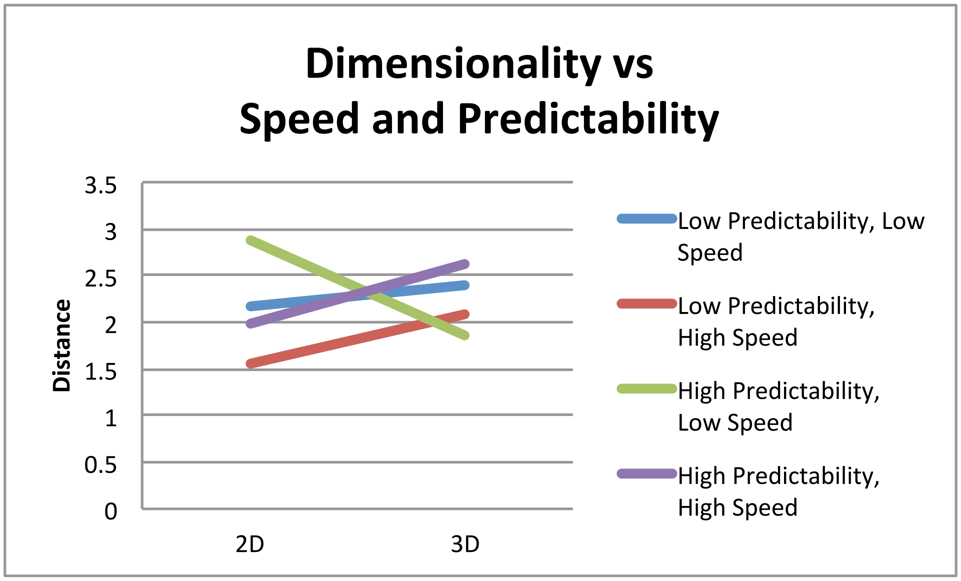

Figure 7.5: 3-way interaction (p <0.008, p <0.0001) with Dimensionality of the robots motion with both Speed and Predictability, where an increase in Dimensionality resulted in increased distance in all conditions except those robots with both high predictability and low speed.

number of participants or N) and inferential (degrees of freedom or df, value of F, and significance or p-value).

High dimensionality robots were those that moved in 3 dimensions, while low dimensionality robots only moved in two (with either height or distance from the plane of the line fixed). Overall, subjects tended to decrease their interaction times as robot dimensionality increased, $\text{Mean}_{\text{3DRobot}} = 41.1$ seconds versus $\text{Mean}_{\text{2DRobot}} = 43.7$ seconds, $F(1,63) = 5.09$, $p < 0.03$. This finding was in support of the prediction based on the classification of the animal behaviors, where high dimensionality is closely related to territory, [52] and thus reduced time of interaction.

7.3.3 Dimensionality of Robot Motion Impact on Preference

Hypothesis 9, as presented in Section 6.1.9, was: *Participants will be more likely to avoid a robot encompassing three dimensions rather than a robot acting in* *a plane.* The participants' preference for each robot were recorded based on their choice to pass (or not) robots displaying an expression with the high or low level of a factor (in a simulation environment, with the sizes based on the real-life robot size and an average human height) and analyzed with a a one-sample t-test (compared to 50%) based on whether their choice was seemingly random.

There was no statistical difference in preference of interaction based on the dimensionality of the robot, $\text{Mean}_{\text{2DRobot}} = 52.6\%$ versus $\text{Mean}_{\text{3DRobot}} = 47.4\%$ (SD = 14.3%) was not significantly different from $t(63) = 1.4$, p >0.05. The 95% confidence interval for mean preference ranged from 46.4 to 53.6%.

7.4 Focus of Robot Motion on Interaction Distance, Interaction Time, and Expression Preference

The results from the three within subjects t-tests for focus of robot motion on distance, time, and expression preference will be presented in this section, along with the Hypotheses 10-12, which will be presented in each Section.

7.4.1 Focus of Robot Motion on Person Increased Interaction Distance

Hypothesis 10: Participants will be more likely to maintain a larger distance when encountering a robot which follows their movements rather than one which guards a space.

This hypothesis was tested by comparing the difference in average distance maintained by all participants from all robots centered on an area (2.29 m) versus those centered on the participant (2.33 m) using a within-subjects t-test. The distance maintained from the robots centered on the participants was not significantly greater than the distance maintained from the robots centered on an area.

7.4.2 Focus of Robot Motion on Person Decreased Interaction Time

Hypothesis 11: Participants will be more likely to maintain a shorter time in the guarded area when encountering a robot which follows their movements rather than one which guards a space.

This hypothesis was tested by comparing the difference in average distance maintained by all participants from all robots centered on an area (46.8 seconds) versus those centered on the participant (39.3 seconds) using a within-subjects t-test. The time interacting with the robots centered on the participants was significantly less than the distance maintained from the robots centered on an area ($t(4992)$=-400, p <.0001).

7.4.3 Focus of Robot Motion on Person Decreased Preference

Hypothesis 12: Participants will be less likely to choose to pass that robot when encountering a robot which follows their movements rather than one which guards a space.

This hypothesis was tested by comparing the difference in percentage of time chosen when presented with all robots centered on an area (64.2%) versus those centered on the participant (42.8%) using a within-subjects t-test. This number does not add up to 100% because these robots were not directly compared to each other. The preference for passing the robots centered on the participants was significantly less than the distance maintained from the robots centered on an area ($t(4992)$=-1313, p <.0001).

7.5 Summary

This section described the details for analyzing the impact of the three factors (speed, predictability, and dimensionality) and assessing the impact of their application by an sUAV on peoples' movements in simulation in order to incorporate the findings into the CD model. The findings based on the nine hypotheses presented in 6 were presented, along with three new hypotheses to answer the primary research question. Descriptions of the statistical methods employed and the significance of each finding were presented, and will be further explored in Section 8.

8. DISCUSSION

This section discusses and interprets the results obtained from the simulation study of human-robot interaction with a sUAV, describes the trends observed from the data in the context of the expressions supported while linking back to the animal behaviors described previously, and identifies the potential confounds that may have impacted the result outcomes. The results from the simulation study revealed three findings with sUAVs for evacuation: i) both inferential and descriptive statistics suggest that expressions focusing on the person were less preferred than those centered on the area, ii) inferential statistics suggest that personal defense behaviors are best for decreasing time of interaction and site defense behaviors are best for increasing distance of interaction, and iii) examining distances in the context of Hall's social distances [6], or potentially reverting to Hediger's zones [5] for territory in animals. Understanding these findings should inform: the CD model (including the addition of a new factor), the adoption of sUAVs for evacuation or guiding applications, and understanding of animal behaviors for human-robot interactions.

