"Do I Run Away?": Proximity, Stress and Discomfort in Human-Drone Interaction in Real and Virtual Environments

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Abstract. Social drones are autonomous flying machines designed to operate in inhabited environments. Yet, little is known about how their proximity might impact people's well-being. This knowledge is critical as drones are often perceived as potential threats due to their design (e.g., visible propellers, unpleasant noise) and capabilities (e.g., moving at high speed, surveillance). In parallel, Virtual Reality (VR) is a promising tool to study human–drone interactions. However, important questions remain as to whether VR is ecologically valid for exploring human–drone interactions. Here, we present a between-within subjects user study (N=42) showing that participants' stress significantly differs between different drone states and locations. They felt more comfortable when the drone retreated from their personal space. Discomfort and stress were strongly correlated with the perceived drone's threat level. Similar findings were found across real and virtual environments. We demonstrate that drones' behaviour and proximity can threaten peoples' well-being and comfort, and propose evidence-based guidelines to mitigate these impacts.

Keywords: Proxemics · Social Drones · Virtual Reality

1 Introduction

Increasing interest in drones as well as technological progress within the fields of artificial intelligence and sensors foreshadow the impending advent of social drones. Designed to help people in their everyday life and increase well-being, these autonomous flying machines [8] might soon become users' favorite running partner [7], security guard [49] or even emotional support device [42]. But behind this radiant future hides the problematic fact that current drones are often perceived as potential physical and privacy-related threats [20]. Beyond the requirement for drones to be trusted to integrate them into society [61], it is important to explore and understand the kinds of negative impacts that drone interactions might have on people. If peoples' encounters with drones cause perceived emotional, physical, or privacy-related threats, then further integration of drones into social spaces might generate stressful environments and trigger defensive behaviors among people (e.g., maintain greater distances [27,87], attack [12]).

Developing a fuller understanding of the reasoning behind people's reactions near drones (Human–Drone Proxemics (HDP)) is therefore critical. Investigating HDP will unlock interaction opportunities relying on closeness (e.g., touch [1,53], body landing [4]), while facilitating the design of proxemic-aware social drones [37]. Like humans in our everyday life, such social drones could accurately adapt their behaviors and design to specific users (e.g., visually impaired [5], children [34]), environments (e.g., public spaces [85], homes [48,9]), context [44] and applications [43]. Thus, this fuller understanding HDI contributes to the development of human-friendly and socially acceptable social drones.

Nevertheless, the potential danger that drones' proximity to humans represents, as well as the practical and legal limitations of these machines, have hindered HDP research to date. To overcome these difficulties, a promising approach is the use of Virtual reality (VR) as a proxy for real-world HDP experiments [91]. While VR has many advantages compared to real-world HDI studies (e.g., safety, replicability), it remains unclear the extent to which a virtual environment might alter underlying proxemic mechanisms and resulting participants' preferences and reactions during human–drone interactions. As such, understanding the extent to which virtual drone interactions approximate real interactions with social drones represents another valuable research question to address.

We present a user study (N=42) aiming to understand 1) the impact of drones' presence and proximity on people's well-being and 2) the extent to which VR alters the results of human–drone proxemic experiments. In a real-world environment and its virtual replica, and for two drone's speed conditions (1 m/s, 0.25m/s), we compared participants' perceived stress in a resting baseline and in different flying phases (static far, approach, static close). We then measured their discomfort level and preferences for different drone's locations. After each speed condition, participants rated how threatening they thought the drone was.

We found that participants' perceived stress significantly differs between different drone states and locations. Drones moving away from participants' personal space induced significant decrease in discomfort. Both discomfort and stress were strongly positively correlated with the perceived drone's threat level. Similar results were discovered in both real and virtual environments, indicating that VR findings can be transferred to the real world. Semi-structured interviews uncovered many factors of threat perception like sound, unpredictability, propellers, camera, proximity, and movements. This study highlights that drones readily threaten peoples' well-being and thus calls into question the readiness of these machines for deployment into social spheres. We nonetheless propose potential guidelines for future work to explore to help bring safe, trusted, and reliable social drones closer to reality.

