Comparison of Human-Drone Distancing Studies across In-Person and Online Modalities

KARISSA JELONEK, SIYA KUNDE, NATHAN SIMMS, GERSON URIARTE, and BRITTANY DUNCAN, University of Nebraska-Lincoln, Lincoln, NE, USA

Human–robot proxemics behaviors can vary based on personal, robot, and environmental factors which, along with their deployment in public-facing interactions, calls for an in-depth exploration. This article explores the impact of altitude and safety modifications of small unmanned aerial vehicle (sUAV) on users' comfortable interaction distance. By leveraging interaction techniques from literature like video, sound, and simulations, we explore personal space interactions in online studies (N = 376) with the sUAV and the Double telepresence robot. We then compare the findings with our in-person interaction data (N = 47). While in-person interactions are the ultimate goal, online methods can be used to reduce resources, allow larger sample sizes, and may lead to a more comprehensive sampling of population than would be expected from in-person studies. The lessons learned from this work are applicable broadly within the social robotics community, even outside those who are interested in proxemics interactions, to conduct future crowd-sourced experiments. The various modalities provided similar trends when compared with data from in-person studies. While the distances may not have been precise compared to those measured in the real world, these experiments are useful to detect patterns in human–robot interactions, and to conduct formative studies before committing resources to in-person testing.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; • **Computer systems organization** → **Robotics**; • **Information systems** → *Crowdsourcing*;

Additional Key Words and Phrases: human–robot interaction, proxemics, crowd sourcing, evaluation methods, interaction design process and methods, scenario-based design

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1 Introduction

This research was partially motivated by the appearance of the COVID-19 global pandemic and the question of how robots might be able to assist and interact with humans, especially in situations where human–human interaction may not be possible or safe. Advances in robotics are allowing robots to perform more complex tasks in the world (delivering food, medicine, and greeting

Authors' Contact Information: Karissa Jelonek (corresponding author), University of Nebraska-Lincoln, Lincoln, NE, USA; e-mail: kjelonek3@huskers.unl.edu; Siya Kunde, University of Nebraska-Lincoln, Lincoln, NE, USA; e-mail: skunde@cse.unl.edu; Nathan Simms, University of Nebraska-Lincoln, Lincoln, NE, USA; e-mail: nsimms2@huskers.unl.edu; Gerson Uriarte, University of Nebraska-Lincoln, Lincoln, NE, USA; e-mail: gersongru@huskers.unl.edu; Brittany Duncan, University of Nebraska-Lincoln, Lincoln, NE, USA; e-mail: bduncan@cse.unl.edu.

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or guiding passersby), but these advances have raised many questions related to human–robot proxemics and individuals' comfort when interacting with robots.

Additionally, this study was motivated by the challenges in conducting **human–robot interaction (HRI)** studies with relatively limited access to in-person participants. Studies conducted in-person are generally localized to the geographic area where experimenters are located and restrict the sample population demographics. This work describes an investigation of human interaction methods and leverages a relatively small set of in-person distancing results, the ability to compare to a previously published study, and a set of methods previously used in human–human distancing to answer fundamental questions regarding methodology for assessing human distancing. This work will inform future researchers on the utility of these methods, and any lessons learned in their application to improve our ability to target limited in-person experimental resources to problems that will likely produce interesting results.

This work explores the following research questions:

- What are the different modalities we can use to prototype human–robot proxemics studies?
- How do the results compare to studies run in-person?

2 Related Work

In this section we cover prior work in the context of interaction modalities utilized in human–human and HRI studies, and literature related to impact of height on human–robot proxemics, in order to situate the current work.

2.1 Modalities in Interaction Studies

2.1.1 Human–Human Interaction. Prior studies in human–human proxemics utilized various methods to understand the personal space that the users wanted to maintain including unobtrusive observations, stop distance [24], video [27], sound [24], adjustable size of stimulus image, chair placement or choice, felt board technique, paper-and-pencil procedures [24, 27], positioning of miniature figures, and preference judgments for photographs showing differing spacing and size of projected faces. In surveying the human–human proxemics methodology landscape [11] found that in-person stop distance measurement is the most reliable and preferred technique for experimental evaluations, while pencil-and-paper and felt board methods are the least reliable. The video (exocentric) [27] and sound [24] modalities were found to be a more reliable comparison to in-person interaction compared to other techniques like paper-and-pencil procedures.

2.1.2 HRI. User perception of robot is affected by the medium used to present the HRI [32]. Prior studies have used various methods to evaluate HRI hypothesis like text [32], slider [14], **three-dimensional (3D)** figurine [14], virtual agent/animated character [15, 18, 21, 25, 31], virtual reality [4, 5, 19], telepresence (live video) [15, 21], pre-recorded video [12, 17, 23, 30–32], and some went a step further and also provided a comparison to in-person studies [7, 12, 15, 18, 19, 21, 25, 30–32].

On one hand we have findings like one by [18] where people were found to have stronger behavioral and attitudinal responses to co-present robots compared to telepresent or virtual agents. While on the other hand studies have found modalities like videos to work well compared to in-person interactions. In-person interaction with the robot can be useful in evaluating the social aspects of the robot, but can lead to higher anxiety level and lower trust [32], but videos can be particularly effective in enhancing users' perceptions of the performance of robots on its intended functionality, without the elevated anxiety. Szafir et al. [25] used videos of animated **small unmanned aerial vehicles (sUAVs)** to understand how to effectively communicate intent, to improve the flight design to inform the follow-up in-person study. Similarly [12] conducted online studies with exocentric video clips and later ran a confirmatory in-person study with ground robot.

In fact, [17, 23] piloted both egocentric and exocentric videos, but decided to opt for egocentric videos, to provide better focus on the movements of the robot, without contextual distractions like age, gender, and ethnic background of the actor in the video. Studies by [15] (egocentric video) and [30, 31] (switch from exocentric to egocentric view) comparing real-world evaluations of interactive prototypes with Web-based video prototypes found results from video modality tend to be consistent with in-person studies, although the former may not contain all the salient factors that may be present in a real-world setting. Our study will test slider, video (egocentric and exocentric to observe differences in distancing based on viewpoints), simulator (egocentric and exocentric), and sound modalities.