8.1 Expression Focus as a New Factor in the CD Model

When examining the participant preference for or against expressions (see Figure 8.1), it became clear that participants seemed to be responding to the focus of the robot and whether it was centered on the area or on their avatar. The top four preferred behaviors were focused on the area, so were independent of the movements of the avatar, while the bottom five were focused on the persona and closely mirrored the person's movement. This led to an examination of the distance, time, and preference of the 9 behaviors focused on the area and the remaining 15 centered on the person; time and preference were significant, which indicated that movements centered on the person could be used to decrease time and preference in an evacuation.

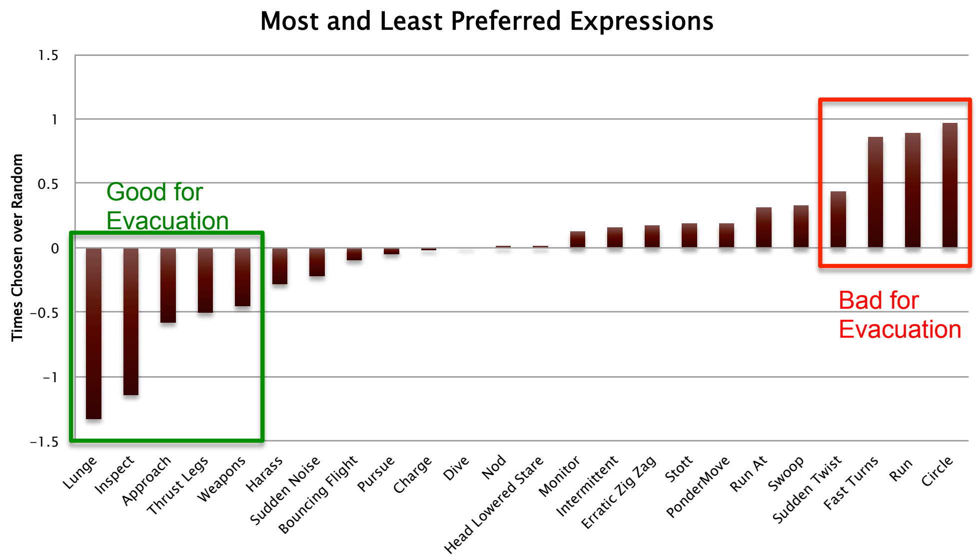

Figure 8.1: Preferred expressions, with the top four (outlined in red) focused on the area and the bottom five (outlined in green) focused on an person. The underlining in orange represents Site Defense and purple represents Personal Defense.

8.2 Animal Behaivors for Evacuation Discussion

The discussion in this chapter will focus on the findings in relation to the general use of either Site or Personal Defense behaviors for evacuation scenarios. The main effects of speed, predictability, and dimensionality will be summarized, before the interactions between these factors are discussed. Following the exploration of the inferential statistics presented in Chapter 7, the descriptive statistics will be explored for their insight into individual expression use, as well as a suggestion for an escalation strategy to be used in evacuation scenarios.

Hypothesis	Result	Significance
1. Increased speed results in increased distance	High Speed (2.06 m) <Low Speed (2.33 m)	$p < 0.02$
2. Increased speed results in decreased time	Low Speed (40.2 secs) <High Speed (44.6 secs)	$p < 0.0002$
3. Increased speed results in decreased preference	Low Speed (44.8 %) <High Speed (55.2 %)	$p < 0.002$

Table 8.1: Speed hypotheses and results, suggesting that low speed expressions are best for evacuations.

8.2.1 Main Effects of Speed, Predictability, and Dimensionality on Interactions

The main effect of speed on participant interactions was consistent across Distance, Time, and Preference, suggesting that low speed is preferred for evacuation in all cases (as shown in Table 8.1). This finding is in contrast to the hypotheses in Chapter 6 where it was hypothesized that high speed expressions would result in larger distances, shorter interactions, and lower preference. Half of each of the site and personal defense behaviors are low speed, with startle display from personal defense being the only behavior (collection of expressions) with only low speed behaviors and no behavior containing only high speed behaviors.

The main effect of predictability on participant interactions was only significant for distance, suggesting that low predictability is preferred for increasing distances in interactions, such as evacuation (as shown in Table 8.2). This finding is in contrast to the hypotheses in Chapter 6 where it was hypothesized that high predictability expressions would result in smaller distances, shorter interactions, and higher preference. Site defense behaviors trended towards (8/9) high predictability, while personal defense was composed of mostly low predictability (10/15) expressions. From site defense, the approaching behavior contained only expressions with high predictability and from personal defense, the protean display behavior was the

Hypothesis	Result	Significance
4. Increased predictability results in decreased distance	Low Predictability (2.05 m) <High Predictability (2.34 m)	p <0.01
5. Increased predictability results in decreased time	Low Predictability (42.8 secs) ≈ High Predictability (42 secs)	p >0.05
6. Increased predictability results in increased preference	Low Predictability (49.9 %) ≈ High Predictability (51.1 %)	p >0.05

Table 8.2: Predictability hypotheses and results, suggesting that high predictability expressions are best for increasing distances.

Hypothesis	Result	Significance
7. Increased dimensionality results in increased distance	2D (2.15 m) ≈ 3D (2.24 m)	p >0.05
8. Increased dimensionality results in decreased time	3D (41.1 secs) <2D (43.7 secs)	p <0.0002
9. Increased dimensionality results in decreased preference	2D (52.6 %) ≈ 3D(47.4 %)	p >0.05

Table 8.3: Dimensionality hypotheses and results, suggesting that 3D expressions are best for decreasing interaction times.

only behavior with only low predictability expressions.

The main effect of dimensionality on participant interactions was only significant for time, suggesting that the use of three dimensions is preferred for decreasing time in interactions, such as evacuation (as shown in Table 8.3). This finding is in support of the hypotheses in Chapter 6 where it was hypothesized that 3D expressions would result in shorter interactions, but inconclusive on the shorter distances and decreased preference. Site defense behaviors trended towards (6/9) 2D expressions, while personal defense was almost evenly split with 8/15 2D expressions. From personal defense, the startle display behavior was the only behavior with only 2D expressions and no behavior had only 3D expressions.

The result of these main effects suggests that low speed, high predictability, 3D expressions should be used for evacuation, but this results in only the approach expression (belonging to the physical attack behavior) from the Personal Defense behaviors falling in this category. To gain more insight into expressions that might be of interest and to explore all significant findings from the ANOVA, the interactions will be presented in the next section.