Contribution Statement This work contributes to the human–drone interaction field with: **1)** A theoretically grounded user study (N=42) that advances our comprehension of people's perceptions and behaviours near drones. We propose guidelines for designers to reduce the perceived threat and increase acceptability of drones operating in close proximity to humans. **2)** The first VR/real-world comparison in HDI that helps understand the transferability of VR findings' to the real world and unveils key considerations for the use of VR to study human–drone proxemics.

2 Related Work

2.1 Proxemic

Function Specific Spaces In 1966, Edward T. Hall described a "series of bubbles or irregularly shaped balloons that serves at maintaining proper spacing between individuals" and coined the term proxemic for these phenomenons [39]. He proposed four zones of high social relevance (intimate, personal, social, and public). Yet as pointed out by Vignemont and Iannetti [87], other "bubbles" exist, and they serve distinct functions [87,3]. Each of these "carrier mechanisms" [41] of people's space management might impact human–drone proxemics [15], or, how close people are comfortable with drones operating near them. Leichtmann emphasizes this point in his meta-analysis of proxemics in human–robot interaction [50], and encourages researchers to discuss the most relevant frameworks to consider given the context of their experiment. Assuming a drone's encounter results in perceived emotional, physical, or privacy-related threats, we consider the proxemic protective function can be a major determinant of people's proxemic behaviours.

Defensive Space Dosey and Meisels (1969) described personal space as a "buffer zone" to serve as protection against perceived emotional, physical, or privacy-related threats [27,3]. Similarly, another space-related concept, peripersonal space (PPS; defined as reaching space around the body) is associated with a "safety margin" [73] around the body. PPS is very flexible [55] and its representation relies on individual-specific integration of salient sensory inputs in a given situation. Orientation of threatening objects [21], their approach [16,86], acute stress [29] and personality (e.g., anxiety [73,82]) are known factors of PPS. Other theories related to defensive behaviours and stressful encounters describe the detection, proximity and intensity of a perceived threat as triggering specific behaviours (Risk Assessment [12,11] and Cognitive appraisal [14,32]). Unlike previous Human–Drone proxemic studies, we will build on these theories to drive the explanation of our results.

2.2 Human–Drone Proxemics

Proxemics has been identified as a critical design concern for social drones [8]. Wojciechowska et al. [91] showed that participants' preferred a straight front moderately fast (0.5m/s) approach, with a drone stopping in the personal space (1.2m). Yet they did not report on whether drone's approaches affected individuals' stress level or threat perception. Reflecting on people's reactions to drone collision, Zhu et al. [93] found that the drone's unpredictability, propeller sound and degree of protection all influenced perceived threat in a crashing situation. They mentioned that less threatened participants were more comfortable with closer drone distances. Whether threat has been induced by the crashing situation or the drone per se remains unclear. Their results are therefore limited in that they investigate participant's perception during a crashing situation and cannot be generalized to more common interactions and drone's behaviours. [1] showed that a safe-to-touch drone induced significantly closer distance and more engaging interactions compared to a control drone. While it shows that the drone's design impact user's overall perception and safety feeling, it doesn't say much about how the drone's behaviour dynamically affect people. Auda et al. [4] report safety as a main participant's concern for drone body landing. Contrarily, exploring natural human–drone interactions, Cauchard et al. [18] report few safety concerns amongst participants. They found the drone's noise and wind are linked to the participants' discomfort level and longer preferred distances from the drone. In light of these results, it remains unclear whether perceived threat or other components (drone's sound, wind) are responsible for people preferred distances and discomfort. Our work aims to deconstruct this phenomenon by providing a theoretically informed and focused contribution on the impact of drone's presence, approach and proximity on individuals' stress, discomfort and threat perception. We investigate whether dynamic variables that determine the drone's behaviours can greatly affect participant's well-being using a child-friendly consumer drone.

While a growing body of literature has begun to examine human factors during human–drone collocated interactions, some researchers [15,52,28] have pointed out the potential impact of safety techniques on peoples' reactions near drones (e.g., minimum distance [2,28,40], transparent wall [40], fixed drone [28,92], or fake drone [20]). In parallel, Virtual reality is a relatively novel yet promising approach for the HDI field. It is safe, reproducible, and moderately realistic [91]. It has been used to investigate human drone proxemics for co-existing context [15], body landing [4], path planning algorithm for in-home monitoring [9] and novel drones' shapes [17]. Yet, VR benefits are valuable only if we understand how and why obtained results are transferable to the real world. In particular, we wonder whether a virtual drone can affect people in a similar way as a real one, in terms of induced stress, threat and discomfort. For this, our work evaluates a direct comparison between VR and real-world environments during a human–drone interaction.