2.1.3 Human-UAV Proxemics. The study by [10] was one of the earliest works to study the comfortable approach distance of UAVs both above and below head height. A later study [3] compared the comfortable approach distance of UAVs and ground robots. However, both of these studies were conducted in-person and thus had relatively small sample sizes and were not able to explore additional factors like propeller guards which might improve comfort levels around UAVs. Alternatively, [6] and [4] explore UAV proxemics in a virtual reality setting but do not validate that their findings correlate to in-person studies. Bretin et al. [7] do offer a comparison between virtual and in-person modalities to examine the effect of UAV speed on comfortable approach distance and its findings support the use of virtual reality as a proxy for in-person UAV studies.

2.2 Impact of Robot Height on Proxemics

Height has been found to affect how people react to robots in many studies [6, 20, 22, 29, 33]. For example, [22] discovered that the size of peoples' proxemics zones are directly proportional to the height of a ground robot, but [20] found that as ground robot height increases, the distance people prefer between themselves and a robot decreases. Meanwhile, [6] used virtual reality to study how much distance people will put between themselves and an aerial robot operating at different heights and found that participants would approach significantly closer to the UAV when it was flying above eye level. Meanwhile, [10] researched how operational height of sUAVs may affect people's comfortable approach distance, and did not find any significant effect. They note that a possible reason for the lack of difference in preference may be the lack of a realistic setting (UAV was tethered) and participants' feeling of security. Wojciechowska et al. [29] varied the altitude of the sUAV in study and found that a constant altitude trajectory (at 1.75 m $\approx$ 5.74 ft) is preferred over increasing or decreasing altitude trajectories. Our in-person and online studies will test the impact of straight trajectories where an un-tethered sUAV will maintain its altitude as it approaches the user.

This work will expand on previous UAV-human proxemics research by offering a comprehensive study with over 400 total participants exploring how different modalities including sliders, realistic videos, UAV simulation videos, audio, and in-person studies affect participants' comfortable approach distance when interacting with a UAV operating at different heights and with different safety modifications. Additionally, it explores the effect of egocentric and exocentric perspectives on participants' UAV interactions. Through this comprehensive study of interaction modalities we make recommendations for future proto studies to better target in-person tests given the expected smaller samples.

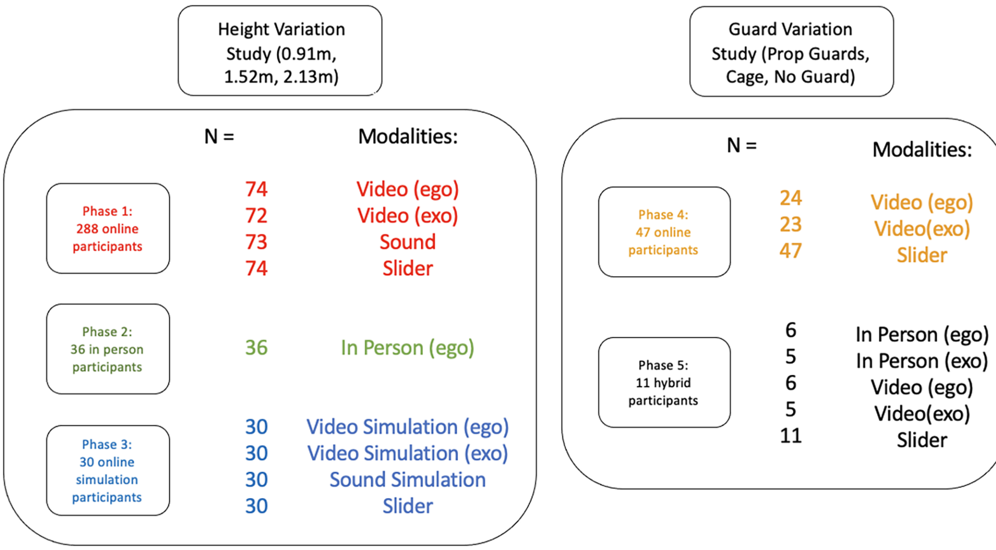

Fig. 1. Summary of study.

3 Experiment

This article presents a study to address the research questions: *What are the different modalities we can use to prototype human–robot proxemics studies?* and *How do the results from online studies compare to studies run in-person?*

To answer these research questions, we conducted experiments on how height variation and UAV modifications change the distance at which participants were comfortable being approached by a UAV. An overview of the five phases of the study can be seen in Figure 1.

The height variation study was run first. An online study was conducted which included the following interaction modalities: 2D-distancing slider, egocentric video, exocentric video, and sound clips (shown in Figure 2). The results of the online study were then compared to data from in-person studies: one previously conducted by [3], and the other conducted in our lab. Later a UAV simulator was designed in Unity, a game engine which can be used to create 3D environments and interactive simulations, to replicate the conditions of this initial study in order to test three additional modalities: simulated egocentric video, simulated exocentric video, and simulated sound clips. While these simulator videos may sacrifice some realism compared to videos of actual operations, they offer great potential for future studies where participants could not only view the robot but also control or respond to it, allowing for safe and interactive online HRI studies.

Next, we conducted a second study on how UAV modifications might affect the comfortable approach distance chosen by participants. Again, a larger online study was conducted first, and the results were then compared to a smaller hybrid study in which participants completed the study both online and in-person. For the in-person portion of this study we also incorporated an exocentric viewpoint by having participants watch as the UAV approached a human compeer from our lab.

In these studies participants were not given a specific scenario in which the robot interaction was taking place. Participants were told "The UAV is going to take off, rise to the height and then it is going to begin approaching you. When approaching please audibly say stop when you begin to feel uncomfortable with the distance of the UAV." These instructions were intentionally vague to allow for the consideration of many possible different scenarios in which a human and UAV might interact with each other. However, several participants commented that their comfort with the