8.2.2 Interaction Effects of Speed, Predictability, and Dimensionality on Interactions

All three factors have an interaction when looking at participant distancing, which means all conditions increase distance when comparing 2D to 3D expressions, except low speed and high predictability behaviors, which decrease from 2D to 3D (as seen in Figure 8.2). Expressions that are low speed, high predictability, and 2D led to the largest distances and primarily belong to the Site Defense behaviors. The expressions head lowered stare down, monitor, inspect, and circle silently overhead are all from Site Defense, with the final three also belonging to the Approach behavior. From Personal Defense, the run at moderate speed and nod at opponent expressions fall into this category.

Both speed and predictability have interactions with dimensionality when looking at average time of interaction, where there is a substantial decrease in high speed expressions when looking at 2D versus 3D (as seen in Figure 8.3) and there is a decrease in high predictability expressions when looking at 2D versus 3D (as seen in Figure 8.4). Expressions that are low speed, high predictability, and 3D or low speed, low predictability, and 2D should have the shortest time of interaction. The expression approach belongs to the first category and belongs to the behavior physical attack in Personal Defense. The second category has the expressions display

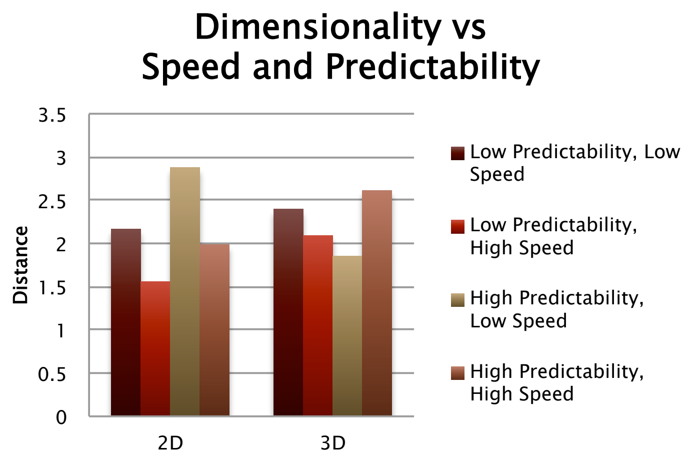

Figure 8.2: Three-way interaction for all factors on distance, showing that Low Speed, High Predictabilty, 2D expressions created the largest distance.

weapons, stott, and sudden noise from the behavior startle display, also in Personal Defense.

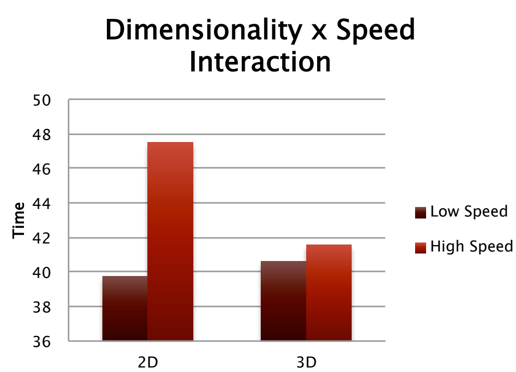

Figure 8.3: Two-way interaction for dimensionality and speed on time, showing that Low Speed and 2D expressions created the shortest time, but Low Speed and 3D wasn't much higher.

Ultimately, after examining the interaction effects, it seems that Site Defense behaviors are best for increasing interaction distances and Personal Defense behaviors

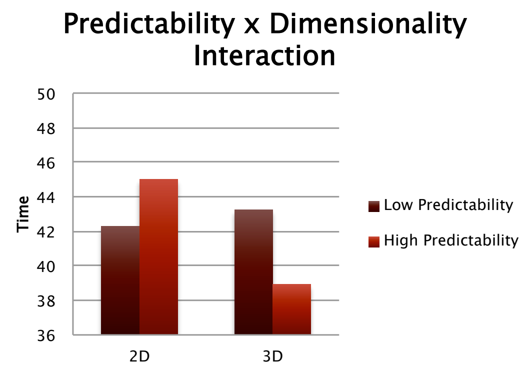

Figure 8.4: Two-way interaction for predictability and dimensionality on time, showing that High Predictabilty and 3D expressions created the shortest time, but if you were to look at 2D expressions, low predictability would be preferred.

are best for decreasing interaction times.

8.3 Understading Main and Interaction Effects on Individual Expressions

The main and interaction effects presented above have been summarized for their ability to increase distance, decrease time, and decrease preference in Tables 8.4 and 8.5. The average column in the table "sums" the checks and minuses in order to predict whether the expression would be useful for an evacuation, so that we can later create an escalation strategy. No Site Defense expressions were expected to increase distance, decrease time, and decrease preference across all four factors, but three expressions when compared across all factors should have averaged to be useful for evacuation; head lowered stare, monitor, and inspect are the suggested expressions from Site Defense. Approach is the only Personal Defense expression that is predicted to increase distance, decrease time, and decrease preference across all factors, while nod at opponent is averaged to be useful for evacuation. On the other hand, intermittent locomotion and bouncing flight path from Personal Defense are predicted to decrease distance, increase time, and increase preference across all

	Speed			Predict			Dimension			Focus			Average		
Expression	D	T	P	D	T	P	D	T	P	D	T	P	D	T	P
Head Lowered, Stare	✓	✓	✓	✓	≈	≈	✗	✗	≈	≈	✓	✓	✓	✓	✓
Monitor	✓	✓	✓	✓	≈	≈	✗	✗	≈	≈	✓	✓	✓	✓	✓
Inspect	✓	✓	✓	✓	≈	≈	✗	✗	≈	≈	✓	✓	✓	✓	✓
Harass	✓	✓	✓	✗	≈	≈	≈	✓	≈	≈	✓	✓	≈	✓	✓
Lunge	✗	✗	✗	✓	✓	≈	≈	✓	≈	≈	✓	✓	≈	✓	≈
Swoop	✗	✗	✗	✓	✓	≈	≈	✓	≈	≈	✓	✓	≈	✓	≈
Silently Circle Overhead	✓	✓	✓	✓	≈	≈	✗	✗	≈	≈	✗	✗	✓	✗	≈
Pursue	✗	✗	✗	✓	✗	≈	≈	✗	≈	≈	✓	✓	≈	✗	≈
Run	✗	✗	✗	✓	✗	≈	≈	✗	≈	≈	✗	✗	≈	✗	✗

Table 8.4: Site Defense expressions summary, with checks for increasing distance (D), decreasing time (T), and decreasing preference (P).

factors, which is the opposite of what would be necessary for evacuation, but would likely be helpful for guiding.

