The Role of Drone's Digital Facial Emotions and Gaze in Shaping Individuals' Social Proxemics and Interpretation

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The potential for drones to engage with people and find applications in social contexts is often constrained by their mechanical design, leading to concerns and negative associations that significantly affect people's acceptance of drones in their personal space. In this study, we explore how social cues can impact the spatial dynamic of Human–Drone Interaction (HDI). Within a fully immersive virtual environment, 25 participants engaged with and navigated around a drone that communicated several facial emotions on a digital display such as Joy, Sadness and Anger, and enacted distinct "gaze" behaviors (i.e., following participants or averting its gaze). Our results indicate that participants responded to the drone's gaze in a manner akin to what is reported during human interaction: maintaining a greater distance when the drone established eye contact and instinctively getting closer when it averted its gaze. A more granular analysis revealed that participants who lacked prior familiarity with drones or possessed neutral to positive attitudes toward them demonstrated a higher sensitivity to the drone's digital facial emotions. This finding highlights the potential for leveraging social cues to facilitate the integration of drones into various human-centric environments and tailor their design and behavior to suit specific individuals and situations.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; **Virtual reality**.

Additional Key Words and Phrases: Proxemics, Human-Drone Interaction, Social Robotics, Virtual Reality, Social Cues

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1 INTRODUCTION

In recent years, drones have become increasingly ubiquitous in various domains, ranging from surveillance and logistics to photography and recreation. The development of autonomous drones is advancing at a remarkable pace, raising the prospect that encountering self-navigating drones in our daily lives may soon become normal. However, this surge in autonomous drone deployment has brought to the forefront a pressing challenge – how best to ensure seamless integration of drones into social contexts and their harmonious interaction with humans. To address this challenge effectively, it is crucial to delve into the dynamics of peoples' spatial relationships with drones (i.e., Human–Drone

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Proxemics). Understanding how people adapt their distances from drones is essential to prevent discomfort arising from inappropriate proxemic behaviors and to achieve a harmonious coexistence.

A key reason making it challenging to seamlessly integrate drones into our daily lives is their mechanical nature, resulting from their efficient task-oriented design. Their mechanical design, including aspects like sound, behavior, and appearance, is often negatively connoted and associated with potential threats [18]. Moreover, the absence of human-like features can contribute to the categorization of drones as cold machines seemingly devoid of social nuance. This, in turn, creates a barrier to people establishing meaningful social connections with drones [17]. While there are scenarios where drones excel as efficient, task-focused roles, adhering to a uniform design approach that limits all drones to a non-social embodiment stifles the full potential of this technology in engaging our social nature. Establishing meaningful social connections is important for various reasons: it enhances user experience, improves safety and acceptance, facilitates collaboration, and fosters emotional engagement [15]. For instance, drones designed for delivery services or search and rescue operations that can interact socially may create a more satisfying and reassuring experience for users. Human cognition allows us to attribute intentions, thoughts, and emotions not only to living entities but also to non-living ones, such as machines. This cognitive trait empowers designers to infuse technology with social elements, triggering social mechanisms that enhance user engagement, well-being, and interaction [25]. The field of Social Robotics has traditionally focused on ground-based robots, but the unique nature of flying robots introduces a novel interaction paradigm with distinct challenges and opportunities, demanding a fundamental shift in perspective if we are to understand what it means to develop *flying* social robots.

The exploration of emotional facial expressions for drones has recently gained attention, exemplified by the work of Herdel et al. (2021), who designed recognizable emotional faces for drones [46]. Despite this notable advancement in the field, the impact of these cues on human engagement and interaction with drones remains unexplored. Our study bridges this gap by evaluating the effects of digital facial emotions displayed by drones in active interaction scenarios, as opposed to passive video observation. In addition, gaze direction, a powerful cue conveying a wealth of social information, is well-established as playing a significant role on influencing proxemic behavior among humans (or how close people will stand to each other). In Human–Drone Interaction (HDI) research, participants have referred to the drone's camera as its "eyes" [18], suggesting that the direction these 'eyes' point has the potential to influence people's perception of the drone. This leads us to question whether different drone "gaze behaviors" might significantly shape individuals' interpretation of displayed emotions, potentially resulting in distinct proxemic responses. In the present study, we address the following research questions:

- **RQ1:** How do the digital facial emotions of a drone affect individuals' proxemic behaviors?
- **RQ2:** How does a drone's gaze behavior impact user proxemic behaviors and their interpretation of displayed emotions?

To address these questions in a controlled and adaptable environment, we leverage the design flexibility of Virtual Reality (VR). VR allows us to overcome key limitations of real-world HDI proxemic studies while drawing upon a wealth of prior research validating its use in studying human interactions (see section 3.1.1). These limitations include: 1) technological constraints and feasibility; creating the drone we employed in the real world would have been challenging, particularly in ensuring stable flight movements with the added digital face and accurate drone gaze behavior relative to the participants' positions. One study attempted to add a face to a drone but had to use cables for stabilization [81], illustrating the difficulties of maintaining flight accuracy in real-world conditions when adding external components; 2) VR provides controlled and replicable experimental settings, eliminating the variability and unpredictability common

with real drones, which are often difficult to control; and 3) safety concerns, which pose significant challenges with real drones. Experimenters are often forced to implement safety measures, such as imposing a minimum distance [2, 32, 44] , using transparent walls [44] , fixing the drone's position [32, 81] , or employing fake drones [24] . Some researchers [17, 32, 55] have criticized these methods, pointing out the potential impact safety measures may have on participants' reactions near drones, thereby questioning the ecological validity of such approaches. Moreover, VR enables us to accurately measure participants' movements while providing them total freedom to navigate, better aligning with methodological requirements to observe natural proxemic behaviors as opposed to the typical stop-approach procedures used in real-world studies.

In our study, 25 participants are immersed in a virtual environment, where they interact with and navigate around a drone displaying various digital facial emotions (Joy, Sadness, Anger, Surprise, Fear) and gaze behaviors (Follow and Avert). However, due to their low recognition accuracy (76% for Surprise and 54% for Fear), we have chosen to exclude these expressions—Surprise and Fear— from the main analysis. This decision ensures a more focused examination of the reliable and accurately recognized emotional cues. **Our results** reveal that the drone's gaze significantly influences participants' proxemic behaviors, with their responses mirroring those observed in human interactions. In addition, we found that participants who lacked prior familiarity with drones or held neutral to positive attitudes toward these aerial machines were also significantly influenced by the drone's digital facial emotions. Their favorable disposition toward robot interactions appears to heighten their receptiveness to the emotional signals conveyed by the drone. Once more, participants' spatial dynamics when confronted with varied emotional expressions on the drone coincide with patterns observed in human–human interactions [65, 70] and human–robot interactions [11]. This suggests that the using social cues bears potential for facilitating the integration of drones into diverse environments and tailor their design and behavior to suit specific individuals and situations.

Contribution Statement. In this study, we examined the impact of a drone's emotional expressions (Joy, Anger, Sadness) and gaze movements (Following participant's face, Averting gaze) on people's proxemic behaviors. Conducted within an immersive virtual environment, the study observed the natural behaviors of 25 individuals as they engaged with and navigated around a drone displaying combinations of digital facial emotions and gaze-based social cues. Importantly, our findings apply specifically to the controlled setting employed, an immersive virtual environment featuring no airflow and reduced drone sound. This specific context allowed us to isolate the social dynamics of human–drone interaction. Our research contributes to the field of Social Drones and HDI in the following ways:

(1) **Enhanced Understanding of Human–Drone Proxemics:** By capturing and analyzing natural human behaviors in response to social cues displayed by a drone, our study advances the understanding of human–drone proxemics. We reveal how the social proxemic function [43] shapes personal space boundaries in human–drone interactions. Notably, our findings demonstrate that individuals respond to drone social cues in ways that parallel their reactions in human–human [65, 70] and human–robot interactions [11].
(2) **In-Depth Analysis of Social Cue Interpretation:** Our analysis offers insights into how individuals interpret and respond to social cues in the context of human–drone interactions. We focus on participants' reactions to the drone's digital facial emotions and gaze behaviors, providing a nuanced understanding of this dynamic.
(3) **Thoughtful Virtual Study Design:** The design of our immersive virtual study serves as a well-structured and adaptable framework for future researchers interested in exploring human–drone interactions. This study design provides a foundation for those seeking to leverage Virtual Reality (VR) for similar investigations in the field.

The Unity project which includes the drone's 3D model, audio files and images, virtual environment, scripts and datasets utilized or produced in this study are accessible to the public through a GitHub repository [1].

2 RELATED WORK

This section provides an overview of the existing research landscape in Human–Drone Interaction (HDI), with a focus on proxemics and social drones. It sets the stage for our study by summarizing key findings and gaps in these areas.

2.1 Social Drones

2.1.1 Definition. Baytas et al. (2019) offered a broad definition of social drones, characterizing them as autonomous entities that operate within inhabited environments, highlighting the inevitability of social interactions between these autonomous drones and humans [9]. This perspective extends the notion of the social dimension to encompass various autonomous machines, irrespective of whether their primary function is predominantly social. Alternatively, drawing inspiration from the field of Social Robotics [15], another approach envisions Social Drones as entities designed to engage users on a deeper level, promoting well-being and facilitating interactions. These drones are equipped to communicate naturally through verbal and non-verbal cues, comprehend human behaviors to respond appropriately, and effectively interact with individuals to achieve their objectives. In summary, the former perspective delineates when the social dimension becomes relevant, while the latter furnishes an aspirational description of the attributes social drones should aspire to embody. By integrating social cues into existing drones, our work represents a progression from the first definition toward the second, aiming to enhance drones with the capabilities outlined in the latter description.

Social drones can be categorized as a distinct subgroup within the broader field of Social Robotics. However, whereas the focus of social robotics has traditionally been on the development of ground-based robots, flying robots offer a novel interaction paradigm full of new potential for social engagement. Drones possess distinctive attributes, notably their capacity to fly, their striking appearance, which generally lacks anthropomorphic or zoomorphic features, the sounds they emit, and the air movement they generate. Furthermore, they may not evoke the same associations in the popular imagination as traditional ground-based robots do. Early research indicates that insights derived from Human–Robot Interaction (HRI) studies with ground-based robots do not seamlessly apply to HDI [2, 32]. This substantial shift in the design space of Social Robotics underscores the necessity of treating drones as an entirely new and distinct entity, requiring fresh perspectives and approaches.

2.1.2 Current Research on Social Drones. In this context, a growing number of researchers have explored drones as potential agents in social contexts, including domestic drones designed for home environments [40, 49, 62], flying companions [41, 51, 56], and even emotional support drones [38]. Researchers have rapidly investigated ways for drones to naturally communicate with others through various means, such as lights to indicate communication intentions [42] or direction [75] and flying movements to convey emotions [23, 71], intent [74] and the drone's state [31].

Drone's Emotional Face. Within this communication perspective, Herdel et al. (2021) departed from the traditional drone design and introduced specifically designed digital displays for drones to convey facial emotional states [46]. Their study efficiently demonstrated that people could recognize a drone's emotions and attribute narratives and social meaning to them. However, it is important to acknowledge that recognizing facial emotions on a screen and deducing their origin is a somewhat distant experience from a real-life emotional interaction.

[1] Link to the Unity Project available on a dedicated GitHub Repository

While Herdel's work demonstrates the potential for using social mechanisms to influence human–drone interaction, it remains unclear how these findings would translate into real-world scenarios. For example, another study that portrayed the drone as a positive social entity significantly improved participants' perceptions of the drone before interaction [17], but this positive perception did not lead to actual behavioral changes during interaction. This highlights the importance of assessing the impact of social cues beyond surveys and observing natural behaviors in interaction scenarios. Our work aims to address this gap and takes a step forward by empirically testing how people's behavior and perceptions of the drone change based on the displayed facial emotions during interaction and navigation around it.