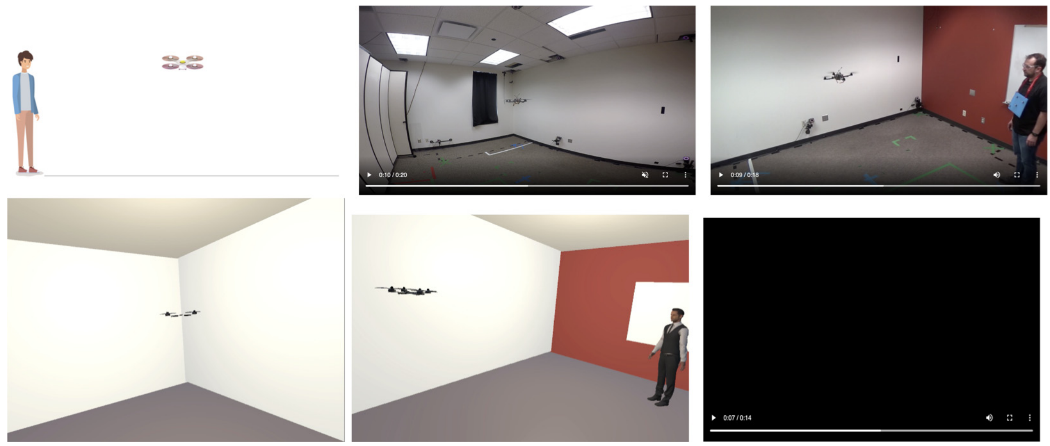

Fig. 2. The different modalities used in the study included slider, egocentric video, exocentric video, egocentric simulator, exocentric simulator, and sound. The user remained stationary as the robot approached. Here all robots are at a height of 1.52 m.

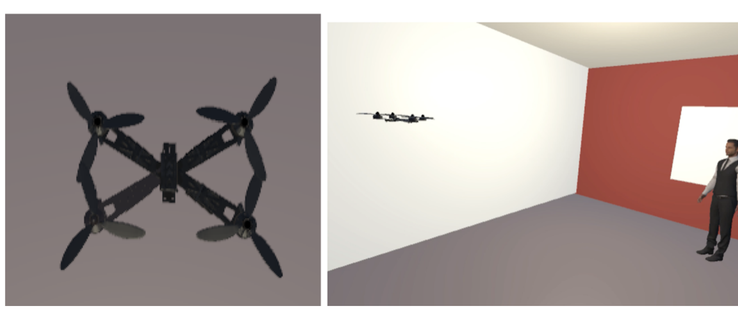

Fig. 3. Unity UAV model and environment.

robot would depend on factors such as what the UAV's purpose was, who/what was operating the UAV, and whether or not the UAV had a camera attached.

3.1 Materials

For the height variation study, Asctec Hummingbird sUAV and the Double telepresence robot were used in our studies similar to [3]. The ground robot operated at a height (measured to the top of the robot) of 1.52 m. The operational height of the aerial robot was set to 0.91 m, 1.52 m, or 2.13 m (3 ft, 5 ft, or 7 ft, respectively). The robots' approach speed was set to 0.2 m/s. A Vicon motion capture system was used to track the UAV's movement and control its flight path along an autonomous pre-planned route. In order to track the robot and the user, Vicon markers were placed on the robots, while the user was asked to wear a pre-made marker object around their neck. For the simulation portion of this study, the Unity game engine was used to create a simulated environment and UAV model (shown in Figure 3).

For the study on how UAV modifications affect the comfortable approach distance, a DJI Flame Wheel F330 was used for the in-person studies and to record the videos for the online study. This UAV was flown without modification, with propeller guards, and enclosed in a cage for each participant (shown in Figure 4). For the videos the drone was recorded at a height of 1.52 m with

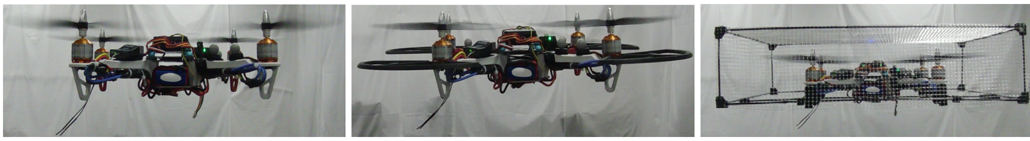

Fig. 4. DJI Flame Wheel F330s with no modifications, propeller guards, and cage enclosure.

an approach speed of 0.2 m/s. For the hybrid study, each participant was instructed to lift the non-operational UAV to the height at which they would like the UAV to approach. This height was recorded and was the height at which the UAV approached the participant for that flight. This process was repeated for each of the three study conditions (drone with no modification, propeller guards, and cage).

3.2 Testbed

3.2.1 Height Variation Study. The overall study setup for recording the videos and conducting the in-person height-variation study replicated the baseline study by [3] including the study space (testbed figure attached in Appendix A).

The participant interacted with the robot in the enclosed section of the room (4.88 m by 3.53 m). The participant stood in the marked (S) while the robot approached from its start location marked with (R). The experimenter controlled the robots (UAV and ground robot) from the outside section (4.88 m by 1.03 m). A backup human pilot observed the experiments via live video feed (through two Sony CX440 video cameras), ready to take control of robots if necessary.

While this system was followed for the in-person study, the same setup with a male actor portrayed as the user (similar to [30]) was used to capture the exocentric video, and lastly the camera was placed roughly at the height of 1.5 m for the egocentric video and sound clips.

The UAV simulation videos were created using Unity. The simulated environment was designed to replicate the in-person study and videos closely. This included scaling the room, the UAV, the human, and the camera height to be proportional to the dimensions in the original setup and using similar background coloring. Of course, some visual fidelity is lost when replicating an environment virtually and some elements like markings on the floor and walls were removed for simplicity.

3.2.2 Guard Variation Study. For the study on how various additional UAV guards affect participants' comfort with the UAV, the testbed was an indoor netted area (see Appendix A for testbed dimensions). The participants were instructed to stand behind a piece of tape inside the netted area either facing the UAV from 3.5 m away or to the side of the UAV depending on whether they were assigned the egocentric or exocentric viewpoint condition.

3.3 Studies

The following online and in-person studies were conducted:

3.3.1 Height Variation Studies. Amazon's **Mechanical Turk (MTurk)** [2] was used to recruit participants for the online study. Following recommended practices [1, 13], we pre-screened participants by requiring them to have number of approved HITs > 5,000 and HIT approval rate for all Requesters' HITs > 97% in their MTurk history.