Based on the inferential statistics summarized in the previous paragraphs, the descriptive statistics were added to Table 8.6 to determine whether there were enough expressions to generate an escalation strategy. The descriptive statistics were mixed, with only inspect coming back as increasing distance, decreasing time, and decreasing preference and nod at opponent as the only expression that fell in the middle in each category. Each of the other expressions had at least one category that was good for evacuation with bouncing flight and intermittent locomotion increasing distance, monitor and head lowered stare down decreasing time, and approach as non-preferred. Since these statistics were mixed, the descriptive statistics may give some clarity with regards to the escalation strategy.

The descriptive statistics were examined for their insights to generating an escalation strategy and were added to Table 8.7. All expressions with distances in the

	Speed			Predict			Dimension			Focus			Average		
Expression	D	T	P	D	T	P	D	T	P	D	T	P	D	T	P
Approach	✓	✓	✓	✓	✓	≈	✓	✓	≈	≈	✓	✓	✓	✓	✓
Nod at Opponent	✓	✓	✓	✓	≈	≈	✗	✗	≈	≈	✓	✓	✓	✓	✓
Display Weapons	✓	✓	✓	✗	≈	≈	≈	✗	≈	≈	✓	✓	≈	✓	✓
Stott	✓	✓	✓	✗	≈	≈	≈	✗	≈	≈	✓	✓	≈	✓	✓
Sudden Noise	✓	✓	✓	✗	≈	≈	≈	✗	≈	≈	✓	✓	≈	✓	✓
Erratic Zig Zag	✓	✓	✓	✗	≈	≈	≈	✓	≈	≈	✗	✗	≈	✓	≈
Ponderous Movements	✓	✓	✓	✗	≈	≈	≈	✓	≈	≈	✗	✗	≈	✓	≈
Charge	✗	✗	✗	✓	✓	≈	≈	✓	≈	≈	✓	✓	≈	✓	≈
Dive	✗	✗	✗	✓	✓	≈	≈	✓	≈	≈	✓	✓	≈	✓	≈
Run at Moderate Speed	✓	✓	✓	✓	≈	≈	✗	✗	≈	≈	✗	✗	✓	✗	≈
Fast Turns	✗	✗	✗	✗	✓	≈	≈	✓	≈	≈	✗	✗	≈	✗	≈
Sudden Twists	✗	✗	✗	✗	✓	≈	≈	✓	≈	≈	✗	✗	≈	✗	≈
Thrust Legs	✗	✗	✗	✗	✗	≈	≈	✗	≈	≈	✓	✓	✗	✗	≈
Intermittent Locomotion	✗	✗	✗	✗	✗	≈	≈	✗	≈	≈	✗	✗	✗	✗	✗
Bouncing Flight Path	✗	✗	✗	✗	✗	≈	≈	✗	≈	≈	✗	✗	✗	✗	✗

Table 8.5: Personal Defense expressions summary, with checks for increasing distance (D), decreasing time (T), and decreasing preference (P).

Expression	Distance	Time	Preference
Inspect	2.8 m	31.3 seconds	Non-Preferred
Intermittent Locomotion	3.2 m		
Bouncing Flight Path	3 m		
Monitor		34.1 seconds	
Approach			Non-Preferred
Nod at Opponent			
Head Lowered, Stare Down	1.7 m	25.2 seconds	

Table 8.6: Projected best and worst behaviors based on inferential statistics. Based on the top quarter and bottom quarter of expressions, low time was under 34.2 seconds and high time was above 45 seconds. Based on the same criteria, low distance was under 1.8 m and high distance was above 2.7 m. Preference was again based on the top and bottom quarter.

Expression	Distance	Time	Preference
Inspect	2.8 m	31.3 seconds	Non-Preferred
Sudden Twists	3.21 m	27.8 seconds	Preferred
Lunge	4.9 m	47.2 seconds	Non-Preferred
Intermittent Locomotion	3.19 m		
Bouncing Flight Path	3 m		
Ponderous Movement	.77 m	33.6 seconds	
Head Lowered, Stare Down	1.7 m	25.2 seconds	
Erratic Zig Zag	.35 m		
Swoop	.42 m		Preferred
Run at Moderate Speed	1.29 m		Preferred
Circle	4.5 m	45.3 seconds	Preferred
Run	1.57 m	47.5 seconds	Preferred

Table 8.7: Projected best and worst behaviors based on descriptive statistics, these were drawn from the top and bottom quarter of expressions for distance; low distance was under 1.8 m and high distance was above 2.7 m. Based on the same criteria, low time was under 34.2 seconds and high time was above 45 seconds. Preference was again based on the top and bottom quarter.

top or bottom quarter were included, and inspect was again the only expression found to increase distance while decreasing time and preference. On the other hand, run decreased distance, increased time, and increased preference. The other expressions were mixed: lunge was good for distance and preference but increased time, sudden twists was good for distance and time but increased preference, circle was good for distance but bad for time and preference, with swoop and run at moderate speed bad for distance and preference.

8.4 Understanding Social Zones for sUAVs Displaying Animal Behaviors

When examining the distances of participants from the robot, it was natural to consider distances within the context of Hall's social distances, particularly because it was curious that an earlier study [4] did not find the distances in further end of the personal zone as would have been expected. When looking at the segmentation of the expressions from this model, it led to the consideration that Hediger's animal social zones may be more applicable due to the design of the experiment. Each of these paths will be discussed further throughout this section.

8.4.1 Applying Hall's Social Distances

Hall [6] developed human interpersonal distances based on his observations and abstracted from Hediger's animal interaction zones due to the uniqueness of human interactions. Throughout the history of human-robot interaction, ground robots have been shown to conform to these distances and it has been suggested that they adapt their behaviors accordingly. As shown in Figure 8.5, five out of 24 expressions fell into zones other than social. The close expressions were erratic zig zag from Personal Defense and swoop from Site Defense in the intimate zone (for significant others and children), as well as ponderous movmement from Personal Defense in the personal zone for close friends. Two expressions (circle and lunge), both from Site Defense, were in the public zone for people who you aren't interacting.