Drone's Eyes. Furthermore, in Herdel's work, the drone's eyes were integrated with the overall expression rather than considered as separate conveyors of meaning. Yet eye gaze plays a vital role in human–human interaction, conveying information, regulating social intimacy, managing turn-taking, and expressing social or emotional states [3, 7, 52]. Notably, the fact that people often perceive the drone's camera as its eyes suggests that it may already play a role, even though it has not been formally investigated in HDI [18]. While the effects of eye gaze have been demonstrated in HRI [3, 59], it remains unclear how these findings translate to HDI. Our work aims to address this gap by considering the drone's gaze as a separate variable. We present two opposing gaze behaviors: following and averting gaze, allowing for a direct comparison with similar studies in human–human [8] and HRI [59]. Moreover, the subtlety of the message conveyed by emotional facial expressions can significantly change with different gaze behaviors. Admoni and Scassellati's review on Social Eye Gaze in Human–Robot Interaction underscores the complementary relationship between gaze and facial expressions [3]. While previous studies have explored the effects of robot gaze behaviors, Admoni and Scassellati suggest that further research into their interactions with other gestures could enhance our understanding of nonverbal communication in robotics. Our work also addresses this gap by examining the relationship between the displayed gaze and digital facial emotions and how it may impact the interpretation of the drone's emotional state in the context of HDI.

The transition from conceptual or hypothetical drone designs to observing real user behavior during interactions is facilitated by the design flexibility provided by Virtual Reality (VR). VR uniquely allows for testing and observing innovative drone designs in interactive scenarios, overcoming challenges such as logistical constraints, safety concerns, and technological limitations associated with real-world implementations. Moreover, VR offers researchers the advantage of controlling confounding variables, reducing development time, and providing a controlled environment for detailed analysis, making it a valuable tool for exploring user behavior in HDI. VR has been effectively employed to assess the appearance of innovative drones [21, 49]. In fact, it has been classified as the second-best method in terms of realism, just behind collocated flight, according to Wojciechowska et al. [80]. Moreover, VR is considered a safe and reproducible environment for testing. A recent comparative study indicates that when controlling for potential influences of VR on the phenomena of interest, as discussed in subsection 3.1, the outcomes in VR closely align with those observed in real-world experimental settings [18] when studying proxemics with social drones.

2.2 Proxemics

2.2.1 Definition. In 1966, Edward T. Hall introduced the term "proxemics" to describe the phenomena characterized by "a series of bubbles or irregularly shaped balloons" that individuals maintain to regulate spacing between each other [43]. Initially focused on describing how people manage their spatial relationships with others, the concept of proxemics has evolved over time. While Hall's original work primarily examined social aspects of spatial relationships, researchers have since expanded the concept, identifying various functions related to proxemics [4, 28]. In daily life, proxemic

mechanisms dictate various aspects of human interaction. For instance, individuals maintain specific distances when engaged in conversations (Social function), navigate crowded environments while striving to reach a goal (Goal-oriented function), adjust their positions in response to aversive stimuli like unpleasant noises (Arousal regulation function [64]), or create distance from potential threats, such as menacing dogs (Defensive function [4, 30, 67]). Proxemic behaviors are fundamental social cues, offering insights into individuals and their interactions with their surroundings. Inappropriate proxemic behaviors, such as personal space intrusion, can lead to increased stress and negative perceptions, with increased detrimental effect when caused by robots [68]. Each of these "carrier mechanisms" [45] associated with people's spatial management has the potential to influence human–drone proxemics [17]. Notably, in the early stages of the HDI field, proxemics emerged as a significant challenge in the development of social drones [9].

2.2.2 Human–Drone Proxemics. As the field of HDI continues to develop, recent research has shed light on proxemic behaviors in the context of drones. Several studies uncovered insights into the role of the protective proxemic function in HDI [1, 17, 76, 82], which was subsequently confirmed and theorised in a dedicated study by Bretin et al. [18]. Their findings revealed that individuals' personal space boundaries around drones are closely linked to their perception of the level of threat posed by the drone. The perception of threat is inherently linked to drones' design, underscoring the significance of exploring design modifications, such as the incorporation of social cues, to address this issue. Our study aligns directly with this line of research.

Taking an objective standpoint on the relevance of proxemic functions in HDI, as recommended by Leitchmann et al. (2020) in their meta-analysis of proxemics in HRI [54], it becomes evident that the defensive function plays a substantial role in shaping individuals' proxemic behaviors around drones, with many empirical evidence as discussed in previous research [18]. Additionally, the sound emitted by drones has emerged as a significant factor motivating individuals to increase their distance [22, 77, 82], suggesting that the arousal regulation function is also relevant in this context. However, the relevance of the social proxemic function described by Hall is somewhat contentious. Early observations of individuals' behavior when navigating around drones don't seem to indicate a notable role for this function [17].

In a previous study, employing a social presentation to portray the drone as a positive social entity significantly improved participants' perceptions of the drone before interaction [17]. However, this initial perception did not persist during interaction, and no significant proxemic differences were observed. Participants largely viewed the drone as a mere obstacle. Researchers attributed this failure to establish a social connection to the highly mechanical and non-social nature of drones, a conclusion supported by participant feedback. Interestingly, Yeh et al. found that adding a face to a drone resulted in decreased maintained distances [81]. Yet, such result could be explained by the decreased saliency of the threatening components of the drone [18], supported by the feedback "I concentrated more on the face of the drone and therefore did not think so much about the propellers". Their study alone does not provide conclusive evidence about drones' potential to exert substantial social influence that would lead to actual behavioral changes.

In contrast, the field of HRI boasts a wealth of studies indicating that humanoid ground robots can indeed be perceived as social agents and wield significant social influence. Of particular interest to this study, Bhagya et al. found a significant effect or robots' facial emotions, presented in the form of emojis, on individuals proxemic behavior when initiating conversation [11]. In particular, Anger led to individuals maintaining the greatest distance, while expressions of Sadness resulted in the closest proximity. Furthermore, an influential study by Mumm and Mutlu (2011) examined the role of robots' gaze in influencing proxemics. Their research revealed that people consistently maintained a greater distance from the robot when it maintained eye contact compared to when it averted its gaze, similar to behavior observed in human social interactions [59].

In light of these contrasting observations, our study seeks to unravel the role of the social proxemic function in HDI. While the absence of social features in drones has previously been linked to the failure to establish a social connection, we anticipate that the digital facial emotions designed by Herdel will enable the social proxemic function to play a substantial role in shaping individuals' proxemic behaviors in the context of HDI.

3 METHODOLOGY

This study explores the impact of the drone's digital facial emotions and gaze behavior on human participants' proxemics (how close they are willing to get to the drone) during two distinct tasks: 1) engaging in a conversation with the drone, and 2) walking around the drone to retrieve information displayed on its back. To address the complexities of human–drone proxemics, we have designed a methodology that prioritizes ecological validity and aligns with the latest findings in the field. As noted in Hall's early work on social proxemics, distancing from others is not a conscious, rational decision but an instinctive response to various sensory inputs [43]. Some researchers argue that using the stop-distance procedure may compromise ecological validity, as it forces participants to consciously think about distancing [17]. Instead of this common method used in Human-Drone Proxemics studies (e.g., [44, 55, 81]), we chose a more natural approach to observe participants' proxemic behaviors, similar to the methods used in previous works (e.g., [8, 11, 17, 59].

Approach and initiate dialog. In the first phase of our methodology, participants were instructed to approach and initiate a conversation with the drone. This approach serves multiple purposes. First, it temporarily directs participants' attention to the drone, allowing for a more focused perception of the drone's face, which contains the stimuli of interest. Additionally, this conversation task may prime participants to perceive the drone as a social agent rather than as a mere obstacle in their path. This methodological choice draws inspiration from Bhagya et al. (2019), who examined the influence of emojis in conveying a robot's emotional state on proxemic preferences [11]. By adopting a similar task, we facilitate a meaningful comparison of proxemic preferences between ground-based and flying robots, offering valuable insights into the role of drones in social interaction.

Retrieve information on its back. Following the conversation, participants are required to navigate around the drone to access visual information (i.e., identify basic 2D shapes) located behind it. This navigation task, inspired by previous works ([8, 59]), allows us to observe participants' paths and the distance they maintain while circumnavigating the drone (see Figure 1). Unlike previous studies, we employ shapes such as squares, circles and triangles (see Figure 5), rather than words, to prevent word readability from influencing participants' approach behaviors.

Our research also delves into the interplay between gaze and digital facial emotions. Alongside manipulation checks, participants provide responses to questions akin to those used in Herdel et al. (2021) [46] to evaluate the interpretation of digital facial emotions, their emotional impact, and the extent to which participants perceive them as relevant to themselves. Detailed information about the use of Virtual Reality (VR) in this study and the design of the stimuli of interests is provided in the next section.

3.1 Setup and Apparatus

3.1.1 Design of Virtual Environment. In this study, we carried out our study in virtual reality (VR), a deliberate choice made to transcend the inherent technical, design, and safety constraints often encountered in real-world Human–Drone Interaction (HDI) experiments [17, 32, 55]. Our participants were immersed in a room-scale virtual environment meticulously designed to replicate the physical experimental room (see Figure 2). Within this virtual space, they engaged in conversations with a drone and navigated around it to access visual information. To track participants' movements and proxemic behaviors accurately, we drew inspiration from Baileson et al. (2002) [8] and Bretin et al. (2022) [17].

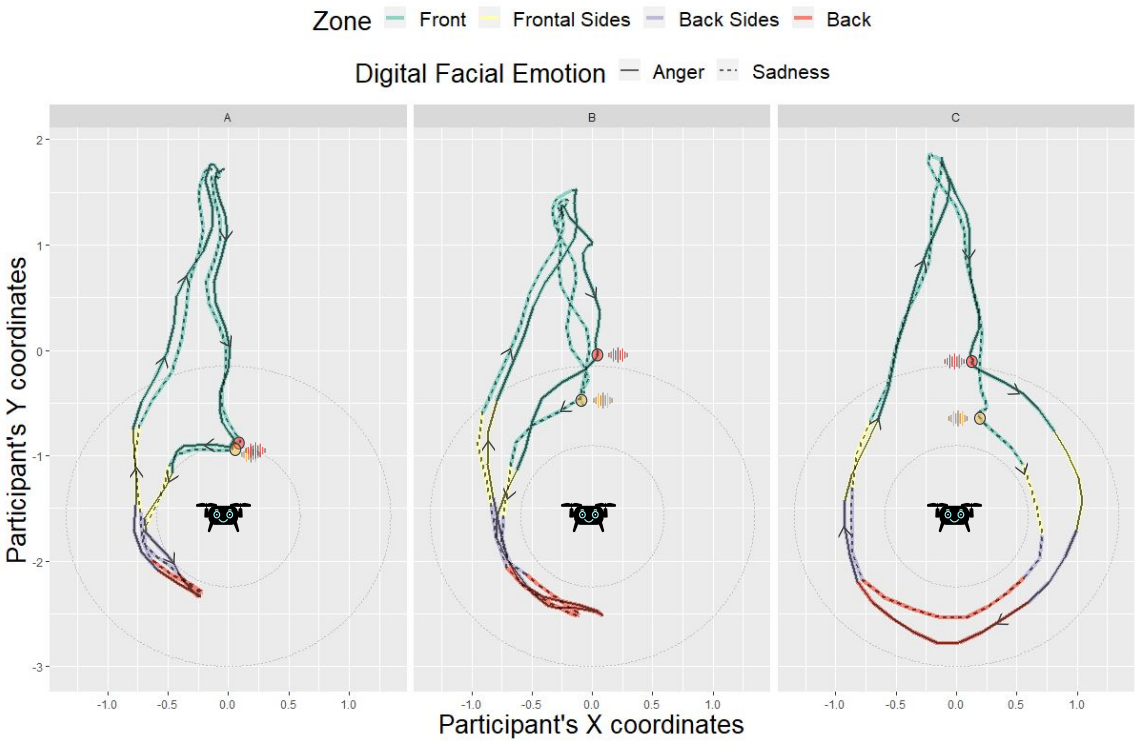

Fig. 1. Visualization of participants' trajectories tracked through the VR headset during the task. We've chosen three distinct profiles to emphasize the variability in proxemic sensitivity to the drone's expressions. For clarity, we present paths only for the Follow gaze behaviors, comparing Anger and Sadness expressions. The points where participants paused to initiate conversation are marked by speech logos and circles (red for Anger, orange for Sadness). We can observe that participant A exhibits highly consistent proxemic behavior unaffected by the drone's expressions. In contrast, Participant B exhibits variability primarily within the front zone, maintaining a greater distance when initiating conversation with Anger compared to Sadness. Notably, this difference tends to diminish afterward, possibly illustrating a phenomenon elaborated in section 5.1 of the discussion. This phenomenon suggests that participants may shift their perception of the drone from a social entity to a mere obstacle due to the nature of the assigned task (from engaging in conversation to reaching a point behind it). Lastly, Participant C exhibits a pronounced influence of the digital facial emotions, remaining visibly important in the front (blue path) and frontal side (yellow path) zones, and diminishing upon return to the starting point. This participant also follows a distinct path to accomplish the task.