2.3 Virtual Reality as a Methodological Tool

Virtual Reality (VR) as a research methodology draws researchers' attention for years. In 1999, Loomis et al. [54] introduced VR as a promising solution to the issues of its field. It would "eliminate the trade-off between mundane realism and experimental control, [...] target population more representatively and reduce the difficulty of replication" [13]. Since then, virtual environments have been extensively used in Social Psychology [71], in Human–Computer Interaction (HCI) [57,60,23] or Human–Robot Interaction (HRI) [72,90]. It remains that these benefits rely on the ability of VR to induce natural participants' reactions to the stimuli of interest. It has been shown that VR can reproduce stressful situations and instinctive defensive reactions [69,70,6], but participants will react differently based on their immersion (i.e., Place and plausibility illusion [79], Presence [24] and Embodiment [88,33]). As it varies between individuals [25,64], immersion is hard to predict but can be measured [75,66,77]. Comparing proxemic preferences and impressions of a humanoid ground robot between a real and virtual environment, Kamid et al. [47] did not find significant differences in terms of desired space despite different subjective impressions. Conversely, Li et al. [51] found inconsistent proxemic preferences between Live and VR ground robots but no major changes between different VR settings. These mixed results and the lack of theory-driven explanations leaves a gap of uncertainty regarding the validity of VR for Human–Robot proxemic experiments. In addition, drones are drastically different from ground robots. As suggested by a previous direct comparison [2], the driven mechanisms of people proxemic may be different between ground and flying robots, involving different considerations for the use of VR for proxemic experiments. Therefore, we conducted a comparison between virtual reality (VR) and real-world scenarios in the context of human-drone interaction (HDI) to gain insights into how VR findings can be applied in the real world, and to identify important factors to consider when using VR to study HDI.

3 Methodology

This study aims to investigate 1) the impact of drones' presence and proximity on people's well-being and 2) the extent to which VR alters the results of human–drone proxemic experiments. To that end, we compared participants' perceived stress between a resting baseline and different flying conditions (static far, approach, and static close) for two drone speed conditions (1 m/s, 0.25m/s). Participants perceived drone's threat level is assessed after each speed condition. This way, we can identify whether a flying drone induces any perceived stress and if its state (approaching, static), proximity (close, far), and speed can modulate it. It also allows for investigating the association between the stress induced by the drone and its threat level. Participants then performed a modified stop-distancing procedure (see subsection 3.2). We asked the participants to rate their level of discomfort and how ideal the current drone position was for different locations (from 40 cm to 450cm from the participant). This allows understanding participants' proxemic preferences and thereby mapping how discomfort varies with the distance. Although the intimate zone margin [39] is 0.45, we chose to position the drone within that range rather than at its border. For this, we opted for a slightly closer distance (0.4m). Finally, participants are divided into two groups: one experiences a real-world setting and the other its virtual replica. We investigate the impact of the environment on perceived stress, discomfort, and distance ratings. We also statistically evaluate each environment to check whether we obtain similar findings.

3.1 Experimental Design and Hypotheses

This study consists of a block (A) investigating the impact of different HDI situations on participants' perceived stress and its relationship with the perceived drone's threat level, and a block (B) assessing proxemic preferences in a modified stop-distancing procedure. Both blocks (A then B) are performed twice, one time for each speed condition (1 m/s or 0.25m/s), either in a real or virtual environment. Block B investigates the participant's perception towards the stopping distance after the drone has approached at a certain speed. The participant observes the drone's speed in block A. Thus, block A must come before B.