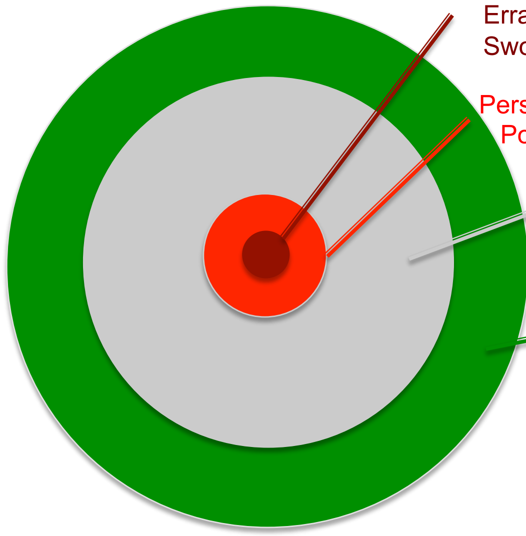

Figure 8.5: Graphical depiction of the Hall [6] zones depicting the expressions with an average minimum distance within each zone. Intimate is depicted in maroon, personal in red, social in grey, and public in green. Personal defense expressions are marked as "PD", while site defense expressions are marked with "SD".

8.4.2 Examining Hediger's Animal Social Zones

The use of Hediger's distances (the precursor to Hall's distances) [5] may be more appropriate in the context of these experiments because the participants had to make one of three choices when interacting with the robots: i) *fight* through the expression and pass the robot, ii) interact with the robot from a social distance, or iii) *flight* or depart away from the robot. Some robots were more aggressive and crossed what Hediger would term the "critical distance," which results in a fight response from the participant. Other robots were aggressive and crossed the "escape distance," from which the participants would initiate a flight response. While Hediger's distances are not generalized for multiple animals, they are specific to each species and thus a suggested application of Hediger's distances from these experiments based on the top quarter and bottom quarter of behaviors is shown in Figure 8.6. This distancing also makes more sense than using Hall's distances in this work due to the nature of the relationship, or lack thereof, between the participants and the robots; Hall's distances area based on the relationships between interactants, while Hediger appeals to the baser, animalistic relationships. Hediger himself said that "man is moreover the only creature able to free himself from the elementary function of escape," but this is not necessarily the case in the experiment conducted here nor in an evacuation scenario, which are both heightened fight-or-flight responses.

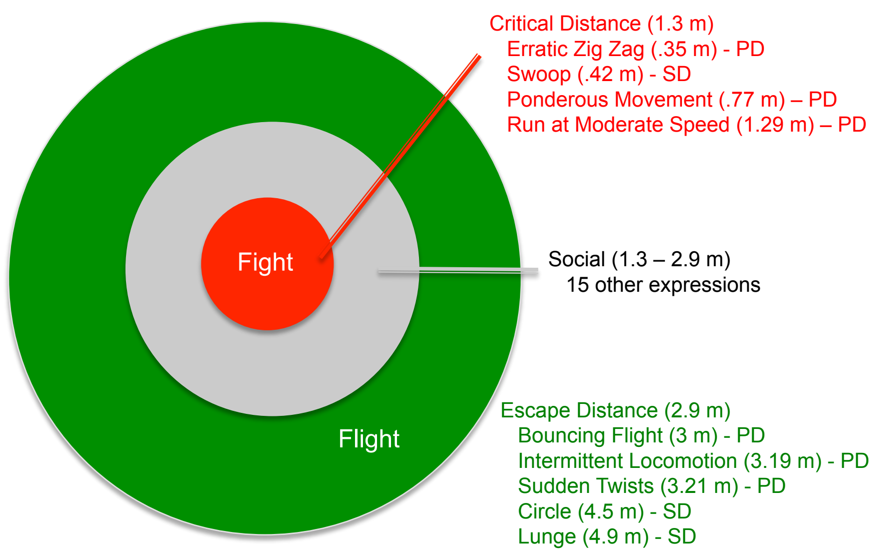

Figure 8.6: Graphical depiction of the Hediger [5] zones from this experiment, with critical distance (fight) in red, social in grey, and excape distance (flight) in green. Personal defense expressions are marked as "PD", while site defense expressions are marked with "SD".

8.5 Escalation Strategy

Using the information presented throughout this chapter, including the descriptive and inferential statistics, as well as the social zones discussion, an escalation strategy will be recommended for evacuation scenarios. Lunge will increase distance and is not preferred (but may increase time, which would be offset by it being placed at the beginning), sudden twists will increase distance and decrease time (but may be preferred), and inspect should be the final expression within the Flight zone because it increases distance, decreases time, and decreases preference. As we move into the social zone, we would apply the Approach expression, which was recommended by Inferential Statistics. In the Fight zone we would use Head Lowered, Stare Down and Ponderous Movement even though they decreased distance because they also decreased time. Finally, the last expression if still being approached would be Withdrawal.

8.6 Summary

This section presented three findings in regards to sUAVs for evacuation: i) expressions focusing on the person, rather than the area, are good for decreasing time and preference, ii) personal defense behaviors are best for decreasing time of interaction, while site defense behaviors are best for increasing distance of interaction, and iii) Hediger's [5] zones may be more applicable than Hall's [6] when considering animal behaviors in sUAVs. Additionally, an escalation strategy was suggested when using robots for evacuation: lunge, sudden twists, inspect, approach, head lowered stare down, ponderous movement, and withdrawal. Understanding these findings should inform: the CD model (including the addition of a new factor), the adoption of sUAVs for evacuation or guiding applications, and understanding of animal behaviors for human-robot interactions.

9. CONCLUSIONS AND FUTURE WORK

This research addressed four open research areas identified from the literature through an approach guided by the CD model and behavior-based robotics principles. Four findings and five primary contributions will be discussed in the Conclusions section. Both short-term and long-term future work will be presented in the Future Work section.

9.1 Conclusions

This dissertation describes the investigation of the impact of an autonomous sUAV exhibiting animal behaviors on the movement of human participants. A comprehensive review of current work on sUAVs with people who are not controlling them, animal behaviors, expectations for human-human and human-ground robot interactions, and evacuation literature were presented. Details on development of an approach, implementation details, design of an experiment, and results were also presented.

An initial review of literature suggested four points which are relevant to this work: i) a model of factors effecting comfortable interaction distancing would be informative to researchers in psychology, social science, and HRI, ii) there is a gap in research of sUAVs (or any UAVs) interacting with a person who is not controlling them, iii) human-human and human-ground robot interactions have been thoroughly studied but this work may not apply to human-sUAV interactions, and iv) animal behaviors suggest other natural interactions with humans. The approach suggests that the CD model can be used to predict comfortable distances and should be updated to include identified animal behaviors which present an existence proof that was tested through the implementation and experiments described in this document.