This involved utilizing the VR headset's positional data within the Immersive Virtual Environment (IVE) to capture participants' paths during navigation around the drone and accurately evaluate interpersonal distances across different experimental conditions (see Figure 1). Additionally, participants employed the handheld controller to interact with 2D virtual screens projected onto virtual models of computer screens within the virtual environment. This allowed them to complete the task and respond to questions. Similar to the actions of pointing and clicking with a mouse on a computer, participants utilized the ray casted by the controller for pointing and the trigger button to initiate the click action.

Ecological Validity in Virtual HDI Studies. While the concept of ecological validity in virtual Human–Drone proxemics studies has not yet been formally demonstrated, prior research suggests its potential as a valid methodology. To align with best practices, we followed a protocol inspired by Bretin et al. (2023) to optimize ecological validity and allow for external evaluation of virtual HDI experiments [18]. This multi-step approach comprises: **(1)** Identifying the relevant

Fig. 2. The experimental room (right) next to their virtual replica (left) in Unity 3D. Participants' paths were recorded in the simulation allowing the accurate assessment of proxemic preferences around the drone, in a safe and realistic environment.

underlying mechanisms associated with the variables under study; **(2)** Recognizing how VR technology may influence these factors; **(3)** Outlining strategies to minimize VR's influence on the observed outcomes.

Virtual reality can potentially introduce challenges related to altered motor abilities [6, 39] and distance perception [48, 53, 57], two known factors of proxemic behaviors. To mitigate these limitations, we have devised a solution. Our approach involved the creation of an accurate virtual replica of the experimental room, calibrating the virtual participant's position to mirror their real-world location (see Figure 3), and employing a standalone VR headset, the Pico Neo 3 Pro Eye, eliminating the need for cumbersome cables.

Fig. 3. Illustration of the alignment between the Real and Virtual Environments. As the VR safety boundaries (blue grid) are approached in VR (left image), the real-world environment seamlessly blends with and ultimately supersedes the virtual environment (middle and right image). While the safety boundaries were originally aligned with the room dimensions during the study, for this demonstration, the boundaries have been modified. This adjustment allows us to showcase the spatial alignment between the two environments.

The utilization of a virtual replica serves multiple critical purposes. It enhances the sense of presence within the immersive virtual environment (IVE), as supported by Smolentsev et al. (2017) [73]. Additionally, an IVE that faithfully represents the actual environment avoids perceived distance compression, as noted by Interrante et al. (2006)[48]. The accuracy of the virtual replica is essential for participants to perceive it as a true representation of the real environment. This authenticity primarily depends on the scale of the room and the congruence of large objects within it with their real-world counterparts, as noted by Skarbez et al. (2021) [72]. The use of this replica allowed participants to move

freely within the entire room without encountering cables, virtual barriers, or unexpected obstacles. Overall, our course of action effectively addresses the motor abilities and distance perception challenges posed by VR technology.

In our study, we specifically explored social proxemics by investigating how social cues displayed by a drone influence individuals' proxemic behaviors. Importantly, there is, to our knowledge, no existing evidence to suggest that virtual reality affects the perception or interpretation of social stimuli, such as the drone's digital facial emotions and gaze behavior. Indeed, researchers have extensively used VR in the field of social psychology to investigate the impact of factors like facial emotions [65] and various gaze behaviors [8] on interpersonal space.

3.1.2 Design of Drone and Stimuli.

Drone's characteristics. To enhance ecological validity and ensure participants responded to the social drone as if it were real, we used a 3D model of an actual DJI Tello drone (98 x 92.5 x 41 mm) paired with spatial audio based on a recorded sample of the drone's sound. The sound was sourced from a drone sound test video [78] and adjusted in pitch to closely match the real DJI Tello drone owned by the experimenter. This audio was spatialized using Unity's 3D sound engine, with the drone object as the sound source and the participants' VR headsets as the receivers. The sound intensity dynamically adjusted with the distance between the drone and participants, and the audio balance shifted between the left and right channels based on participants' orientation relative to the drone. This setup aimed to create a more immersive and realistic auditory experience, closely mimicking the presence of a real drone. We have also replicated its size and animated the virtual drone to include rotating propellers and simulated hovering imperfections, such as shakes. Similar techniques have successfully induced a sense of threat from the drone and received feedback describing the virtual drone as real [18]. The primary missing component is the airflow produced by the rotating propellers, which we acknowledge as a limitation and discuss further in subsection 5.4.

The drone hovered in a stationary position at eye level with the participants. This positioning aimed to maximize the visibility of the stimuli (i.e., the drone's face) and prevent potential height differences from affecting proxemic preferences. Previous research indicates that engaging with the drone at eye level feels more natural for participants, regardless of their cultural background, when concerns about physical harm are absent [22, 33].

To minimize the influence of non-social factors, such as perceived threat and noise annoyance, the virtual drone was equipped with protective propeller guards, and its flying noise was reduced to a subjectively low annoyance level. While this may seem like a limitation in terms of the transferability of results to real-world drones, it also serves an important purpose by helping isolate the specific social phenomenon under study, which is further discussed in subsection 5.4.

Digital Facial Emotions. The digital facial emotions displayed in this study were designed by Herdel et. al (2021) [46]. They developed cartoon-like facial emotions for drones that rely on Action Units to convey specific emotions that are highly recognizable to human interactants. Their work centered on the six basic emotions: Joy, Sadness, Fear, Anger, Surprise, and Disgust, with three varying levels of intensity: low, medium, and high. This emotional framework has been selected due to evidence demonstrating the universality of basic emotions across diverse cultures [34], and its wide use across studies exploring the perception of emotion displayed by robots [14, 20]. These motivations remain valid for our work and are strengthened by Bhagya et al. (2019) who used the same model to investigate the impact of ground robots' emotional emojis on proxemic preferences [11]. In Herdel's study, each categorical emotion has been successfully conveyed with high recognition rates, except for Disgust, which was often confused with Sadness and reached 29% recognition [46]. Therefore, Disgust has been removed from our study. Within each emotion category, medium-intensity facial expressions have reached the highest recognition scores, motivating their use in our study.

Fig. 4. Some drone designs inspired by Herdel et al. [46] used in the study: from left to right, representing Surprise, Joy, and Sadness, with diverse gaze behaviors illustrating potential interactions with the drone's digital facial emotions.

Gaze behaviors. Another critical aspect of our study is the design of the drone's gaze and behavioral characteristics. It is imperative that participants can readily identify where the drone is directing its gaze (and thus attention), and interpret this as a social cue, rather than an uninformative visual display. Extensive prior research has indicated that perceived accuracy in gaze direction diminishes when the gaze is presented from the side [5], restricted to head movements, or projected onto a 3D sphere instead of a 2D screen or 3D face-like mask [29]. In this study, we use the white pupils of the simplified eyes to indicate the drone's gaze direction (see Figure 4). The drone has a limited field of view which may require "head movements" corresponding to drone rotation. As in Baileson et al. (2001), the drone's rotation is limited to 85 degrees in either direction [8], imitating a standing person who can only move their head. One potential challenge associated with employing flat screens to depict gaze is the "Mona Lisa effect," a phenomenon where observers perceive that the gaze follows them from any angle [58]. We ask specific questions (see section 3.2.1) to assess the extent to which this phenomenon occurred during the experiment, using manipulation checks for the gaze conditions (Follow/Avert). To enhance the human-likeness of the drone's gaze, we have introduced organic features such as blinks, smooth pursuits when the drone's gaze follow participants, limited focused time and saccades when it fixes random points to avoid eye contact. These nuanced behaviors contribute to a more lifelike representation of how a human might gaze and interact socially. In the Follow condition, the drone maintains sustained eye contact with the participant and smoothly rotates when they move beyond the limits of its field of view, with the rotation constrained to a maximum of 80 degrees. If participants venture beyond this "watching zone," the drone gradually returns to its default orientation. Conversely, in the Avert condition, the drone's gaze is directed at random points within its field of view and occasionally incorporates subtle rotations, simulating the behavior of someone glancing at objects in front of them. Importantly, the Avert condition deliberately avoids eye contact with the participants, focusing instead on points distant from their position.

Task-Related Stimuli. Participants perform two tasks in this study. First, they interact with the drone by asking it for a specific letter, which the drone communicates vocally. The audio stimulus originates from a male English speaker, whose recording of the alphabet was sampled to extract the relevant letters for the study. The drone serves as the audio source, delivering the letter vocally to participants through their headsets. For replication purposes, the audio files have been uploaded to the study's GitHub repository [16]. After receiving the letter from the drone, participants must identify the corresponding shape displayed on the back of the drone (see Figure 5). These shapes were custom-designed by the experimenters and integrated as sprites on the drone's back display. The shapes have been made available on the experiment's GitHub for reproducibility. The visual letters, however, were generated internally using Unity's built-in TextMeshPro component and can be easily recreated within any Unity based environment or by accessing the publicly available unity project [2].

[2]Link to the Unity Project available on a dedicated GitHub Repository

3.2 Study Design

The study employs a 5x2 within-subject design with two independent variables: "Facial Emotion" (5 levels: Anger, Fear, Sadness, Surprise, Joy) and "Gaze Behavior" (2 levels: Follow, Avert). Additionally, we explored whether the gaze behavior influences the interpretation of perceived facial cues. The order of experimental conditions is randomized using a Latin square design. Detailed information on the design of the independent variables for the digital facial emotions and gaze behaviors is provided in subsubsection 3.1.2.

The primary dependent variable is the measured physical distance from the drone maintained by participants while performing tasks, which is calculated using tracking data from the headset within the virtual environment (see Figure 1).

3.2.1 Measures.

Proxemic measure. In both tasks, we utilized the minimum distance from the drone (in meters) maintained by participants as the primary proxemic index. This approach aligns with established methodology in prior research [8, 17]. Calculating the average distance participants maintained is often unsuitable due to the varying time spent at different distances in the dynamic tasks, which can lead to inconsistent outcomes. Additionally, we considered the impact of participants' relative orientation to the drone on their proxemic behavior, as observed in a previous HDI study [80]. Instead of prescribing specific walking angles for participants, we opted to maintain a natural task environment. To achieve this, we collected data on participants' and the drone's relative orientations as participants moved naturally around the drone. We subsequently calculated the proxemic index for different angles. This allowed us to define four distinct zones corresponding to the *Front* of the drone (-45 to 45 degrees), *Side Front* (45 to 90 and -45 to -90 degrees), *Side Back* (90 to 135 and -90 to -135 degrees), and the *Back* of the drone (from -135 or 135 to 180 degrees), as illustrated in Figure 1. This approach enhances the granularity of our proxemic analysis.