The online studies were conducted with the Double ground robot, and sUAV flying at heights of 0.91 m, 1.52 m, and 2.13 m (shown in Figure 5). The participants were randomly assigned to conditions, and the interaction order was counter-balanced between participants. Once participants accessed the study via Mturk, they first entered background information and answered a pre-interaction questionnaire, next positioned a random order of [1.52 m Double, and 0.91 m, 1.52 m,

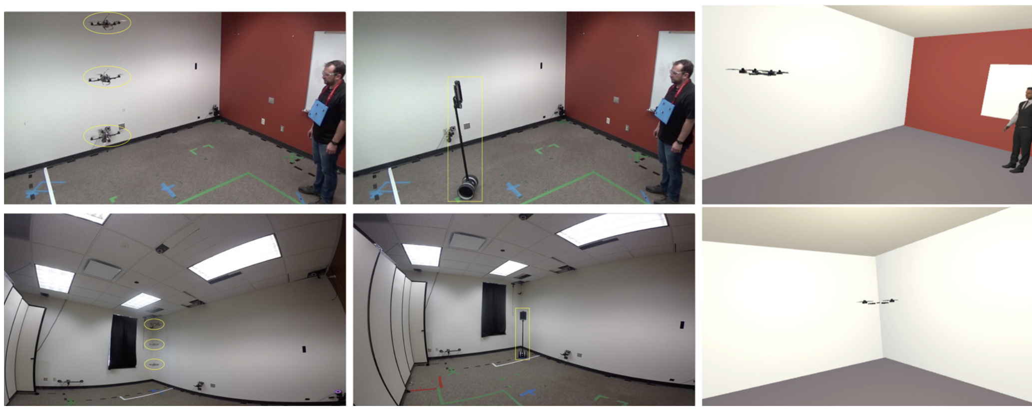

Fig. 5. The videos were captured with the sUAV flying 0.91 m, 1.52 m, or 2.13 m height, and the Double ground robot, from exocentric and egocentric point-of-view. Similar conditions were faced by users in the in-person study.

2.13 m sUAV] in their online modality, and finished with an exit questionnaire. Post-interaction questionnaires were administered after the first interaction with Double and the sUAV.

2D-Distancing Using Sliders. A UI comprised of a slider was used with the human's image on left (static), and the robot's image on the slider handle (movable), with the scene presented to the user from exocentric point-of-view. The user was provided the following instructions:

> "Imagine that you are the figure on the left. How far apart would you place the following two figures by dragging the figure on the right?"

Video Stop-Distancing. Each user was shown a video of the robot approaching from either egocentric or exocentric point-of-view, and provided the following instructions:

> "Start the following video with sound on. Once the approach distance of the robot in the video begins to make you feel uncomfortable, stop the video. Finally, click submit."

Sound Stop-Distancing. User was provided a sound clip of the robot approaching (recorded from egocentric point-of-view), and provided the following instructions:

> "Start the following video with sound on. Imagine a robot is approaching you. Once the approach sound of the robot in the video begins to make you feel uncomfortable, stop the video. Finally, click submit."

Spectrograms of the sound clips used in this study can be seen in Figure 6. The video audio files had a higher amplitude than the simulated audio which can be seen in the spectrograms by the color intensity. The audio frequency ranges from approximately 140–11k Hz in the video audio files and approximately 140–18k Hz in the simulation audio files.

An in-person study was conducted with the sUAV flying at different altitudes: 0.91 m, 1.52 m, or 2.13 m. The participants were randomly assigned to conditions, and the interaction order was counter-balanced between participants. Once the participant arrived at the experiment location in our university lab, their consent was obtained and they answered a pre-questionnaire to record background information and pre-interaction measures. Next they were asked to wear the fiducial markers' object and participants not wearing eye glasses were also asked to wear safety glasses for

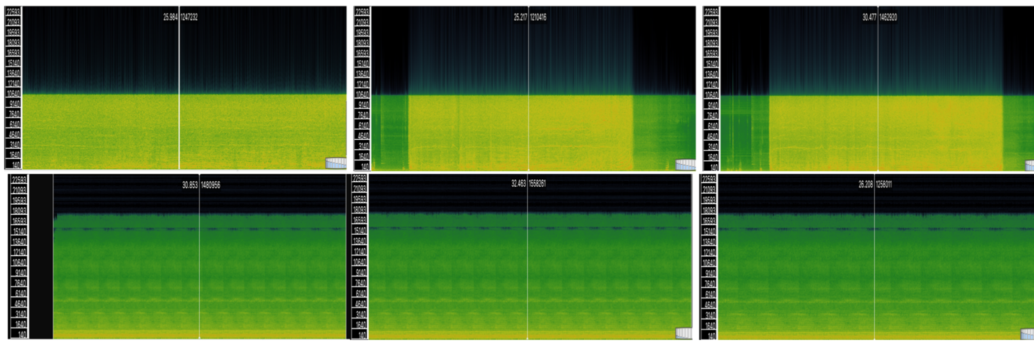

Fig. 6. Spectrograms of audio files taken from egocentric perspective of actual (top row) and simulated (bottom row) UAV flights at 0.91 m (left), 1.52 m (center), and 2.13 m (right).

all interactions. Once the robot started approaching the user, they were asked to say "stop" once the robot's closeness began to make them feel uncomfortable. The stop-distancing technique is similar to the one in [3, 8] and follows recommendations for use by [11]. On completion of each of the three interaction sessions, they were asked to fill out a post-interaction questionnaire to collect their feedback and post-interaction measures.

Later, participants for an additional online study were recruited via MTurk to consider how responses might vary given a simulated UAV compared to the in-person study and real UAV videos. The simulated UAV flew a fixed path and participants could not control the simulated environment except to stop the UAV's flight by hitting the pause button. This phase of the study was designed to closely match the egocentric, exocentric, and sound videos used in Phase 1 of the study. A virtual reality environment could allow for more user control and interaction in research studies, but comes at the expense of visual realism. Thus the goal of this portion of the study was to explore whether the participant responses to the simulated videos correlate to responses to videos created in a real-world setting without adding an additional element of user control. This is valuable for determining the validity of using simulated environments in future human-UAV interaction studies. Similar to the previous phases, participants first answered the initial questionnaire with demographic information and information on their current mood. Participants then watched three egocentric videos, three exocentric videos, and three sound clips of a UAV simulation. In the videos, a UAV approached either the camera or a human model. After watching the videos and listening to the sound clips, participants completed a post-task questionnaire which asked them to complete an assessment of their mood during the tasks and several other questions regarding the task. Lastly, participants completed an exit questionnaire asking them their opinions on several statements and gave them the option to write any additional comments about the study.