*Block **(A)*** follows a 2x2x4 mixed split-plot design with the *Environment* as a two-level (Real, VR) between-participant factor, the drone's *Speed* as a two-level (1 m/s, 0.25 m/s) within-participant factor, and the *Phase* as a four-level within-participant factor (Baseline, Static Far, Approach, Static Close). The dependent variable is the self-reported stress for each phase for each condition. The drone's threat level is assessed for each condition. If the drone is perceived as a potential threat, the participant's perceived stress should evolve as the situational threat changes from a static distant threat, to an approaching (looming) threat, to a static close threat. We, therefore, expect **H0** participants' perceived stress to be significantly different between the different phases, with the approach being the most stressful due to the danger ambiguity [12] (unknown stop distance) and the instinctive response to looming objects [86], followed by the close static threat (within PPS), the distant static threat and finally the resting baseline. Looming objects (i.e., approaching) trigger specific defensive responses that can be modulated by the threat the object represents and its approach speed [86]. We, therefore, expect **H1:** the perceived stress to be significantly higher when approaching at 1 m/s compared to 0.25 m/s and **H2:** the reported participant threat to be positively associated with the perceived stress. **H3:** We expect the previous hypothesis to be verified in both environments but considering the reduced danger that the drone represents in VR, we expect the perceived stress to be significantly lower in the virtual environment compared to in the real world.

*Block **(B)*** follows a 2x2x6 mixed split-plot design with as input variables the *Speed*, *Environment* and the six-level within-participant variable *Stop_ distance* (C0: Intimate Space (40cm), C1: 83cm, C2: Personal Space (120cm), C3: 240cm, C4: Social Space (360cm), C5: 450cm). The stop distance starts near the intimate space's frontier (where the drone stops its approach) and then reaches half of the personal space, its frontier, half of the social space, its frontier, and finally the maximum distance allowed by the experimental setting which is within the public space. Hall's framework [39] is extensively used in human–drone proxemics [52,91,40], using these scales allows other researchers to more easily compare their results with ours. We aim to map people's personal space via the measure of their discomfort level and distance ratings (too close or too far from their ideal distance). **H4:** We expect the discomfort level to be significantly higher at the intimate frontier (PPS) compared to the other conditions. **H5:** the discomfort level to be positively associated with the perceived threat level. The speed conditions' order was randomized using a Latin square.

3.2 Measures

Self-Reported Stress For each phase, participants verbally indicated their perceived stress on a scale from 0 (no stress at all) – 5 (moderate stress) – to 10 (extreme stress). This was validated in [76].

Threat Level After each speed condition, participants rated how threatening they think the drone was on a scale from 0 (not threatening at all) – 5 (moderately threatening) – to 10 (extremely threatening).

Stop Distance and Discomfort Ratings After each condition, we performed a distancing procedure. Initially located at the intimate's frontier, the drone moved back 5 times. Considering Hall's framework [39], the drone stop-positions corresponded to the intimate space (40 cm), half of the personal space (83 cm), personal space limit (120 cm), half of the social space (240 cm), social space limit (360 cm), and in the public space (max distance of 450 cm). For each stop position, we asked "How ideal is the drone stop position, from -100 (Too close) to 0 (ideal stop distance) to 100 (Too far)? A negative number means you consider the drone stopped too close to you and the higher the number is the more intense you feel about it. Conversely, a positive number means you think it is too far. A rating close to zero means you think the drone is not far from what you consider its ideal stop position." In addition, they must verbally estimate their level of discomfort. The experimenter asked "How much do you rate your level of discomfort on a scale from 0 (no discomfort at all), to 100 (maximum discomfort)? 50 is moderate discomfort. The higher you rate, the more discomfort you feel." A similar rating has already been used in previous experiments [89].

Questionnaires Before the experiment, participants responded to a demographics questionnaire (age, gender, prior experience with drones and virtual reality, reluctance about drones' safety), Big Five Inventory (BFI) – 10 (measures the participants' five personality dimensions of extraversion, agreeableness, conscientiousness, neuroticism, openness) [68], the Fear of pain questionnaire (FPQ) – 9 (measures the fear and anxiety associated with pain) [58], and the STAI (State-Trait Anxiety Inventory) [83]. Each of the questionnaires is used to assess potential confounding factors. Trait anxiety, personality (neuroticism), fear of pain has been shown to impact the size of the defensive distances [73,67,82] or the risks that a situation represents [38]. Questionnaires have been created on FormR and were answered online before the experiment on the experimenter's computer in the lab. Participants in the VR group additionally answered the Igroup Presence Questionnaire (presence assessment) [75], Avatar Embodiment Questionnaire [66], and a plausibility questionnaire [77].