Self-Assessment Manikin (SAM) + Likert Scale ratings. We used the Self-Assessment Manikin (SAM) to assess the impact of the drone's displayed emotions on participants [13]. SAM evaluates affective dimensions including valence, arousal, and dominance. To complement these measurements and enhance insights into participants' emotional responses, we incorporated Likert scale questions inspired by Herdel et al.'s coding schemes [46]. These Likert scale questions assessed various aspects, including:

- **Affect:** How much participants believe the drone's emotional state impacts their own emotional state.
- **Empathy:** The degree to which participants feel that they share the drone's emotional state or have empathy towards the drone.
- **Self-Relevance:** The degree to which participants perceive that the drone's emotional state reflects how it feels about them.
- **Direction of the drone's state:** Whether the drone's expression seem to precede a future action.

Manipulation Checks. To ensure the effectiveness and reliability of the experimental manipulation of independent variables, we employed manipulation checks. After each condition, participants answered questions designed to confirm that the intended emotions have been successfully conveyed and that the two gaze behaviors (Follow/Avert) have been distinctly perceived. The questions included: **1)** Rate the extent to which you felt the drone was looking at you (Answers: Not at all, Slightly, Moderately, A lot, All the time). **2)** What emotion would you associate with the drone's facial expression? (Answers: Joy, Sadness, Anger, Surprise, Fear).

Pre-experiment Questionnaires. Before the experiment commenced, participants completed questionnaires aimed at evaluating potential confounding variables related to individual traits. We administer the Negative Attitudes towards Robots Scale (NARS) and Robot Anxiety Scale (RAS) questionnaires, originally developed to assess communication avoidance behaviors during human–robot interactions [60, 61]. We adapted these questionnaires to our research context by replacing "Robot" with "Drone." We also gathered information on various demographic variables, including gender, age, previous drone experience, pet ownership, and cultural background [33], which may act as potential confounding factors in the context of Human–Drone Proxemics.

Post-experiment Questionnaires. After completing the experiment, participants responded to the Igroup Presence Questionnaire (IPQ) [69] and the Fast Motion Sickness Scale (FMS) [50]. These questionnaires assessed the level of immersion experienced within the virtual environment and any symptoms of motion sickness, helping us judge the quality of the immersive virtual environment.

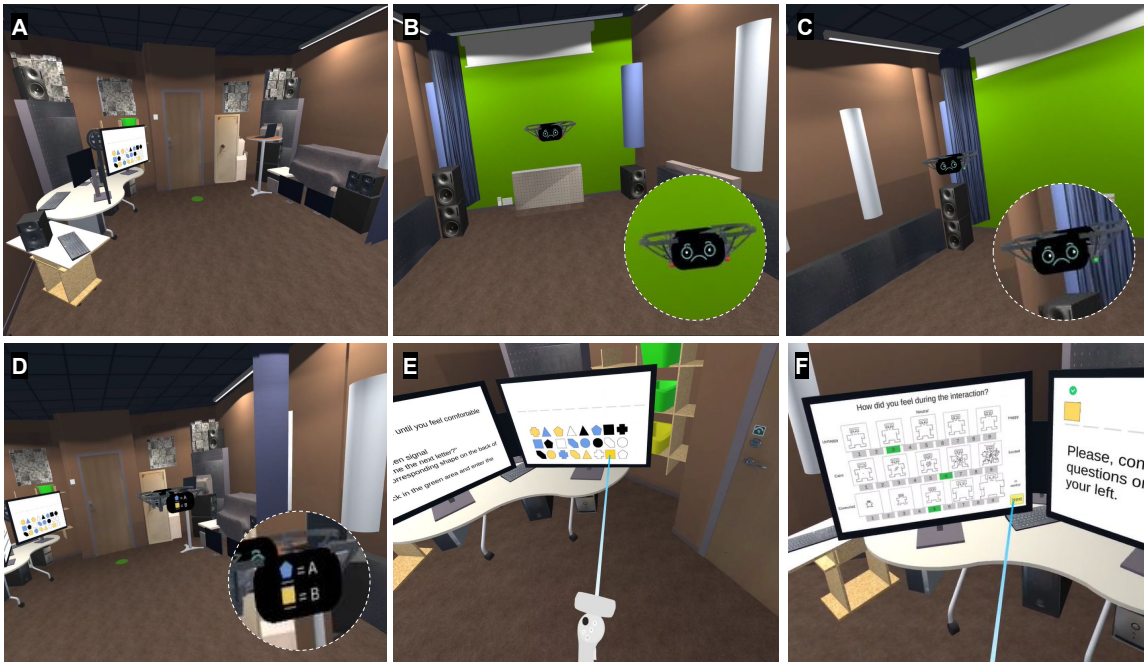

Fig. 5. **A**– After taking a moment to familiarize themselves with the virtual environment, participants stand on the green spot—both the starting point and the interaction zone with virtual screens in the study. **B**– From this starting position, participants approach the drone, featuring a combination of Face and Gaze conditions (illustrated here as Sadness and Follow). They initiate communication with a "Hey," signaling their intent. The drone's light turns green, prompting participants to ask for the next letter with "Can you tell me the next letter?" The drone verbally communicates the letter "B," which participants use in the subsequent steps. **C**– Participants navigate around the drone to access the screen on its back. **D**– On the screen, participants identify the shape corresponding to the letter provided by the drone. In this specific example, the letter "B" corresponds to the correct shape, which is represented by the yellow square as the next element in the shape sequence. **E**– Returning to their initial position, participants input the correct shape in the shape sequence. Incorrect inputs can be removed by clicking on them, while correct inputs prompt questions on the left screen. **F**–Participants, using the controllers (see subsection 3.1), then answer questions, including a Self-Assessment Questionnaire and Likert scales, as detailed in section 3.2.1. The study cycle, starting from step A, continues until participants successfully complete the shape sequence, with the sequence's length aligned with the number of distinct sets of conditions.

3.3 Protocol

Participants received an invitation that outlined an experiment designed to explore people's perceptions of social drones in a virtual environment. It included links to essential documents, such as the Participant Information Sheet, Consent Form, a Demographic Questionnaire, the Negative Attitudes Towards Robots Scale (NARS), the Robot Anxiety Scale (RAS), and a scheduling link via Calendly to book their participation slot. On the designated date and time, participants were welcomed at the laboratory and guided to the experimental room. During this session, the experimenter reviewed the study's purpose and procedures, and participants could ask questions and were asked to provide written informed consent. Simultaneously, the experimenter ensured that the real and virtual positions of the headset match (see Figure 3). Participants then equipped the VR headset, immersing themselves in the replica of the experimental room. The content displayed in the virtual environment and the steps participants undergo are depicted in Figure 5. After a brief familiarization session in VR, during which participants had the opportunity to walk in the room and observe the environment, they were instructed to stand at the indicated spot in the virtual environment. We reminded them of their task and encouraged them to take their time. The task required participants to enter a code composed of shapes in a specific order, unknown to them.

(1) **Approach and initiate dialog:** To reveal the next element of the sequence, they needed to approach the drone and vocally request a letter. The corresponding shape on the screen, located on the back of the drone, indicated which shape must be placed next.
(2) **Retrieve information on its back:** Participants had to move around the drone to view it, and then return to the virtual screen to provide the shape entry.

Whenever a new element was added to the sequence, participants had to answer a series of questions, using the handheld controller (see subsection 3.1), that appeared on the computer screen placed on the table. They clicked the 'Next' button to proceed to the next questions, until they were instructed to repeat the procedure from the beginning. Once the sequence was completed, and the final questions were answered, participants could remove the headset. They were then invited to complete the IPQ and FMS questionnaires on the experimenter's computer. The whole experiment took approximately 30 minutes. Participants were debriefed and thanked in the end.

3.4 Participants

For this study, we recruited a total of 26 participants. However, 25 were retained for analysis, as one participant, who openly identified as neurodivergent, faced challenges in completing the tasks and was consequently excluded. The final sample consisted of 11 males, 12 females, 1 non-binary individual, and 1 who preferred not to disclose their gender. The chosen sample size adheres to the standards set by the HCI field for within-subject designs [19] and is comparable to or larger than the sample sizes used in previous studies related to human-drone proxemics, some of which employed similar or smaller sample sizes [32, 81]. The participants' ages ranged from 23 to 53, with a mean age of 31.58. The participants were from various regions: Europe (21), Asia Pacific (3), and the Middle East (2). Regarding their prior experience with drones, 2 participants had never seen a drone, 17 had seen a drone, and 9 had used them. Recruitment was conducted through online advertisements and word of mouth within the institute. All participants provided informed consent before participating in the study. The participants received a bottle of flavored water and a cereal bar as compensation. The research received ethical approval from the University of Glasgow Ethics Committee (reference number: 300220159). Prior to the experiment, participants completed a demographic questionnaire, the NARS and the RAS.

Table 1. Demographics Summary

Number of Participants		25
Gender	Male	11
	Female	12
	Non-binary	1
	Prefer not to say	1
Age	M	31.58
	SD	8
	Range	23-53
Origin Region	Europe	20
	Asia Pacific	3
	Middle East	2
Drones' Experience	Not at All	2
	A Little	14
	Quite a Bit	9
	A Lot	0
VR Experience	Not at All	2
	A Little	16
	Quite a Bit	7
	A Lot	0
Pet Owner	Yes	16
	No	9

4 RESULTS

In the following section, we present the outcomes of our statistical analysis. As mentioned earlier, the proxemic index employed in this study refers to the minimum distance observed during interactions with the drone, assessed across four distinct zones: the front, front sides, back sides, and back of the drone. To assist readers in navigating through the results, we incorporated summary boxes and a color-coded system. Moreover, Figure 6 provides a visual overview of the primary measures and examinations conducted in this study. **Yellow boxes** summarize the verified impact of potential confounding variables measured prior to the study via questionnaires, on participants proxemic behaviors. **The green box** outlines the results of validating the independent variables in the study. **Blue boxes** emphasize the findings of the main proxemic analysis, which involves examining the influence of the drone's digital facial emotions and distinct gaze behaviors on individuals' proxemic behavior. A more detailed analysis explored significant impacts observed within subgroups of participants. **Red boxes** spotlight the results of the emotion interpretation analysis, delving into participants' perception and interpretation of the displayed social cues during interaction with the drone. Note that the colors in the figure are unrelated to the following color code.

4.1 Confounding Variables

Before delving into the primary analysis, we conducted an evaluation of potential confounding variables, which were measured prior to the study. The statistical tests were performed using R, specifically utilizing the ggstatsplot package [63], which was also used to generate the visualizations for the analysis.