3.3.2 Guard Variation Study. An initial study was conducted online via MTurk. Participants first answered the same initial questionnaire used in the previous phase of the study. They then were given a slider task where they were instructed to move the slider to position a human, an unmodified UAV, and a UAV enclosed in a cage to what they believed would be their closest comfortable approach distance. Next participants watched pre-recorded videos of a UAV flying at 1.52 m height at a speed of 0.2 m/s. Participants were randomly assigned to watch either an egocentric (UAV approaching the camera) or exocentric (UAV approaching a human) view of the UAV. After each video participants were given a post-task questionnaire. Lastly, an exit questionnaire was completed at the end of the study.

Next a hybrid study was performed where participants completed the study both online and in-person. Participants were randomly assigned to complete either the online or physical portion of the study first. Participants were also randomly assigned to either an egocentric or exocentric viewpoint. For the in-person exocentric study, a graduate student volunteer was approached by the UAV while the study participant watched from the UAV approach from the side. For both the egocentric and exocentric viewpoints, the study participant was to audibly say stop to stop the UAV's approach when they became uncomfortable with the UAV's approach distance.

3.4 Attention Checks

For all online portions of this study, we incorporated several attention checks. Attention checks included asking participants to enter a word or number that was displayed or said during a previous video clip, selecting a certain answer for a multiple choice question, and entering the names of interactants shown during the slider task. These checks were inserted to verify that the participants were carefully reading instructions and watching video clips instead of mindlessly clicking through tasks.

3.5 Participants

3.5.1 Height Variation Study. In the online study conducted on MTurk, participants were paid a fixed compensation ($3 USD) for a task that took 34 minutes on average to complete. We controlled for the quality of our data by excluding data from 65 participants who failed attention check task (described in Section 3.4), and 13 participants where we discovered that some had answered the study multiple times despite clear instructions not to do so due to how the studies were published on MTurk. Ultimately, the study had 288 participants (187 male and 101 female) between the ages of 19 and 69 ($\mu = 36.9$, $\sigma = 10.6$).

The in-person study conducted at a university research lab had 36 participants (19 male and 17 female) between the ages of 19 and 67 ($\mu = 33.36$, $\sigma = 16.69$). Participants were compensated $15 for participating in the 1-hour duration study. For two participants in Study 2 the sUAV crashed before interaction. Since this may have impacted their approach distances, their data were not used and two new participants were run with the same treatment conditions to get data for all 36.

A subsequent online study was then run using the simulated UAV videos. This study involved 30 participants (16 male and 14 female). Data from participants who failed an attention check were not included. Participants ranged from 22 to 64 years old ($\mu = 41.5$, $\sigma = 13.1$). They were compensated $5 for their task which took on average 33 minutes to complete.

3.5.2 Guard Variation Study. An online study was conducted to determine how additions including propeller guards and a cage would affect results. This study included 47 participants (35 male and 13 female) between the ages of 20 and 65 ($\mu = 35.8$, $\sigma = 11.6$).

The hybrid study involved 11 participants (7 male and 4 female) between the ages of 20 and 37 ($\mu = 26.3$, $\sigma = 5.0$) who completed both the online and in-person studies. Six participants completed the online segment first and five participants completed the in-person segment first. The in-person segment took place at a university research lab and participants were compensated $15 for 1 hour of participation.

3.5.3 Prior Interactions with Robot(s). In all combined online and in-person studies conducted by us, 52.7% of the participants reported to have interacted with a robot previously. It is important to note that the question, "Have you ever interacted with a robot?" was phrased broadly to include single interactions or those in museums or with robot vacuums.

Table 1. Approach Distances (in Meters) Measured for In-Person Studies

Study	Condition	μ	σ	p-value
Study by [3]	UAV	0.64	0.22	<0.001
	Double	0.35	0.23	
Study described in Section 4.1.1	0.91 m	0.67	0.26	0.82
	1.52 m	0.65	0.23	
	2.13 m	0.65	0.18	

p-values correspond to the conditions of each study.

Table 2. Projective Comfortable Approach Distance (in Meters) Calculated for Online Slider, Video, and Sound Methods

	UAV-3	UAV-5	UAV-7	Double
Slider	1.72 ± 1.18	1.73 ± 1.16	1.82 ± 1.18	1.28 ± 1.12
Video (ego)	1.57 ± 0.86	1.52 ± 0.81	1.41 ± 0.74	1.24 ± 0.80
Video (exo)	1.40 ± 0.65	1.48 ± 0.74	1.33 ± 0.60	0.78 ± 0.66
Sound	1.67 ± 1.07	1.66 ± 1.05	1.65 ± 1.08	0.87 ± 0.64

4 Results

Results will be presented from the height variation and guard modification studies to compare results from the various modalities on distancing, user comments, and participant affect.

The data from all the online studies were converted to distances (in meters) using the proportions applied to the slider study assuming a human of average height (1.5 m), distance (3.65 m) between user and robot start positions, as well as the ROS bag files used to record the flight paths in video and sound studies converted to correspond to the video/audio timestamps. All results are reported using the final submitted value from the online form, unless reported otherwise.

4.1 Height Variation Study

4.1.1 In-Person Study. In the in-person study we conducted with the sUAV flying at three different altitudes, the comfortable approach distances at 0.91 m (μ = 0.67, σ = 0.26), 1.52 m (μ = 0.65, σ = 0.23), and 2.13 m (μ = 0.65, σ = 0.18) were not statistically significantly different (Table 1). The distance values are however closer in magnitude and in the same zone (personal) as results reported by [3] and [10]. It's interesting that during the in-person interaction some users allowed the robot to approach very close, and did not stop the approaching robot 38.88% of the times and stopped it only at the last moment 5.55% of the times.

4.1.2 Online Video Studies. Table 2 summarizes the results for this section. The UAV with the closest approach distance for both the egocentric and exocentric videos had an altitude of 2.13 m.