The implementation took place in the Unity simulation environment on an AirRobot AR100B platform. An experimental method and design was described to assess the effectiveness of specific animal behavior expressions before implementing the behaviors in the final experiment and to provide a feedback mechanism to improve the CD model. The study, consisting of simulation experiments in a CAVE environment at Texas A&M University involved a total of 64 participants and resulted in data to evaluate the nine hypotheses. These hypotheses address factors related to movement and were used to evaluate the primary research question before addition to the formal model of human distancing.

The four findings from the experiment in regards to sUAVs for evacuation were: i) approaches of an aerial vehicle do not cause peoples' movements to change in the same way as HHI or ground robot interactions, ii) Hediger's [5] zones may be more applicable than Hall's [6] when considering animal behaviors in sUAVs, iii) expressions focusing on the person, rather than the area, are good for decreasing time and preference, and iv) personal defense behaviors are best for decreasing time of interaction (by about 4 seconds, $p<.004$), while site defense behaviors are best for increasing distance of interaction (by about .5 m, $p<.003$). Additionally, an escalation strategy was suggested when using robots for evacuation: lunge, sudden twists, inspect, approach, head lowered stare down, ponderous movement, and withdrawal.

Five primary contributions are provided by this dissertation work, which can be seperated into intellectual merit and broader impacts. The four intellectual merit contributions to the fields of HRI and the social sciences are: i) the first work to suggest that sUAV interactions may not conform to the Computers are Social Actors model, ii) the first formal model of human distancing (the "Comfortable Distance" model), iii) a new set of recommended design guidelines for sUAV movements in close proximity to uninformed participants, and iv) the expansion of the CD model to incorporate findings from sUAV interactions. The broader impact contributions are to the field of public safety, and are: i) the first work to suggest that sUAV interactions may not conform to the Computers are Social Actors model, which could lead to unsafe interactions, and ii) a better understanding of how these vehicles could be used in evacuations and other public safety applications.

9.2 Future Work

Future work will initially focus on addressing the weaknesses of the current experimental design by testing escalation strategies in a real world environment, most specifically to address whether the distancing is true to real world interactions and to investigate the effect of the necessity of passing the robots in the maze. This work will address the questions: *Do distances directly map from the CAVE simulated environment to collocated interactions?* and *How quickly is an alternative taken when interacting with a real robot, particularly when presented with an inconvienience when avoiding the robot (e.g., having to go up and back down stairs)?*

After investigating the questions regarding the experimental methods presented here, future work will be concerned with continuing investigations on interactions within the CD model. This will focus initially on additional interactions between agent factors and interactions between environmental factors. After these investigations, a large dataset of distancing with information about personal factors should have been collected and will be examined to understand interactions between these factors.

Additional studies that could follow on from this work would investigate factors such as: swarm actions vs different numbers of people and different vehicle designs. When investigating the numbers of robots versus numbers of people, it would be interesting to look at 1-to-1 against 1-to-3 and 3-to-1 to see if there is any herd mentality displayed in these interactions and whether people can become quickly overwhelmed if outnumbered. Different vehicle designs could be investigated for a multitude of factors, but those specifically of interest are: size, rotor placement, presence of rotor guards, and color.

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APPENDIX A

PRE-TRIAL SURVEY

Pre-Questionnaire

Gender: Male Female

Age: ____

Occupation: ______________________________________

Education level: Some High School High School Some College

College Graduate School

Major: ____

Culture you most identify with: American Chinese Indian Japanese

Korean Mexican Native American Other:

Computer Experience: 1 2 3 4 5 6

Beginner Expert

Have you ever interacted with a robot? Yes No

If yes, how often? Once Yearly Monthly Weekly Daily

If yes, which type of robot? (Please circle all applicable answers.)

- a consumer robot such as a Roomba or pool cleaning robot?
- an industrial robot, telepresence robot, or other robot in the workplace?
- an educational robot such as Lego Mindstorms or an interactive robot in a museum?
- an entertainment robot such as a Parrot AR.drone, DJI Phantom, or Sony Aibo?

Have you ever owned a robot? Yes No

If yes, which type of robot? (Please circle all applicable answers.)

- a consumer robot such as a Roomba or pool cleaning robot?
- an industrial robot, telepresence robot, or other robot in the workplace?
- an educational robot such as Lego Mindstorms or an interactive robot in a museum?
- an entertainment robot such as a Parrot AR.drone, DJI Phantom, or Sony Aibo?

Have you ever played video games? _______________

If yes, how often? Once Yearly Monthly Weekly Daily

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Have you ever owned a pet? ______________________

If yes, what kind? ______________________________

Have you ever owned a remote-controlled helicopter or airplane or an unmanned aerial system?
Yes No

If yes, what kind? ______________________________

Have you ever operated a remote-controlled helicopter or airplane or an unmanned aerial system? Yes No

If yes, what kind? ______________________________

Are you a pilot of any type of aircraft? ______________________

If yes, what kind? ______________________________

This scale consists of a number of words that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you have felt this way in the **past few weeks**.

Use the following scale to record your answers.

1	2	3	4	5
very slightly or not at all	a little	moderately	quite a bit	extremely

__ interested	__ irritable
__ distressed	__ alert
__ excited	__ ashamed
__ upset	__ inspired
__ strong	__ nervous
__ guilty	__ determined
__ scared	__ attentive
__ hostile	__ jittery
__ enthusiastic	__ active
__ proud	__ afraid

This scale consists of a number of words that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you have felt this way **today**.

Use the following scale to record your answers.

1	2	3	4	5
very slightly or not at all	a little	moderately	quite a bit	extremely

__ interested

__ distressed

__ excited

__ upset

__ strong

__ guilty

__ scared

__ hostile

__ enthusiastic

__ proud

__ irritable

__ alert

__ ashamed

__ inspired

__ nervous

__ determined

__ attentive

__ jittery

__ active

__ afraid

On the following pages, there are phrases describing people's behaviors. Please use the rating scale below to describe how accurately each statement describes ***you***. Describe yourself as you generally are now, not as you wish to be in the future. Describe yourself as you honestly see yourself, in relation to other people you know of the same sex as you are, and roughly your same age. So that you can describe yourself in an honest manner, your responses will be kept in absolute confidence. Please read each statement carefully, and then fill in the bubble that corresponds to the number on the scale.

Response Options

1: Very Inaccurate
2: Moderately Inaccurate
3: Neither Inaccurate nor Accurate
4: Moderately Accurate
5: Very Accurate

Try to surpass others' accomplishments.