4.1.1 ***Experience with Drones.*** For this analysis, we regrouped the two participants with no prior drone experience into the category of participants with little experience (those who had seen a drone but not used one). We then

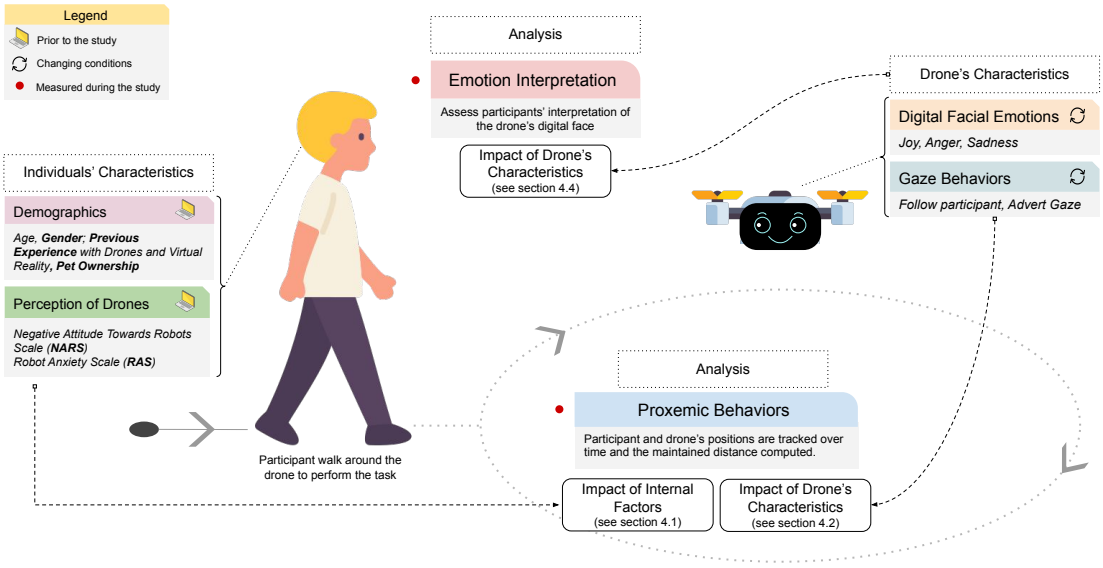

Fig. 6. A schematic summary of the primary measures and examinations conducted in this study is provided. The investigation included assessing the potential impact of confounding factors related to individuals' characteristics on proxemic behaviors while navigating around the drone, as reported in subsection 4.1. Furthermore, the study examined the influence of the drone's digital face, encompassing various digital facial emotions (*Joy, Anger, Sadness*) and gaze behaviors (*Following participants, Adverting gaze*), on proxemics behaviors, detailed in subsection 4.3. Additionally, the interpretation of these cues was investigated, with results presented in subsection 4.4.

Table 2. Mean Minimum Distance (in meters) for Each Zone, Categorized by Gender and Experience Levels with Drones and VR. Welch's t-tests revealed significant differences between males and females, as well as experienced and non-experienced individuals with VR and drones, in different zones. Significant differences are indicated by *.

		Conditions			
		Front	Front Sides	Back Sides	Back
Gender	Male (N=11)	0.67 *	0.56 *	0.57 *	0.63 *
	Female (N=12)	0.83 *	0.73 *	0.73 *	0.83 *
Drones' Experience	Little to none (N=16)	0.81	0.70	0.70	0.80 *
	Experienced (N=9)	0.67	0.58	0.58	0.66 *
VR Experience	Little to none (N=18)	0.81	0.70 *	0.70 *	0.80 *
	Experienced (N=7)	0.65	0.55 *	0.55 *	0.61 *

compared this newly formed group of less experienced drone interactants (N=16) with participants who were more highly experienced with drones (N=9;. i.e., all of these participants had already used a drone). The results of the Welch's t-test, with Holm-corrected p-values to account for multiple comparisons [63], indicate that experienced participants maintained a significantly closer minimum distance from the drone in the Back zone compared to their less experienced counterparts . Although large effect sizes were observed, the analyses for the Front and Front Sides zones yielded p-values just above the conventional 0.05 threshold. This outcome may be partially influenced by unbalanced sample sizes, which can reduce the statistical power of the test. Statistical power refers to the test's ability to detect a true

effect; when sample sizes are unbalanced, it can lead to less reliable estimates from smaller groups. The analysis for the Back Sides zone did not reveal a statistically significant disparity.

Front	$t(20.23) = 2.06$, $p = 0.051$, $g = 0.80$, $M_{Little} = 0.81m$, $M_{Experienced} = 0.67m$
Front Sides	$t(20.04) = 2.06$, $p = 0.052$, $g = 0.80$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.58m$
Back Sides	$t(19.27) = 2.00$, $p = 0.059$, $g = 0.78$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.58m$
Back	$t(21.35) = 2.15$, ***p=0.042*** **(*)**, $g = 0.83$, $M_{Little} = 0.80m$, $M_{Experienced} = 0.66m$

The effect sizes (Hedges' g), in accordance with Cohen's (1988) conventions, ranged from moderate to large, with values between .78 and .83. The mean minimum distances (in meters) for each group are displayed in Table 2.

4.1.2 ***Experience with Virtual Reality.*** In a similar fashion, we reorganized the two participants with no prior experience in VR into the category of participants with little experience (those who have tried it once). We then compared this group (N=18) with participants who were well-experienced in VR, having experienced it several times (N=7). The outcomes of Welch's t-test, with Holm-corrected p-values to account for multiple comparisons [63], revealed that experienced participants maintained a significantly closer minimum distance from the drone in each zone when compared to their less experienced counterparts, except for the front where the disparity was not statistically significant.

Front	$t(9.99) = 1.80$, $p = 0.10$, $g = 0.76$, $M_{Little} = 0.81m$, $M_{Experienced} = 0.65m$
Front Sides	$t(12.93) = 2.32$, ***p=0.04*** **(*)**, $g = 0.94$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.55m$
Back Sides	$t(14.19) = 2.78$, ***p=0.01*** **(*)**, $g = 1.10$, $M_{Little} = 0.70m$, $M_{Experienced} = 0.55m$
Back	$t(17.61) = 3.36$, ***p=3.56e-03*** **(*)**, $g = 1.29$, $M_{Little} = 0.80m$, $M_{Experienced} = 0.61m$

The effect sizes (Hedges' g), following Cohen's (1988) conventions, were medium to large, with values ranging between .76 and 1.29. The mean minimum distances (in meters) for each group are displayed in Table 2.

Impact of Previous Experiences

- Individuals with **prior drone experience** chose to stand significantly closer to the drone in the Back zone compared to those less familiar with drones. While the analyses for the Front and Front Sides zones did not reach statistical significance, the large effect sizes and their proximity to the conventional threshold of significance suggest that this aspect merits consideration and further discussion. The potential impact of prior exposure to drones in shaping proxemic behaviors is further elaborated upon in subsection 5.2. Additionally, this variable emerged as a noteworthy differentiator among participants when examining the influence of drone digital facial emotions on proxemic behaviors (see section 4.3.2).
- People with multiple **experiences in Virtual Reality** (VR) tend to position themselves significantly closer to the drone than those who have only tried VR once, except in the Front zone. With large effect sizes, these findings are considered important and warrant further discussion. We explore potential explanations in the Discussion section, as detailed in subsection 5.4.
- The test of independence indicated that experience with drones and virtual reality were unrelated to each other, implying distinct impacts of both variables.

4.1.3 ***Genders.*** Welch's t-test, conducted on 23 (out of 25 participants, excluding the two who identified as non-binary or preferred not to say), with Holm-corrected p-values to account for multiple comparisons [63], revealed that females (N=12) maintained a significantly greater minimum distance from the drone across all zones compared to males (N=11).

Front	$t(20.72) = -2.15$, ***p=0.04*** **(*)**, $g = -0.86$, $M_{Male} = 0.67m$, $M_{Female} = 0.83m$
Front Sides	$t(20.63) = -2.92$, ***p=8.27e-03*** **(*)**, $g = -1.17$, $M_{Male} = 0.56m$, $M_{Female} = 0.73m$
Back Sides	$t(20.41) = -2.86$, ***p=9.62e-3*** **(*)**, $g = -1.14$, $M_{Male} = 0.57m$, $M_{Female} = 0.73m$
Back	$t(19.68) = -3.12$, ***p=5.44e-03*** **(*)**, $g = -1.24$, $M_{Male} = 0.64m$, $M_{Female} = 0.83m$

The effect sizes (Hedges' g), in line with Cohen's (1988) conventions, were notably large (>0.8). The mean minimum distances (in meters) for each group are displayed in Table 2.

4.1.4 ***Independence between Previous Experiences and Gender.*** Pearson's chi-squared test of independence was conducted across the 23 participants who identified as either male (N=11) or female (N=12). The analysis showed no significant association between gender and the level of experience with drones ($\chi^2(2) = 3.30$, $p = 0.19$) or virtual reality ($\chi^2(2) = 2.39$, $p = 0.30$). Additionally, another Pearson's chi-squared test of independence found that experience with drones and virtual reality were also independent of each other ($\chi^2(4) = 1.44$, $p = 0.84$).

Impact of Gender – Female participants maintained a significantly greater minimum distance from the drone in each zone compared to males (see subsubsection 4.1.3), showing a large effect size (Hedges' $g > .8$). While gender effects can originate from various sources, we tested for known influential variables such as experience with drones or VR. However, participants' gender was not found to be significantly associated with their level of experience with drones or VR.

4.1.5 ***Anxiety Towards Drones.*** A Pearson correlation analysis was conducted to examine the relationship between the adapted Robot Anxiety Scale (RAS) scores and the minimum distance measured within each zone. The results revealed a statistically significant ($p < 0.05$) small positive correlation between the Discourse Anxiety subscale and the minimum distance measured within the Front ($r = 0.18$, $p = 1.86e-02$), Front Sides ($r = 0.22$, $p = 2.18e-03$), and Back Sides ($r = 0.19$, $p = 8.56e-03$) zones. However, no significant correlation was found for the Back of the drone.

4.1.6 ***Negative Attitude towards Drones.*** A Pearson correlation analysis was also performed to investigate the relationship between the adapted Negative Attitude Towards Robots Scale (NARS) scores and the minimum distance measured within each zone. The findings are as follows:

- We identified a statistically significant ($p < 0.05$) small negative correlation between the Negative Attitudes toward Social Influence of Robots and the minimum distance measured within the Front ($r = -0.19$, $p = 6.95e-03$), Front Sides ($r = -0.18$, $p = 1.33e-02$), Back Sides ($r = -0.22$, $p = 1.26e-03$), and the Back of the drone ($r = -0.22$, $p = 1.39e-03$).
- A statistically significant ($p < 0.05$) small to moderate positive correlation was observed between the Negative Attitudes toward Situations and Interactions with Robots and the minimum distance measured within the Front ($r = 0.22$, $p = 1.43e-03$), Front Sides ($r = 0.31$, $p = 1.86e-06$), Back Sides ($r = 0.30$, $p = 6.27e-06$), and the Back of the drone ($r = 0.27$, $p = 8.99e-05$).
- A statistically significant ($p < 0.05$) small positive correlation was found between the Negative Attitudes toward Emotions in Interaction with Robots and the minimum distance measured within the Front ($r = 0.19$, $p = 6.95e-03$) and Front Sides ($r = 0.15$, $p = 4.19e-02$) zones.

The results indicate specific correlations between participants' negative attitudes toward different aspects of drone interaction and the proximity they maintained to the drone in various zones.

Impact of Prior Drone Perception

- **Anxiety** related to conversing with drones showed a small positive correlation with the maintained distance when navigating around the drone in all zones except for its back. This observation is elaborated upon in section 5.1.
- Increased **reluctance to drones' social influence** led to closer maintained distances when navigating around the drone. This noteworthy result is further explored in subsection 5.2.
- In contrast, negative **attitude towards social interactions** exhibited small to moderate positive correlations with the minimum distance maintained in all zones.
- Participants expressing a less favorable **attitude towards emotions** in interactions with drones maintained a greater distance from the drone, particularly within the front and front sides. This finding is further discussed in section 5.1.
- Though modest effect sizes were noted for each statistically significant correlation, these findings remain important within the study's context, offering insightful glimpses into the mechanisms of Human–Drone interactions and proxemic behaviors. The extensive discussions arising from these results in section 5 underscore their contribution to a nuanced understanding of the subject.
- Moreover, negative attitudes towards social interactions and social influence with robots emerged as notable differentiating factors among participants when exploring the impact of drone digital facial emotions on proxemic behaviors (see section 4.3.2).

4.1.7 ***Pet Ownership.*** According to Welch's t-test, there was no statistically significant difference in the minimum maintained distance between pet owners (N=16) and non-pet owners (N=9) in any zone.