4.1.3 Online Simulation Study. The results for this section are summarized in Table 3 and compared to the results in Sections 4.1.1 and 4.1.2 in Figure 7. For both the real UAV videos and the simulated UAV, participants allowed the UAV to approach more closely when viewing the UAV from the exocentric viewpoint, making the exocentric approach distances closer to the in-person approach distances for all three heights. The participants also stopped the simulated UAV sounds farthest away, as the participants had with the real UAV sounds. The participants also allowed the

Table 3. Projective Comfortable Approach Distance (in Meters) Calculated for UAV Simulation Modalities

	UAV-3	UAV-5	UAV-7
Slider	1.81 ± 1.12	1.72 ± 1.07	1.53 ± 1.16
Simulator (ego)	1.92 ± 0.76	2.00 ± 0.88	1.88 ± 0.92
Simulator (exo)	1.62 ± 0.85	1.78 ± 0.76	1.65 ± 0.90
Simulator sound	2.36 ± 0.98	2.73 ± 0.75	2.40 ± 1.08

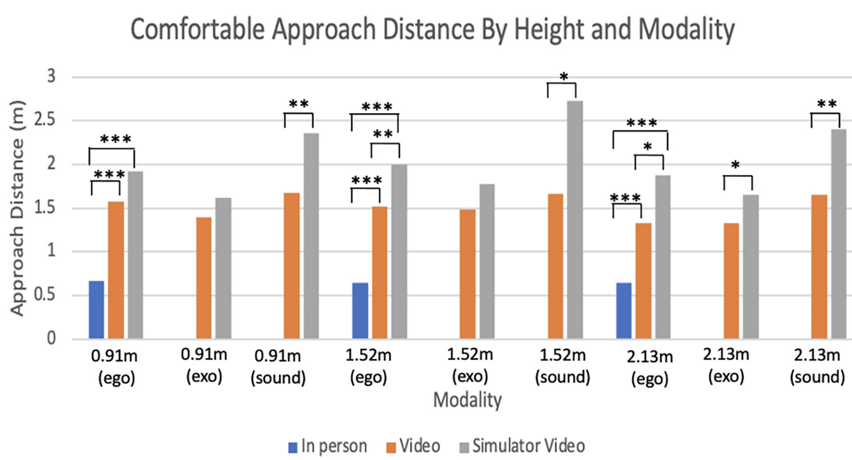

Fig. 7. Approach distances of online and in-person height variation studies. One star represents a p-value less than 0.05, two stars represent a p-value less than 0.01, and three stars represent a p-value less than 0.001.

video UAVs to approach more closely than the simulated UAVs for all three heights and from both the egocentric and exocentric viewpoints.

4.1.4 Hybrid Study. In the online studies, 97.88% of users who watched the real UAV videos and 90.0% of those who watched the simulated UAV videos reported to be able to effectively visualize themselves as the user in the study. However, 76.76% of users who watched the real UAV videos and 56.67% of users who watched the simulated UAV videos felt than an in-person interaction might change how close they allowed the robot. Some reasons participants gave for why they felt an in-person interaction might change how close they would allow the robot included:

— "I could rely more concretely on my observations of how the robot looked."
— "I would have space to move away from it."
— "The robot would follow my commands and follow any proposed interactions."

4.2 Guard Variation Results

4.2.1 Online Study. Table 5 and Figure 8 summarize the results for this section. The UAV with the cage enclosure had the closest approach distance for both the egocentric and exocentric viewpoints. The videos with an exocentric viewpoint had closer approach distances for all three UAV variations than the egocentric viewpoints which is consistent with the results of the height variation studies.

Table 4. Projective Comfortable Approach Distance (in Meters) for UAVs with Propeller Guards and Cage Safety Modifications

	No Guard	Propeller Guard	Cage
Video (ego)	1.61	1.50	1.36
Video (exo)	1.20	1.41	0.98

Table 5. Comfortable Approach Distance (in Meters) for UAVs with Propeller Guards and Cage Safety Modifications

	No Guard	Propeller Guard	Cage
In-person (ego)	0.72 ± 0.30	0.77 ± 0.40	0.72 ± 0.42
In-person (exo)	0.76 ± 0.36	1.19 ± 0.84	0.83 ± 0.29

4.2.2 Hybrid Study. For the in-person portion of this study, participants were able to select the height at which they preferred the UAV to approach them or the volunteer. The average preferred height was 1.39 m ($\sigma = 0.22$) for flights with the propeller guards, 1.44 m ($\sigma = 0.27$) for flights with the cage, and 1.48 m ($\sigma = 0.29$) for flights with no guard condition. Combined, the average preferred height for all flights was 1.44 m ($\sigma = 0.25$). Only two participants choose a height above their heads for any of the three flight conditions. This is contrary to what was found in the height variation study where participants allowed the UAV to approach them most closely when it was at an altitude of 2.13 m.

As in the height variation study, participants in the hybrid study generally allowed the UAV to approach them more closely in-person than they allowed the UAVs in the videos. Contrary to the online study results from both this study and the height variation study, the participants with an egocentric viewpoint had closer approach distances than the exocentric viewpoint for all three flight conditions. The results are summarized in Table 4.

The approach distance results for the in-person portion of this study were mixed. However, several participants expressed feeling safer with the cage and propeller guards in place. It's possible the larger appearance of the UAV with these additions caused participants to stop the UAV farther away. Participant comments regarding the guards included:

- "Guards definitely influenced my perception of increased security. It seems like if it got to close to me, I could more easily grab the guard box without [sic] risk of damage to myself or the robot."
- "No moment of panic near the end before the robot stopped. I knew it would stop, and if it didn't, the guards would mostly protect me."

4.3 User Comments

In the exit questionnaire the users were asked "Do you have any other comments about this experiment?" and "Is there anything that has not been addressed that you find important?" Some example comments are listed below as they were written by the participants via the online or paper questionnaire forms. Participants, in general, expressed curiosity and engagement; other common feelings are summarized briefly in this section.

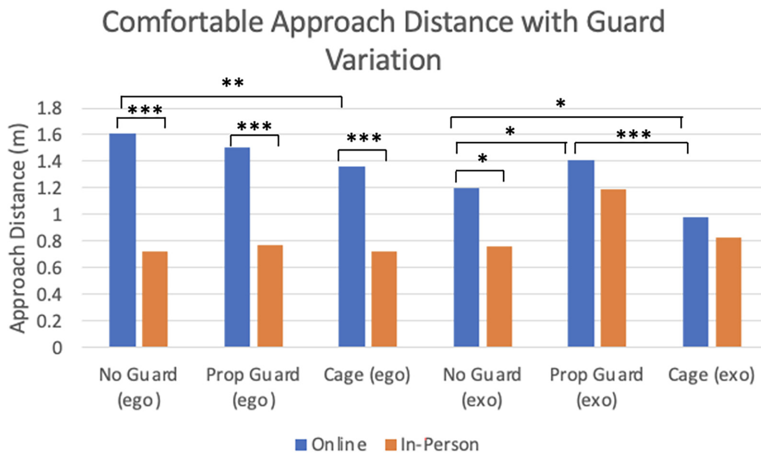

Fig. 8. Approach distances of online and in-person guard variation studies. One star represents a p-value less than 0.05, two stars represent a p-value less than 0.01, and three stars represent a p-value less than 0.001.