Semi-directed Interview Post-experiment semi-directed interviews were then conducted focusing on threat perception, coping or defensive strategy, and VR. We used an affinity diagram [56] to find patterns and themes in participants' responses. To develop the insights, we transcribed the interviews, and categorized responses by first-degree similarity (e.g., same drone's component, virtual environment characteristics or behaviours), then regrouped responses by concept (e.g., safety, appeal, annoyance).

3.3 Setup and Apparatus

Drone Programming For the real-world condition, we programmed a DJI Tello (98 x 92.5 x 41 mm) on Python using the DJI Tello SDK. Connected by Wi-Fi to

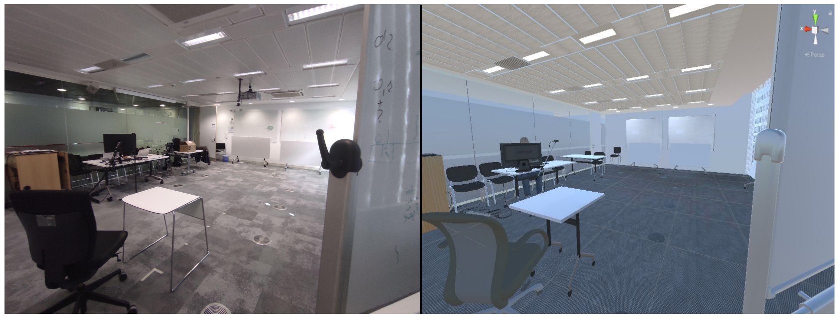

Fig. 1. Experimental Room (left) and its replica created in Unity 3D (right)

the experimenter's computer, the drone executes the commands such as taking off and moving forward for X distance at Y speed allowing us to accurately predict its stop distance. The drone's accuracy relies on optical flow. We optimized the environment by ensuring suitable lighting and using the drone manufacturer's mission pads which serve as identifiable surface patterns that guide the drone. Relying on this accuracy and fixing the initial participant-drone distance (450cm), we can move the drone to a specific proxemic area (e.g., personal space - 120cm, intimate space - 40cm). The experimenter manually set the drone's height to match the eye level per participant. The drone is partially autonomous in that it follows a pre-programmed algorithm but the experimenter still has control via the computer. The DJI Tello has been used in recent HDI experiments [36,35].

Virtual Environment The virtual experiment was created with Unity 3D and consists of a replica of the real setting as it has been done in a previous virtual HDP experiment [15]. We aimed to accurately reproduce the main elements of the real environments to increase the presence [78,81] and foster natural participant's reaction [79,80]. Distances, drone's characteristics (appearance, sound, and behavior), room's dimensions and arrangement, and avatars' position (participant and experimenter) have also been carefully reproduced to limit the alteration of potential confounding factors in participants' evaluation of the situation (risk assessment [12] or cognitive appraisal [32]). The spatial audio we used relies on a high-quality drone recording, and the size replicate the real drone's size. We animated the virtual drone to show the rotating propellers, and imitate hovering imperfections (e.g., shakes).

3.4 Participants

We recruited 42 participants (17 male, 24 female, and one non-binary), mainly undergraduate and post-graduate students from scientific backgrounds (Computing Science, Psychology, Veterinary), between 21 to 42 years old (M=26.69, SD=4.98) and with little experience with drones or VR and mainly from Europe (35%) and Asia/Pacific (43%). We randomly assigned each participant to one of the two groups (Real-world/VR), trying to maximize the gender parity and reach a similar size.

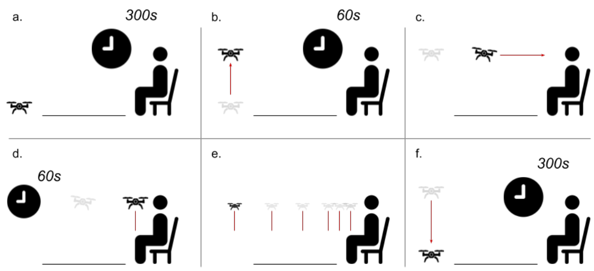

Fig. 2. Overview of the protocol. a) Resting baseline (300s): The drone is on the ground at 450cm from the participant. b) The drone takes off and remains stationary for 60s. c) "Face detection approach": the drone approaches the participant at the target speed condition (0.25 or 1 m/s) and stops at the intimate frontier (40cm). d) Static Close: It stays in front of the participant for 60s. e) Distancing procedure: Stop distance and discomfort ratings for 6 predefined drone positions. f) Resting period: The drone lands and rests for 300s. Then the protocol resets to step b for the second speed condition.