Front	$t(19.35) = -0.63, p = 0.53, g = -0.25, M_{Pet} = 0.75m, M_{NoPet} = 0.79m$
Front Sides	$t(18.04) = -0.71, p = 0.49, g = -0.28, M_{Pet} = 0.64m, M_{NoPet} = 0.69m$
Back Sides	$t(17.77) = -0.65, p = 0.52, g = -0.26, M_{Pet} = 0.64m, M_{NoPet} = 0.69m$
Back	$t(21.25) = -0.37, p = 0.71, g = -0.14, M_{Pet} = 0.74m, M_{NoPet} = 0.77m$

4.2 Manipulation Checks

After each condition, participants answer questions designed to confirm that the intended emotions have been successfully conveyed and that the two gaze behaviors (Follow/Avert) have been distinctly perceived.

Table 3. Confusion Matrix Illustrating the Accuracy of Emotion Recognition for Drone's Digital Facial Emotions

		Conditions				
		Joy	**Anger**	**Sad**	**Surprise**	**Fear**
Responses	**Joy**	45 (90%)	1 (2%)	0 (0%)	5 (10%)	5 (10%)
	Anger	0 (0%)	47 (94%)	0 (0%)	1 (2%)	1 (2%)
	Sad	2 (4%)	0 (0%)	47 (94%)	3 (6%)	10 (20%)
	Surprise	2 (4%)	1 (2%)	1 (2%)	38 (76%)	7 (14%)
	Fear	2 (4%)	1 (2%)	2 (4%)	3 (6%)	27 (54%)

Note: Rows indicate the choices made by participants, and columns represent displayed digital facial emotions. Correct recognitions are highlighted in green, while notable errors (>= 10%) are shaded in gray. Participants demonstrated higher accuracy in recognizing Joy, Anger, and Sadness, but encountered challenges in correctly identifying Surprise and Fear. Notably, Fear achieved only 54% accuracy and was frequently confused with Surprise (14%) and Sadness (20%).

4.2.1 ***Emotion Recognition.*** As presented in the confusion matrix (see Table 3), the recognition rates for the facial emotions of Joy, Anger, and Sadness consistently exceeded 90%. In contrast, the recognition rates for the Surprise (76%) and Fear (54%) facial emotions were noticeably lower. Given that our study primarily investigates the influence of displayed digital facial emotions on proxemic behaviors, the accurate recognition of these expressions is of utmost importance. To ensure the precision of our analysis, we have opted to exclude from the main analysis the less-accurately recognized Surprise and Fear expressions. This decision ensures a more focused examination of the reliable and accurately recognized emotional cues. Additionally, we calculated the recognition accuracy of individual participants to assess whether some participants performed notably poorly, which could potentially impact both their subsequent behavior and our analysis. The overall recognition accuracy was relatively high, with a mean accuracy of M=0.85 and a standard deviation of sd=0.14. However, we observed an exception with accuracy rate as low as 50%. Consequently, we are removing this particular data point for the subsequent analysis of the impact of digital facial emotions on proxemic behaviors.

4.2.2 ***Gaze Perception.*** As a manipulation check, we aimed to verify the effectiveness of our designed gaze behaviors – "follow" and "avert" – in shaping participants' perception of the extent to which they felt the drone was looking at them. As detailed in subsubsection 3.1.2, the drone's gaze was conveyed through dynamic pupils' movements (see Figure 4), coupled with restricted drone rotations simulating head movements. A Pearson's chi-squared test of independence confirmed a statistically significant association between the drone's gaze behavior and participants' perceptions of being watched (see Figure 7). This validation supports the suitability of our gaze behavior variable for examining its influence on proxemic responses.

Validation of Independent Variables

- **Digital Facial Emotions –** Joy, Anger, and Sadness digital facial emotions had consistently high recognition rates above 90%, whereas Surprise (76%) and Fear (54%) were less accurately recognized (see

Table 3). Although overall recognition accuracy was relatively high among participants (M=0.85), an outlier with a 50% accuracy rate was identified. For precision in studying the impact of displayed digital facial emotions on proxemic behaviors, less-accurately recognized Surprise and Fear expressions, along with the participant with low recognition rate, were excluded from the main proxemic analysis.

- **Gaze Behaviors –** Our manipulation check confirmed a significant association between the drone's 'follow' and 'avert' gaze behaviors and participants' perceptions of being watched (see Figure 7), supporting the suitability of our gaze behavior variable for examining its impact on proxemic responses.

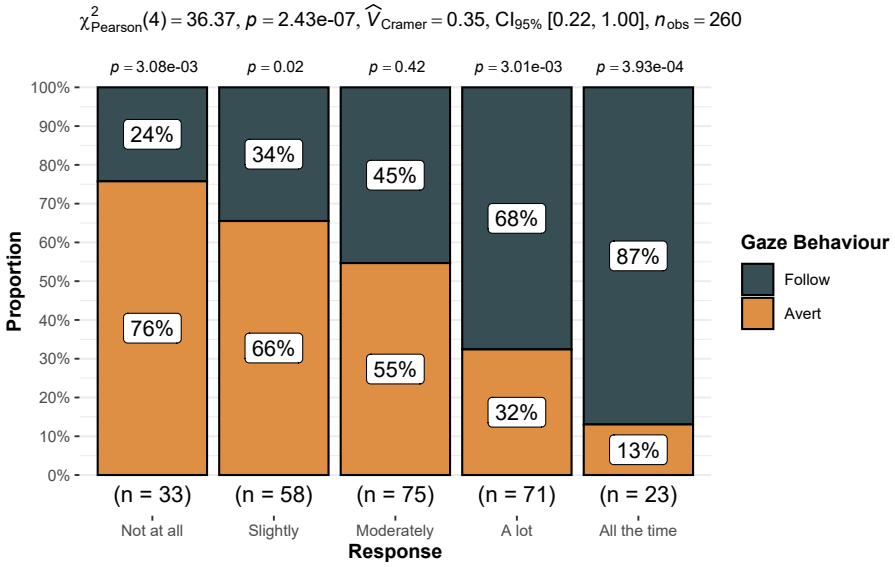

Fig. 7. Participant's Response to "Rate the extent to which you feel the drone was looking at you." From 0 (Not at all) to 4 (All the time). A Pearson's chi-squared test of independence confirmed a statistically significant association between the drone's gaze behavior and participants' perceptions of being watched.

4.3 Proxemic Analysis

A two-way analysis of variance (ANOVA) was conducted to explore the impact of two independent variables: digital facial emotions (*Joy, Anger, Sad*) and gaze behavior (*Avert, Follow*) on the minimum distance measured during the task across four distinct zones around the drone. We assessed data for normality (Shapiro-Wilk test, $p > 0.05$) and verified homogeneity of variances (Levene's test, $p > 0.05$). Additionally, we addressed the sphericity assumption using Mauchly's test and applied the Greenhouse-Geisser sphericity correction for factors violating this assumption.

The analysis revealed a significant main effect of Gaze Behavior ($F(1, 24) = 7.153, p = 0.039, ges = 0.004$) specifically in the Front zone. However, there were no significant effects of digital facial emotions, and no significant interactions between the two variables. All p-values were adjusted using the Bonferroni multiple testing correction method [63].

4.3.1 ***Gaze Behavior.*** Subsequent pairwise comparisons, conducted via paired t-tests, revealed a significant difference ($t = -2.5, p = 0.015, p < 0.05$) in the mean minimum distance between the two gaze conditions in the Front zone.

Participants maintained a significantly greater distance when the drone's gaze *followed* them, as opposed to when it avoided eye contact in the *Avert* condition. This finding underscores the influence of the drone's gaze behavior on participants, leading to a greater proxemic response in the Front zone.

Finding 1 – When positioned in front of the drone, participants maintained a significantly greater distance when the drone's gaze followed them, in contrast to when it avoided eye contact.

4.3.2 ***Digital Facial Emotions.*** Prior to the study, we conducted a thorough assessment of potential confounding variables, including the NARS (Negative Attitude towards Robots Scale), RAS (Robot Anxiety Scale), and participants' prior experience with drones. These factors were examined due to their potential to affect perceptions of the drone, interpretation of displayed cues, and subsequent proxemic behavior (see subsection 4.1). Although our initial analysis did not yield significant effects of digital facial emotions across the overall participant pool, we believe that exploring the data with these confounding variables in mind allows for a deeper understanding of the nuanced interactions at play, especially given that proxemic behaviors are highly sensitive to personal characteristics [43]. By considering these confounding factors, we aim to provide a richer interpretation of how digital facial emotions might influence proxemic behavior, particularly among specific subsets of participants.

Impact of Attitudes Towards Drones.

- **Attitude Towards Social Interaction:** The NARS Social Interaction subscale, designed to measure individuals' negative attitudes toward interacting with social robots, exhibited a significant moderate correlation with maintained distances (see subsubsection 4.1.6). We conducted Fisher's repeated measures one-way ANOVA on a subset of participants who displayed somewhat neutral or even positive attitudes toward drone interactions as indicated by NARS Social Interaction scores below -0.75 (see Figure 8). This analysis revealed a statistically significant difference ($F = 5.74, p = 0.009, p < 0.05$) in minimum distances in the Front zone within this subgroup (N=11), with a medium effect size ($partial\ \omega^2 = 0.02$) following Field's (2013) conventions. Subsequent post hoc pairwise t-tests disclosed that, within this subgroup, the Anger expression ($M = 0.78m$) prompted participants to maintain greater distances compared to Joy ($M = 0.73m$, $p = 0.02$) and Sad ($M = 0.71m$, $p = 0.02$) expressions. No significant effect was found in the other zones.
- **Overall Attitude Towards Drones and Social Influence:** Categorizing participants based on low or neutral NARS scores (NARS < 0.75, N = 23) yielded significant differences in Front zone proxemic responses related to digital facial emotions ($F = 3.39, p = 0.04, partial\ \omega^2 = 0.005$), with Anger ($M = 0.78m$) eliciting greater distances compared to Joy ($M = 0.74m$, $p = 0.03$). Similar categorization based on low or neutral NARS Social Influence subscale scores (NARS_SI < 0.75, N = 19) also resulted in significant differences in Front zone proxemic responses related to digital facial emotions ($F = 4.74, p = 0.01, partial\ \omega^2 = 0.007$), with Anger ($M = 0.79m$) eliciting greater distances compared to Joy ($M = 0.75m$, $p = 0.04$) and Sad ($M = 0.74$, $p = 0.04$). No significant effect was found in the other zones.

Previous Experience with Drones. Moreover, we observed a significant effect of digital facial emotions in the Front zone within participants with little to no prior experience with drones (N = 16, $F = 3.42, p = 0.04, partial\ \omega^2 = 0.007$). However, despite a higher mean distance for Anger ($M = 0.84m$), pairwise comparisons did not identify any statistically significant differences with Sad ($M = 0.80m$) or Joy ($M = 0.80m$). No significant effect was found in the other zones.