Participants expressed a preference for the ground robot compared to the aerial vehicle. For the UAV, the participants commented on the noise generated by the vehicle and expressed negative feelings toward the propeller blades. A few users commented on allowing the robot to approach. Finally, the general comments pointed to overall feelings of interest in the study.

Height Variation Study.

- "The sound of the UAVs is what makes me dislike them, I think."
- "It is hard visualize interaction with a robot via computer screen, in person interaction could present a totally different experience."
- "Were the sounds actually real robots? I didn't think UAVs were that loud."

Simulation Study.

- "I'm not afraid of drones, I just feel like I'm being spied on and it's generally difficult to tell who's 'piloting' it."
- "The first-person POV helped me do a better job of imagining compared to the side view."
- "The audio didn't make me feel like the robot was approaching, it just annoyed me because of the duration of the noise."

Guard Variation Study.

- "Again, without having anything to gauge intent, I would want the robot to be farther from me than I would a human. If the robot had something to express intent ('facial features' or voice, for example) I'd want it closer to me. As for humans, it depends on the human and what their body language is saying to me, I guess."
- "Just that if I was actually in the presence of the robots, I would most likely allow them to get closer because I would be in a position to move out of the way if anything unexpected happened."
- "If it was moving faster it might put my emotions in a different placement."
- "For the video portions, a VR environment might change my answers."
- "It woud [sic] be interesting to know more about what the robot's hypothetical objective is - reconnaissance/delivery/intimidation/etc."

4.4 Human–Human Distance

In order to baseline the collected numbers and out of interest due to the ongoing pandemic, we asked participants to indicate (using a slider) how close they would allow another human being to approach them. On average participants distanced the human figure 0.85 m away in the initial online height video study, 0.78 m away in the online simulation study, and 0.87 m away in the online guard variation study. One participant commented "Closeness of human preference depends on Covid." These results are relatively similar to those observed in human–human distancing (M = 0.73 m) [9].

4.5 PANAS

The Wilcoxon Signed Rank test was used to compare the participants' self-reported differences of affect PA (sociability) and NA (stress) [28] while interacting with the robot to their affect reported prior to the interaction. When looking at the differences of affect PA (sociability) and NA (stress) [28], the participants reported higher distress during all studies except the online guard variation study compared to how they felt the day of the study. The average pre-interaction NA score for participants across the total study was 17.12 which increased to an average of 17.63 during the study. The in-person portion of the guard variation study showed the highest increase (+3.06) between NA before and during a study.

5 Discussion

5.1 Limitations

The most prominent limitations of this study are due to the testing modalities, where each sacrificed fidelity in different ways. The slider, where the interactants were images, was missing the sound and visuals; the sound modality was missing the visuals; and all online studies were missing the in-person experience. In the current implementation, the slider restricts testing of variables like speed and variable paths that require 3D perceptions and automated movement of the robot. To investigate these factors, one of the other prototyping mediums should take precedence. Despite these differences, 97.88% of users reported that they were able to effectively visualize themselves as the user in the study.

The lack of significant difference for the UAV flying at 0.91 m and 1.52 m was similar in online and in-person studies, but this did not hold for the UAV at 2.13 m. One possibility is that in-person user responses were impacted by other factors like the perception of room size or ceiling height, which were less obvious in the egocentric video and absent in the sound modality. Another explanation is that the physical presence of interactants during in-person interaction afforded viewers with better depth perception and motion parallax [18], which was lacking in the online modalities.

The projective measurement results from online studies are similar to the results of in-person studies, but the distances differ in magnitude. We argue that it is fair to sacrifice the precision in favor of ease of deployment and ability to detect patterns in interaction which can then be refined through smaller in-person tests.

5.2 Implications

While the results were not significant, the slightly closer approach distances for the UAV operating at 2.13 m for the egocentric in-person, video, and simulation video studies correlate with the findings in [6] which found that participants were willing to approach more closely to UAVs operating above eye level in a virtual reality setting. However, this preference for the UAV to operate above eye level was not observed in Phase 5 of this study when participants were given the option to position the UAV at their desired height. The distances noted in our online studies are quite large compared to the in-person studies for all modalities. There are several possible reasons for this, some of which were suggested by user comments. It's possible that in-person participants felt more comfortable during the UAV's approach because they felt more in control since they were able to move away from the UAV if needed. Another possible reason for the closer approaches allowed in the in-person studies is that the in-person participants' interactions with the researchers who were running this study caused those participants to trust the researchers and, by extension, trust the UAV as well. In contrast, online participants were not aware of how the UAV was being controlled during its approach. Additionally, it's possible that the scale of presentation affected user responses and, especially given many of the participants had no prior experience with UAVs, participants were overly cautious in estimating how far away they would wish the UAV to be. Lastly, as the online study allowed us to sample a more diverse population the online results may show a discrepancy between our in-person experiment group and the wider population.

Participants' PANAS scores indicate that participants of both the in-person and online studies experienced higher levels of negative emotions during the study than they did prior to the study. This correlates with the findings of [7] that participants experienced higher levels of stress during a UAV's approach in both real and virtual settings. However, an interesting additional finding in our hybrid study was that participants allowed the UAV to approach them closer than they allowed the UAV to approach the human volunteer. This was contrary to what was seen in all of the online studies which compared egocentric and exocentric views. While this portion of the study had too few participants to draw conclusive findings on this subject, it should be considered that human–robot proxemics may affect and distress nearby observers as well as the individual who is approached by the robot.

Our findings suggest that choosing among the slider, video (ego or exo), simulation, or sound for specific purposes requires a consideration of the social and informational dimensions of the task at hand. Based on the study being conducted, understanding the contextual information conveyed by each method is important in eliciting the most effective response for each method from the user. However, given the information here, we could have tested other potential studies to find one likely to elicit differences (such as increased speed, variable flight paths, etc.).