1 2 3 4 5

Very Inaccurate Very Accurate

Break my promises.

1 2 3 4 5

Very Inaccurate Very Accurate

Am relaxed most of the time.

1 2 3 4 5

Very Inaccurate Very Accurate

Often forget to put things back in their proper place.

1 2 3 4 5

Very Inaccurate Very Accurate

Feel little concern for others.

1 2 3 4 5

Very Inaccurate Very Accurate

Have a rich vocabulary.

1 2 3 4 5

Very Inaccurate Very Accurate

Am the life of the party.

1 2 3 4 5

Very Inaccurate Very Accurate

Try to outdo others.

1 2 3 4 5

Very Inaccurate Very Accurate

Get stressed out easily.

1 2 3 4 5

Very Inaccurate Very Accurate

Have a vivid imagination.

1 2 3 4 5

Very Inaccurate Very Accurate

Am not interested in other people's problems.

1 2 3 4 5

Very Inaccurate Very Accurate

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IRB APPROVAL DATE: 03/31/2015
IRB EXPIRATION DATE: 03/15/2016

Make a mess of things.

1 2 3 4 5

Very Inaccurate Very Accurate

Feel comfortable around people.

1 2 3 4 5

Very Inaccurate Very Accurate

Am afraid that I will do the wrong thing.

1 2 3 4 5

Very Inaccurate Very Accurate

Worry about things.

1 2 3 4 5

Very Inaccurate Very Accurate

Have excellent ideas.

1 2 3 4 5

Very Inaccurate Very Accurate

Am easily disturbed.

1 2 3 4 5

Very Inaccurate Very Accurate

Insult people.

1 2 3 4 5

Very Inaccurate Very Accurate

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IRB EXPIRATION DATE: 03/15/2016

Start conversations.

1 2 3 4 5

Very Inaccurate Very Accurate

Am quick to correct others.

1 2 3 4 5

Very Inaccurate Very Accurate

Leave my belongings around.

1 2 3 4 5

Very Inaccurate Very Accurate

Am quick to understand things.

1 2 3 4 5

Very Inaccurate Very Accurate

Seldom feel blue.

1 2 3 4 5

Very Inaccurate Very Accurate

Am not really interested in others.

1 2 3 4 5

Very Inaccurate Very Accurate

Talk to a lot of different people at parties.

1 2 3 4 5

Very Inaccurate Very Accurate

Feel that I'm unable to deal with things.

1 2 3 4 5

Very Inaccurate Very Accurate

Impose my will on others.

1 2 3 4 5

Very Inaccurate Very Accurate

Avoid responsibilities.

1 2 3 4 5

Very Inaccurate Very Accurate

Demand explanations from others.

1 2 3 4 5

Very Inaccurate Very Accurate

Am exacting in my work.

1 2 3 4 5

Very Inaccurate Very Accurate

Use difficult words.

1 2 3 4 5

Very Inaccurate Very Accurate

Shirk my duties.

1 2 3 4 5

Very Inaccurate Very Accurate

Get upset easily.

1 2 3 4 5

Very Inaccurate Very Accurate

Don't mind being the center of attention.

1 2 3 4 5

Very Inaccurate Very Accurate

Suspect hidden motives in others.

1 2 3 4 5

Very Inaccurate Very Accurate

Want to control the conversation.

1 2 3 4 5

Very Inaccurate Very Accurate

Make people feel at ease.

1 2 3 4 5

Very Inaccurate Very Accurate

IRB NUMBER: IRB2014-0319D
IRB APPROVAL DATE: 03/31/2015
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Spend time reflecting on things.

1	2	3	4	5
Very Inaccurate				Very Accurate

Follow a schedule.

1	2	3	4	5
Very Inaccurate				Very Accurate

Change my mood a lot.

1	2	3	4	5
Very Inaccurate				Very Accurate

Don't talk a lot.

1	2	3	4	5
Very Inaccurate				Very Accurate

Feel that my life lacks direction.

1	2	3	4	5
Very Inaccurate				Very Accurate

Am not afraid of providing criticism.

1	2	3	4	5
Very Inaccurate				Very Accurate

IRB NUMBER: IRB2014-0319D
IRB APPROVAL DATE: 03/31/2015
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Feel others' emotions.

1 2 3 4 5

Very Inaccurate Very Accurate

Am full of ideas.

1 2 3 4 5

Very Inaccurate Very Accurate

Like order.

1 2 3 4 5

Very Inaccurate Very Accurate

Have frequent mood swings.

1 2 3 4 5

Very Inaccurate Very Accurate

Keep in the background.

1 2 3 4 5

Very Inaccurate Very Accurate

Do not like art.

1 2 3 4 5

Very Inaccurate Very Accurate

Challenge others' points of view.

1 2 3 4 5

Very Inaccurate Very Accurate

Take time out for others.

1 2 3 4 5

Very Inaccurate Very Accurate

Have difficulty understanding abstract ideas.

1 2 3 4 5

Very Inaccurate Very Accurate

Get chores done right away.

1 2 3 4 5

Very Inaccurate Very Accurate

Get irritated easily.

1 2 3 4 5

Very Inaccurate Very Accurate

Have little to say.

1 2 3 4 5

Very Inaccurate Very Accurate

Believe that too much tax money goes to support artists.

1 2 3 4 5

Very Inaccurate Very Accurate

Lay down the law to others.

1 2 3 4 5

Very Inaccurate Very Accurate

Look for hidden meanings in things.

1	2	3	4	5
Very Inaccurate				Very Accurate

Have a soft heart.

1	2	3	4	5
Very Inaccurate				Very Accurate

Am not interested in abstract ideas.

1	2	3	4	5
Very Inaccurate				Very Accurate

Pay attention to details.

1	2	3	4	5
Very Inaccurate				Very Accurate

Sympathize with others' feelings.

1	2	3	4	5
Very Inaccurate				Very Accurate

Don't like to draw attention to myself.

1	2	3	4	5
Very Inaccurate				Very Accurate

Put people under pressure.

1	2	3	4	5
Very Inaccurate				Very Accurate

Become overwhelmed by events.

1	2	3	4	5
Very Inaccurate				Very Accurate

Hate to seem pushy.

1	2	3	4	5
Very Inaccurate				Very Accurate

Often feel blue.

1	2	3	4	5
Very Inaccurate				Very Accurate

Do not have a good imagination.

1	2	3	4	5
Very Inaccurate				Very Accurate

Am always prepared.

1	2	3	4	5
Very Inaccurate				Very Accurate

Am interested in people.