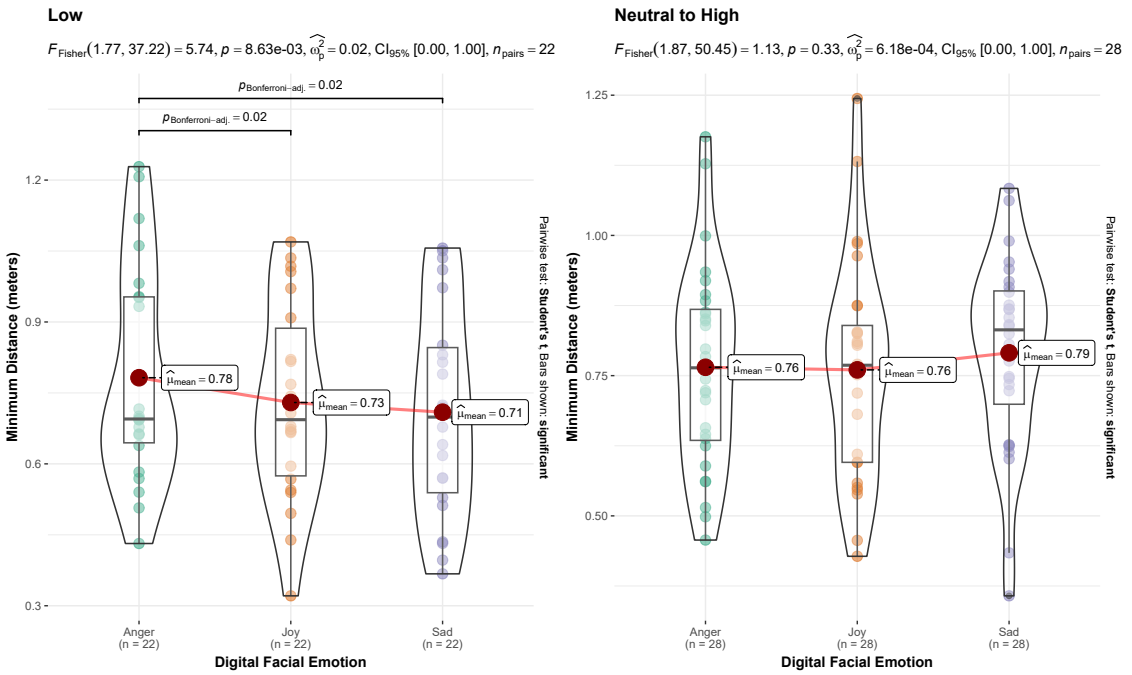

Fig. 8. Minimum Distance by Digital Facial Emotions within the Front zone, for Low (< -.75) and Neutral to High (>= -.75) NARS Interaction Groups. Fisher's repeated measures one-way ANOVA reveals a statistically significant difference ($p < 0.05$) between digital facial emotions for the Low NARS Interaction subset.

Other Confounding Variables. In contrast, attempts to segment participants by Gender, RAS, or VR resulted in either inadequately small sample sizes (fewer than 10 participants) or non-significant outcomes.

Finding 2

- For participants with a low negative attitude towards social interactions with drones, the *Anger* expression resulted in a significantly greater distance maintained when positioned in front of the drone compared to *Joy* and *Sadness*. The digital facial emotions displayed by the drone also significantly influenced proxemic behavior in the front zone among participants with neutral to positive attitudes toward drones, their social influence, and those with little to no experience with drones.
- These results underscore the nuanced interplay of attitudes and displayed facial emotions in shaping proxemic behavior during human–drone interactions, underscoring the importance of considering individual characteristics when investigating dynamics within human–robot interactions which is discussed in subsection 5.2.

4.4 Emotion Interpretation Analysis

In this study, participants' emotional responses to the drone's displayed cues were assessed using the Self-Assessment Manikin (SAM). Additionally, participants provided Likert scale responses inspired by Herdel et al.'s coding schemes [46], to evaluate various aspects, including Affect, Empathy, Self-relevance, and Direction of the Drone's State.

To explore the main effect and interaction of the Drone's digital facial emotions and Gaze on participants' responses, we used the ARTool package on R which applies Aligned Ranks Transformation (ART) on the data, followed by a non-parametric factorial ANOVA [79]. Additionally, we conducted post-hoc pairwise comparisons with Holm adjustment using the extended ART-C procedure [35].

4.4.1 ***Self-Assessment Manikin.*** The Self-Assessment Manikin (SAM) assesses the impact of the drone's displayed emotions on participants' emotional state along three dimensions: Arousal, Valence and Dominance.

Valence. Participants exhibited an overall positive emotional valence during the Joy condition (Mdn=7, M= 6.52, SD=1.2), while it turned negative for both the Anger (Mdn=5, M= 4.5, SD=1.93) and Sad (Mdn=5, M= 4.54, SD=1.89) conditions. We observed a significant effect of digital facial emotions on participants' emotional Valence ($F(2,120) = 34.4$, $p < 0.001$). Post-hoc comparisons revealed that the Joy digital facial emotions of the drone induced a significantly more positive emotional response ($M = 6.52$) compared to both Anger ($M = 4.50$, $p = 9.89e-11$, $p < 0.001$) and Sad ($M = 4.54$, $p = 2.42e-10$, $p < 0.001$). There were no significant effects related to the drone's Gaze, nor were there interactions.

Table 4. Self-Assessment Manikin (SAM) summary results.

		Follow			Avert		
		Joy	**Anger**	**Sad**	**Joy**	**Anger**	**Sad**
Valence	*M*	6.44	4.44	4.52	6.60	4.56	4.56
	SD	1.33	1.83	1.76	1.08	2.06	2.04
Arousal	*M*	3.20	3.72	3.44	2.88	3.52	3.36
	SD	1.89	2.01	1.64	1.48	1.94	2.16
Dominance	*M*	6.68	5.92	6.36	6.84	5.76	6.8
	SD	2.12	2.41	2.41	2.17	2.15	2.40

Arousal. Participants, on average, reported relatively low arousal levels throughout the study (Mdn=3, M=3.53, SD=1.85). We found no significant main effect or interaction between the Drone's digital facial emotions and Gaze behavior on participants' emotional arousal responses.

Dominance. The participants felt a relatively high level of dominance during their interactions with the drone (Mdn=7, M=6.39, SD=2.28). However, this perception of dominance was lowered when the drone displayed an Anger expression. Statistical analysis revealed a significant effect of digital facial emotions ($F(2,120) = 8.19$, $p = 0.00046$, $p< 0.005$), with Anger (Mdn=6, $M = 5.84$) inducing a significantly lower perception of dominance compared to Joy (Mdn=7, $M = 6.76$, $p = 0.00099$, $p< 0.005$) and Sad (Mdn=7, $M = 6.58$, $p = 0.0027$, $p< 0.005$).

Finding 3 – The Joy expression of the drone evoked a significantly more positive emotional response compared to both Anger and Sadness. Additionally, Anger induces a significantly lower perception of dominance compared to Joy and Sadness.

4.4.2 ***Affect.*** To assess the extent to which the drone's cues affected participants, they provided responses to Likert scale questions related to their concerns about the drone's expressions and how much these expressions impacted their

own emotions. Our results, detailed below, suggest that negative emotions, particularly Anger expressions, led to higher participant concern. The Anger expression also had a greater emotional impact when the drone maintained eye contact compared to averting its gaze.

Concern. On average, participants reported relatively low levels of concern (Mdn=2, M=1.79, SD=1.31), ranging between Disagreement (1) and Neutrality (2) in response to the statement that the drone's expression concerned them. The analysis revealed a significant effect of digital facial emotions on participants' concern ($F(2,120) = 20.27$, $p = 2.6e-08$, $p < 0.001$). Specifically, the Anger expression (Mdn=3, $M = 2.34$) induced significantly higher concern compared to both Joy (Mdn=1, $M = 1.12$, $p = 1.43e-08$, $p < 0.001$) and Sad (Mdn=2, $M = 1.9$, $p = 0.016$, $p < 0.05$). Sad also resulted in significantly higher concern compared to Joy ($p = 0.00035$, $p < 0.001$). Notably, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average concern in the Follow gaze condition (Mdn=2, $M = 1.89$) compared to the Avert condition (Mdn=1, $M = 1.68$).

Emotional Impact. Participants' subjective emotional impact was, on average, relatively low (Mdn=1, $M = 1.32$, $SD = 1.17$), with responses ranging between Slight (1) and Moderate (2) on the provided Likert scale. We found no significant main effect or interaction between the Drone's digital facial emotions and Gaze behavior. However, there was a significant effect of Gaze behavior when focusing on the Anger expression ($F(1,24) = 6.78$, $p = 0.016$, $p<0.05$). Participants perceived a significantly greater emotional impact when the drone followed them with its eyes (Mdn=2, M=1.64) compared to when it avoided eye contact (Mdn=1, M=1.16) while displaying an Anger expression.

Finding 4 – Negative emotions, particularly expressions of Anger, resulted in significantly higher participant concern. Additionally, Anger had a greater emotional impact when the drone maintained eye contact compared to averting its gaze.

4.4.3 ***Empathy.*** To gauge participants' empathy toward the drone, they rated how much they shared the drone's emotions. On average, participants reported relatively low levels of empathy, with responses averaging around "Slight" (1) empathy (Mdn=1, $M = 0.99$, $SD = 1.11$). We observed a significant effect of the Drone's digital facial emotions on participants' empathy ($F(2,120) = 4.15$, $p = 0.018$). Specifically, the Joy expression (Mdn=1, $M = 1.24$) led to significantly higher shared emotions compared to the Anger expression (Mdn=1, $M = 0.78$, $p = 0.021$, $p<0.05$), although the difference compared to the Sad expression (Mdn=.5, $M = 0.94$, $p = 0.07$) was not significant. Furthermore, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average empathy in the Avert gaze condition (Mdn=1, $M = 1.1$) compared to the Follow condition (Mdn=1, $M = 0.92$).

Finding 5 – Joy elicited significantly more empathy compared to Anger.

4.4.4 ***Self-Relevance.*** To gauge the self-relevance of the displayed cues for participants, they indicated their agreement to the statement "The drone's expression showed how it felt about you." On average, participants reported relatively low levels of agreement, with responses ranging between Neutral (2) and Disagree (1) (Mdn=2, $M = 1.88$, $SD = 0.84$). We observed a significant effect of the drone's digital facial emotions ($F(2,120) = 4.76$, $p = 0.01$), with Sad expressions being significantly less likely to be perceived as indicative of the drone's feelings toward the participant (Mdn=1.5, $M = 1.40$) when compared to Anger (Mdn=2, $M = 1.86$, $p = 0.0198$, $p<0.05$) and Joy (Mdn=2, $M = 1.82$, $p = 0.0227$, $p<0.05$).

Furthermore, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average agreement in the Follow gaze condition (Mdn=2, M = 1.73) compared to the Avert condition (Mdn=2, M = 1.65).

As a follow-up question, participants were asked whether the drone's expression was more likely due to something in the environment. Again, their responses ranged between Disagree (1) and Neutral (2) (Mdn=2, M= 1.88, SD = 0.84). We haven't found any effect or interaction of digital facial emotions or Gaze Behavior.

Finding 6 – The Sad expression significantly conveyed less about how the drone felt toward individuals compared to expressions of Joy and Anger.

4.4.5 ***Direction of the Drone's State.*** We examined whether participants believed that the drone's state signaled a potential future action or intent, rather than being a consequence of a past event. On average, participants' responses ranged from "Disagree" to "Neutral" for both Anger (Mdn=2, M = 1.7, SD = 1.13) and Sad (Mdn=1, M = 1.42, SD = 1.09), and from "Neutral" (2) to "Agree" (3) for Joy (Mdn=2, M = 2.20, SD = 1.12). A significant effect of the drone's digital facial emotions emerged ($F(2,120) = 10.46$, $p = 6.51e-05$, $p< 0.001$), with Joy being significantly more associated with intent compared to Anger ($p = 0.0097$, $p< 0.001$) and Sad ($p = 4.41e-05$, $p< 0.001$). Furthermore, there was no significant effect of the Drone's Gaze or any interaction effect, despite a slightly higher average agreement in the Follow gaze condition (Mdn=2, M = 1.81) compared to the Avert condition (Mdn=2, M = 1.73).

Finding 7 – Joy exhibits a significantly stronger association with the intent of future actions compared to Anger and Sadness.

5 DISCUSSION

5.1 Social Proxemic Function in HDI

In the realm of Human–Drone Interaction, understanding how individuals manage their spatial relationships with respect to drones is paramount for the successful integration of drones into human social spaces. While social mechanisms have been identified as significant drivers of proxemic behaviors in people's interactions with ground humanoid robots [59], it cannot be assumed that the same principles automatically apply to HDI [2, 32]. Existing research tends to cast doubt on the role of the social proxemic function in HDI, with some researchers attributing this limited role to the highly mechanized nature of drones, which may hinder the establishment of social perceptions [17, 54]. Our study delved into this topic by investigating proxemic behaviors when interacting with a drone that displays social cues in the form of a digital face with different emotional expressions and gaze behavior.