5.3 Recommendations

Many users reported multiple answers for each method and, as opposed to in-person interaction, they could refine their answer by moving the robot closer and further to find their preferred distance. Prior studies in ground robots have found this to not impact the distancing [16, 26], whether the robot approached the user or user approached the robot. But the patterns in our data indicate that the same may not hold true for aerial vehicles. In future studies, researchers might confirm the impact of this by allowing the user to refine their answer after stopping the robot as an iterative process.

With respect to applying the different methods, we would recommend the following. *Sound* seems to be an effective modality if you are testing the size of very different vehicles or acoustics for a deployment space to understand which design might be preferred. *Ego video* is useful for systems that can be fully observed from this relatively limited view to understand the expected perceived size of interaction. *Exo video* would be effective for testing most use cases and deployment details due to the wider view and the standoff, but are limited in their application to exceptionally loud systems, so might be well complimented by a sound or ego video study. The *simulation video* approach distances (both exocentric and egocentric) were farther from the results found in the in-person study than the real UAV video distances and 7.88% fewer participants stated that they were able to effectively visualize themselves as the subject in the videos. Thus, it appears some realism is lost using the simulation modality and caution should be used when attempting to draw conclusions solely from simulation data. However, this modality is potentially useful for studies that are more interactive as it could allow participants to control the robot or respond to it. Future work could explore how participants react to a UAV's approach in a simulated environment where they have control over the human model to more accurately reflect the autonomy a person would have in real-world UAV interactions. Lastly, we found the exocentric simulation results to be more similar to the in-person results than the egocentric simulation results.

6 Conclusion

Through the use of crowd-sourcing platforms, we were able to complete a set of HRI studies with hundreds of participants with diverse backgrounds and ages. The similarity of the online trends to those observed in person may have encouraged a different selection of in-person study (such as one that would impact sound). We found that the exocentric viewpoint yielded results closer to our in-person experiments than the egocentric viewpoint videos of both actual UAV testing and UAV simulations. While we did not generally find significant differences between flights at different heights or UAVs with different guard modifications, we did see some significant differences between testing modalities, suggesting that caution should be used when relying on these testing modalities and that smaller in-person experiments can be helpful for verifying the results of larger online experiments. We hope that the demonstration of these techniques will encourage researchers to leverage these methods for future exploratory work. Discussion includes recommendations for when to use the different modalities.

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Appendix A
Testbed Dimensions

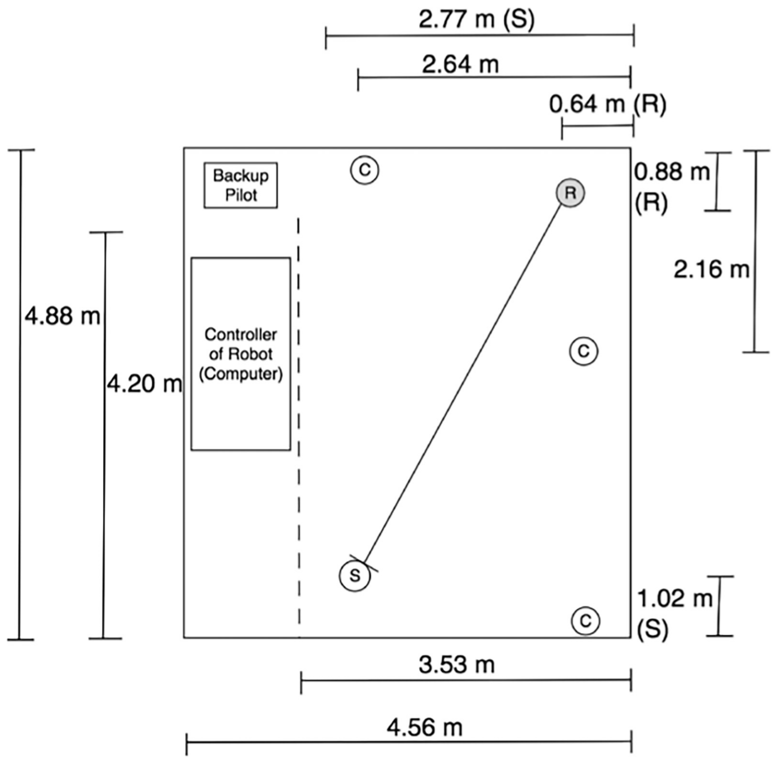

Fig. A1. Dimensions of testing room used in Phases 1 and 2 of the study and replicated in simulator for Phase 3 of the study. (R) represents the starting point of the robot and (S) represents the position of the human subject. The ceiling height in this room was 2.74 m.

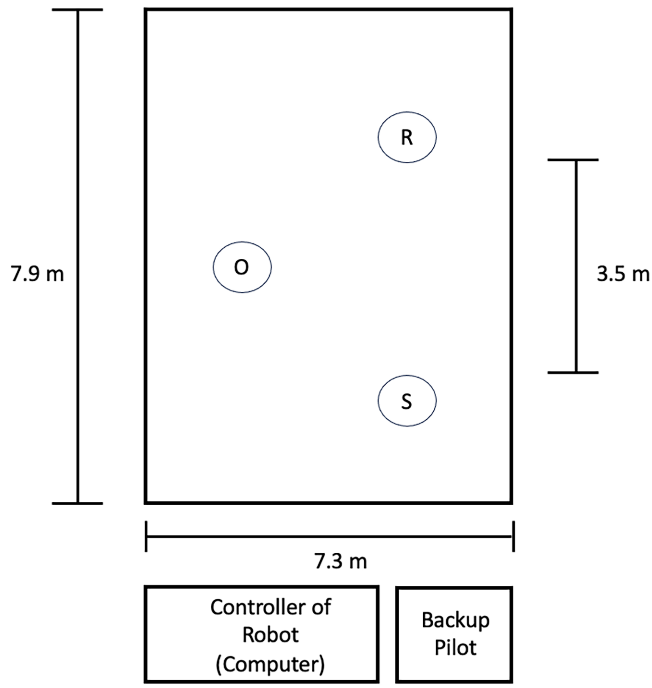

Fig. A2. Dimensions of netted test area used in Phases 4 and 5 of the study. (R) represents the starting point of the robot, (S) represents the position of the human subject that was approached by the robot (participant for egocentric viewpoint or fellow lab member for exocentric viewpoint), and (O) represents the position of the human observer (only present for exocentric viewpoint study). The ceiling height in this room was 2.74 m. The computer controller and a backup pilot were outside of the netted area.

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