1	2	3	4	5
Very Inaccurate				Very Accurate

Am quiet around strangers.

1	2	3	4	5
Very Inaccurate				Very Accurate

Feel lucky most of the time

1	2	3	4	5
Very Inaccurate				Very Accurate

.

On the following pages, there are statements describing feelings about robots. Please use the rating scale below to describe how accurately each statement reflects ***your feelings***. Describe how you generally feel now, not as you wish to feel in the future. So that you can describe yourself in an honest manner, your responses will be kept in absolute confidence. Please read each statement carefully, and then circle the number on the scale.

Response Options

1: I Strongly Disagree
2: I Disagree
3: Undecided
4: I Agree
5: I Strongly Agree

I would feel uneasy if robots really had emotions.

1 2 3 4 5

Strongly Disagree Strongly Agree

Something bad might happen if robots developed into living beings.

1 2 3 4 5

Strongly Disagree Strongly Agree

I would feel relaxed talking with robots.

1 2 3 4 5

Strongly Disagree Strongly Agree

I would feel uneasy if I was given a job where I had to use robots.

1 2 3 4 5

Strongly Disagree Strongly Agree

IRB NUMBER: IRB2014-0319D
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If robots had emotions, I would be able to make friends with them.

1 2 3 4 5

Strongly Disagree Strongly Agree

I feel comforted being with robots that have emotions.

1 2 3 4 5

Strongly Disagree Strongly Agree

The word "robot" means nothing to me.

1 2 3 4 5

Strongly Disagree Strongly Agree

I would feel nervous operating a robot in front of other people.

1 2 3 4 5

Strongly Disagree Strongly Agree

I would hate the idea that robots or artificial intelligences were making judgments about things.

1 2 3 4 5

Strongly Disagree Strongly Agree

I would feel very nervous just standing in front of a robot.

1 2 3 4 5

Strongly Disagree Strongly Agree

I feel that if I depend on robots too much, something bad might happen.

1 2 3 4 5

Strongly Disagree Strongly Agree

I would feel paranoid talking with a robot.

1 2 3 4 5

Strongly Disagree Strongly Agree

I am concerned that robots would be a bad influence on children.

1 2 3 4 5

Strongly Disagree Strongly Agree

I feel that in the future society will be dominated by robots.

1 2 3 4 5

Strongly Disagree Strongly Agree

APPENDIX B

POST-TRIAL SURVEY

Post Questionnaire

This scale consists of a number of words that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you have felt this way **during your interactions with the robot**.

Use the following scale to record your answers.

1	2	3	4	5
very slightly or not at all	a little	moderately	quite a bit	extremely

__ interested
__ distressed
__ excited
__ upset
__ strong
__ guilty
__ scared
__ hostile
__ enthusiastic
__ proud

__ irritable
__ alert
__ ashamed
__ inspired
__ nervous
__ determined
__ attentive
__ jittery
__ active
__ afraid

IRB NUMBER: IRB2014-0319D
IRB APPROVAL DATE: 03/31/2015
IRB EXPIRATION DATE: 03/15/2016

This scale consists of a number of words that describe different traits. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you felt **the robot** exhibited these traits.

Use the following scale to record your answers.

1	2	3	4	5	6	7	8	9	10

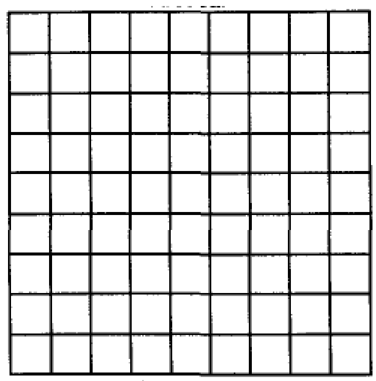
describes very poorly ... describes very well

__ cheerful	__ helpful
__ disobedient	__ enthusiastic
__ honest	__ dishonest
__ extroverted	__ pretenseless
__ unkind	__ happy
__ reliable	__ harsh
__ incompetent	__ helpful
__ trustworthy	__ kind
__ outgoing	__ warm
__ likeable	

Please rate how you are feeling **right now** by marking an X in a square.

Over Stimulated

Stress | Excitement



Unpleasant Feelings | Pleasant Feelings

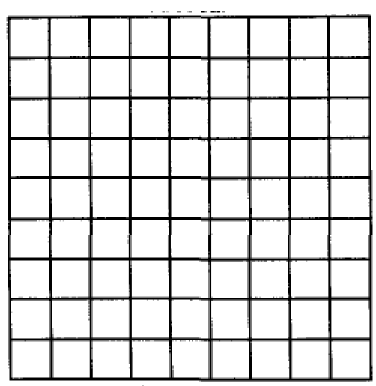
Depression | Relaxation

Sleepiness

Please rate how you felt when **interacting with the robot** by marking an X in the appropriate square.

Over Stimulated

Stress | Excitement



Unpleasant Feelings | Pleasant Feelings

Depression | Relaxation

Sleepiness

Did you feel that the robot was looking at you during interactions? Yes No

Please elaborate:

How comfortable did you feel when encountering the robot?

1 2 3 4 5 6

Not Comfortable Very Comfortable

How safe did you feel during your interaction with the robot?

1 2 3 4 5 6

Not Safe At All Very Safe

How safe did you feel your avatar was during your interaction with the robot?

1 2 3 4 5 6

Not Safe At All Very Safe

How scared were you of the robot?

1 2 3 4 5 6

Not Scared Very Scared

How trustworthy did you find the robot?

1 2 3 4 5 6

Not Trustworthy Very Trustworthy

How much of an impact did the predictability of the robot have on your distance from the robot?

1	2	3	4	5	6
No Impact					Large Impact

Please describe any motions that you felt were unpredictable:

How much of an impact did the speed of the robot have on your distance from the robot?

1	2	3	4	5	6
No Impact					Large Impact

Please describe any motions you felt were too fast or too slow:

How much of an impact did the size of the robot's movements have on your distance from the robot?

1	2	3	4	5	6
No Impact					Large Impact

Please describe any motions you felt were too large or too small:

What part of the robot did you find most interesting?

Camera   Blades   I didn't notice   Other: ___________________

If you encountered this robot outside, would you approach it?

Yes   No

IRB NUMBER: IRB2014-0319D
IRB APPROVAL DATE: 03/31/2015
IRB EXPIRATION DATE: 03/15/2016

If you encountered this robot outside, would it scare you?

Yes No

Do you have any other comments about this robot?

Do you have any comments about this trial?

Do you have any other comments about this experiment?

Is there anything that has not been addressed that you find important?