Role of the Social Function. Our research explored the influence of social cues, primarily the drone's gaze, on individuals' proxemic behavior. Participants consistently maintained a significantly greater distance from the drone when it made eye contact, as opposed to when it averted its gaze. This phenomenon mirrors behaviors observed in both human–human interactions [3, 7, 8] and HRI [59], suggesting a certain degree of transferability of proxemic norms from these contexts to HDI. One possible explanation for this, in line with findings by Mumm et al. (2011) regarding ground robots, is the equilibrium model of proxemics [4, 7]. This model posits that individuals regulate intimacy through physical distance: as increased eye contact leads to greater perceived intimacy, it triggers a distancing response to maintain a comfortable level of closeness, while reduced eye contact can conversely prompt individuals to approach.

Another possible explanation lies in the functional role of gaze in communication, as it provides feedback on the other party's attention and reactions [7]. If individuals perceive the drone is actively paying attention to them via eye contact, they may feel no need to approach further. However, when the drone averts its gaze, participants might be compelled to get closer until they gain the drone's attention, much like in human interactions where people move closer to establish a connection through shared gaze. When proxemic behaviors are viewed as goal-oriented, participants may interpret the drone's gaze as sufficient confirmation that it is aware of them, maintaining their distance to perform their task. In contrast, when eye contact is absent, they may believe they need to reduce the distance to ensure the drone receives their intended communication. This highlights the potential for drones to use gaze cues to signal attention, a concept worth exploring in future research.

Despite the low subjective significance and reported influence of the drone's digital facial emotions, our study revealed a statistically significant impact of these expressions on proxemic behaviors, particularly within specific participant subgroups. Interestingly, expressions of anger led to greater distancing, followed by joy and sadness. These patterns align with observations in human–human interactions [65, 70] and HRI [11]. Anger expressions tend to evoke avoidance behaviors, joy expressions encourage approach behaviors, and sadness lead to a combination of automatic approach tendencies with conscious withdrawal [70]. Notably, the impact of digital emotional faces was most pronounced among two specific groups: individuals with positive or neutral attitudes toward robots and those with limited to no prior experience with drones. This highlights the nuanced nature of proxemic behaviors and their sensitivity to individual differences and past experiences, which we explore further below (see subsection 5.2).

Moreover, the discrepancy between the subjective perceptions of the influence of social cues and the actual behavioral observations underscores the significance of studying HDI beyond surveys. As suggested by Seidel et al. (2010), initial automatic responses to social visual stimuli may be followed by a more conscious and complex re-evaluation, influenced by factors like familiarity with the entity and personality traits [70]. This differentiation between controlled and automatic processes in interpersonal behavior offers valuable insights into the mechanisms of social interaction in HDI.

Context-Dependent Significance. The drone's gaze behavior and digital facial emotions significantly influenced the spatial dynamics of the interaction, suggesting a social proxemic function in specific contexts. This effect is particularly evident in the drone's front zone, where participants initially engage in conversation. However, as focus shifts to task-oriented actions, like retrieving information from behind the drone, its role changes from a social entity to an obstacle. Notably, within the front zone, we found a significant positive correlation between distance maintained and participants' anxiety regarding conversing with the drone, which disappears in the back zone. This shift indicates a change in participants' mindset from social engagement to navigation. Additionally, negative attitudes toward drone emotions impacted proxemic behaviors only in the front zones, suggesting a distancing response triggered by visible emotional displays, which fades when the displays are no longer seen. These findings highlight the dynamic, context-dependent nature of proxemic behaviors and deepen our understanding of HDI in social settings.

In summary, our research sheds light on the social proxemic function in HDI, unveiling its existence and its sensitivity to contextual shifts and individual differences. It shows a potential for drones to tailor their design and behavior to suit specific individuals and situations. To leverage these insights, designers should consider creating drones that can adapt their social cues based on the interaction context. For example, drones could utilize more expressive emotional displays during social engagement while minimizing these cues during task-oriented activities. Furthermore, user-customizable settings for emotional expression could allow individuals to adjust the drone's behavior to match their comfort levels and preferences (e.g. amount of eye-contact), ultimately fostering a more personalized interaction experience.

5.2 Attitudes and Framing in Human–Drone Interaction

Our study of specific participant subgroups reveals how unique interpretations of social cues affect proxemic behaviors. Individuals with open and accepting attitudes toward human–drone interactions are more responsive to a drone's emotional cues. Their positive disposition enhances their receptiveness to these signals. Consistent with prior research, which identified the Negative Attitude Toward Robots Scale (NARS) as a predictor of reactions to drones [10], we found that participants with greater reluctance toward drones maintained closer distances when navigating around them. Their resistance to the drone's social influence likely framed the drone as an object rather than a social agent, impacting their proxemic behaviors—similar to how people might maintain closer distances to mannequins than to actual individuals. Future research should explore the relationship between negative attitudes toward robots (as measured by NARS or other methods) and individuals' interpretation of robots' social cues.

Our findings also highlight the influence of participants' prior exposure to similar technologies. Individuals with limited familiarity with drones exhibited greater sensitivity to emotional cues. This observation underscores the importance of "framing" in interpreting cues during HRI [17, 26, 27, 47]. Framing refers to the mental framework through which individuals interpret their interactions with drones. Without a clear reference for interpreting cues, individuals often rely on previous experiences and beliefs [36]. Experienced drone users, accustomed to viewing drones as technical devices, are likely to interpret their interactions as primarily technical, perceiving the drone's cues as functional rather than social. Conversely, those with less experience may frame their interactions with drones similarly to human interactions, interpreting cues as social signals based on their prior experiences with emotional facial expressions. This observation carries significant implications for the design and implementation of drones in various contexts. It suggests that when developing drones for users who are either open to robot interactions or relatively new to drone technology (e.g., children, the elder), the incorporation of expressive facial features can be a valuable component. Such features might enhance the interaction experience and foster more positive attitudes and engagement.

5.3 Stimulus Significance

On the whole, participants did not establish a strong connection between the drone's expressions and what the drone thought of them or their surrounding environment. The consistently low ratings on various Likert scales suggest that participants may have perceived the drone's expressions as relatively context-neutral and abstract, lacking specific relevance to the interaction context. As outlined by Bradley (2009), detecting stimulus change does not always elicit significant responses, and the task-relevance of the stimulus, referred to as its "significance", affects the magnitude of the response [12]. While participants easily recognized these expressions, the ability of these cues to convey nuanced emotional content or context-specific messages seemed limited. This contrasts with findings from Herdel et al. (2021), where individuals interpreted the drone's emotions beyond mere recognition, creating narratives around the drone's state [46]. This indicates that the interpretation of cues is sensitive to the context in which they are presented, highlighting the importance of context for the transferability of studies examining the impact of drones' social cues.

Beyond the relevance of the displayed social behaviors, it is important to recognize that the context in which these behaviors occur can lead to varied interpretations and reactions. As we strive to integrate these social cues to improve interactions in practical applications, future research should investigate how the context surrounding these cues shapes their significance, influences their interpretation, and ultimately affects individuals' behavioral responses.

5.4 Virtual Reality of HDI Research

In our study, we employed Virtual Reality (VR) as an experimental platform to observe participants' natural behaviors within an immersive, safe, and replicable environment during interactions with an innovative drone design. VR has become an established tool for similar research purposes, with an increasing volume of data and theoretically-grounded studies that enable researchers to gain confidence in their findings and better anticipate the limitations of their results.

Transformed Interaction. Compared to previous virtual studies investigating human–drone proxemics, our work embraces the full potential that VR offers and present a transformed interaction rather than true-to-life simulation [66]. Indeed, both the drone's sound and airflow can elicit physiological excitement and, according to the arousal regulation proxemic function [37, 64], may cause individuals to distance themselves from the drone, influencing our results. While minimizing sound and excluding airflow limit the generalizability of our findings (given that these elements are typically integral to current drone designs and influence proxemics [18, 37]), they also allow for the observation of subtle social adaptations that might be obscured by proxemic responses to these stimuli. VR effectively removes uncontrollable aspects present in real-world settings, creating a unique but close to real experience. Although this may hinder the transferability of findings, acknowledging these limitations ensures transparency and allows for external evaluation of the findings' applicability, while also offering insights relevant to the design of future drone technologies. Nonetheless, this work would benefit from replication in real-world settings to assess its transferability and to gain a deeper understanding of how sound and airflow can influence a drone's social impact on users.

Innovative Design. Furthermore, we introduced an innovative drone design, which, while feasible in real-world settings, has been demonstrated as presenting challenges (e.g., flight stability), as observed in similar attempts [81]. This study not only contributes valuable insights to our understanding of human–drone interaction within VR but also lays a solid foundation for future investigations in the field that seek to harness VR for similar purposes.

Unexpected Effects. Despite efforts to minimize behavior alterations in VR, a significant factor emerged: participants with prior VR experience approached the drone more closely than those without. This suggests that individual characteristics notably influence proxemic behaviors. Possible explanations include a greater comfort level with advanced technology or enhanced motor capabilities. Previous studies indicate that less capable individuals tend to maintain greater distances [6, 39]. Although all participants had equal opportunities to navigate the virtual environment, inexperienced users may have felt hesitant to move freely, possibly fearing collisions with virtual objects. In contrast, experienced users likely had a clearer understanding of VR's capabilities, fostering greater confidence in their navigation. While addressing these subjective perceptions is complex, future research should investigate the factors influencing individuals' perceived ability to navigate virtual environments.

6 CONCLUSION

In summary, our research has highlighted important consequences of social cues on the spatial dynamics of Human–Drone Interactions. Drones, characterized by their mechanical and task-oriented nature and operating in the air, present a unique challenge in seamlessly integrating into social contexts. The transformative potential of social cues for increasing these machines' social acceptance is only just beginning to be explored. Leveraging the flexibility of Virtual Reality (VR), our study has created a controlled and adaptable environment where 25 participants engaged with drones displaying a range of facial expressions and gaze behaviors.

Our study represents a significant contribution to the field of Social Drones and human–drone interactions, with a specific emphasis on the social proxemic function. Within our VR environment, participants exhibited behaviors that resonated with established Human to Human interaction norms. They maintained greater distances when the drone made eye contact and approached closer when the drone averted its gaze, thereby revealing the existence of a social proxemic function in HDI. Additionally, the drone's facial emotion display generated different proxemic responses from participants, with Anger leading to greater distancing, followed by Joy and Sadness. These patterns align with observations in Human–Human and Human–Robot interactions. Nontheless, the impact of emotional facial expressions was only significant among two specific participant groups: individuals with positive or neutral attitudes toward robots and those with limited to no prior experience with drones. This emphasizes the sensitivity of proxemic behaviors to individual differences and past experiences.

Additionally, it is crucial to acknowledge the study's limitations. While conducted within a controlled VR environment, the observed behaviors may not fully represent real-world scenarios. The influence of individuals' VR experience on their subsequent behaviors remains to be investigated. Furthermore, participants' subjective ratings suggest that they perceived the drone's expressions as relatively context-neutral and abstract, lacking specific relevance to the interaction context. Although our study observed automatic behavioral responses to these cues, it is essential to explore the more conscious and nuanced interpretation, as it holds potential for conveying meaningful messages. Hence, further research could delve into the contextual significance of these social cues, providing a better understanding of their practical uses and relevance in real-world human–drone interactions.

In conclusion, our work reveals factors influencing the social proxemic function during HDI. It offers valuable insights into the impact of the drones' gaze and emotional face during Human–Drone Interactions, emphasizing the role of individual participant characteristics, attitudes, and past experiences in shaping people's proxemic behaviors in relation to the drone. As we navigate the evolving era of autonomous drones, understanding and refining the role of social cues to foster harmonious coexistence between drones and humans is crucial.

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