3.5 Protocol

After welcoming the participant to the experimental room, we invited them to fill in the consent form and read the participant protocol. The protocol stated we wish to test a feature of our autonomous drone called the "face-detection approach" and study how people feel about it. They were told the drone will move toward them two times and stop once it detects their face, but did not know the stop distance. We additionally warned them that malfunctioning can happen. They were allowed to move away if they thought they had to or if we asked them to avoid the drone. The VR group wore the Oculus Quest 2 and was immersed in a replica of the experimental room. The rest of the experiment was similar for both groups (see Figure 2). Participants were asked to rate their stress level (0-no stress at all to 10-maximum stress) during each phase and how threatening the drone was (0-not threatening at all to 10-extremely threatening) after each condition. After the experiment, the VR group answered VR-related questionnaires (IPQ [75], Plausibility questionnaire [77], AEQ [66]). We finally performed a semi-directed interview aiming to better understand the process through which they rated their stress and threat level. The VR group shared their impression of the virtual environment while the real-world group described what would be important to make them feel and behave the same if the experiment was performed in VR. We also explored their behaviours in the case of a malfunctioning drone or a similar situation outside of the experimental context.

3.6 Limitations

While this study provides valuable and novel insights into HDI proxemics and people's well being around drones, the generalizability of its results is limited in that they have been obtained in a given context (indoor, sitting on a chair, in presence of the experimenter) for a specific task (face detection approach) and drone and they might significantly differ from other settings. Moreover, while self-reported stress measures are widely used and valuable indicators, they provide only limited information on physiological stress reactivity and biological outcomes compared to measures such as heart rate and skin conductance, and participants may be hesitant or unable to accurately report their true stress levels. Another issue is that the drone slightly moved in the real environment condition due to limitations in hardware and the sensors responsible for balancing the drone. This may have had an impact on participants. This is not an issue in VR, though, as the drone's movements were fully controlled.

4 Results

The subsequent section presents a detailed analysis of the results and statistical tests. Summary tables, which include a direct comparison between real-world and VR measures, can be found in the appendix (see section A).

4.1 Perceived Stress

The study showed that the different phases of the drone's flight had a significant effect on participants' perceived stress, with the Approach phase being the most stressful. However, there was no significant difference in stress levels between fast (1m/s) and slow (0.25m/s) approaches. Additionally, the study found that participants' perceived threat was found to be strongly correlated with their perceived stress. These findings were consistent in both the real and virtual environments, with no statistically significant difference between them.

Phase *(Significant)* A Friedman test was run for each Environment group to determine if there were differences in perceived stress between Phases. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons. There was a statistically significant impact of the phases on perceived stress, in the real ($\chi^2(4)=51.14$, $p < .0001$) and virtual environment ($\chi^2(4)=53.07$, $p < .0001$). In VR, post hoc analysis revealed statistically significant differences in perceived stress between the Baseline (Md = 1.17) and the other phases except the resting period (Static Far [Md=1.89 , p=0.025], Approach [Md=4.5, p=0.003], Static Close [Md=4.14, p=0.005]). The Approach was also significantly different than the Static Far (p=0.028), and the Resting (p=0.003) and the Static Close significantly differed from the Static Far (p=0.044) and the Resting (p=0.003). In the real environment, the perceived stress was statistically significantly different between the Approach (Md= 4.37) and each of the other phases (Baseline [Md=1.35,p=0.0009], Static Far [Md=1.89, p=0.0006], Static Close [Md=3.39, p=0.028], Resting [Md=1.52, p=0.0006]. The Static Close was also significantly different than the Resting (p=0.015).

Speed *(No statistically significant difference)* A Wilcoxon signed-rank test was conducted for each *Environment* group to determine the effect of *Speed* on perceived stress during the drone's approach. In both environments, there was a median decrease in perceived stress between the approach at 1 m/s (Real_Md=4.67, VR_Md=4.61) compared to 0.25m/s (Real_Md=3.95, VR_Md=4.39), but this difference was not statistically significant in the real environment ($z = 32.5$, $p = .121$) and in VR ($z = 36$, $p = .83$).

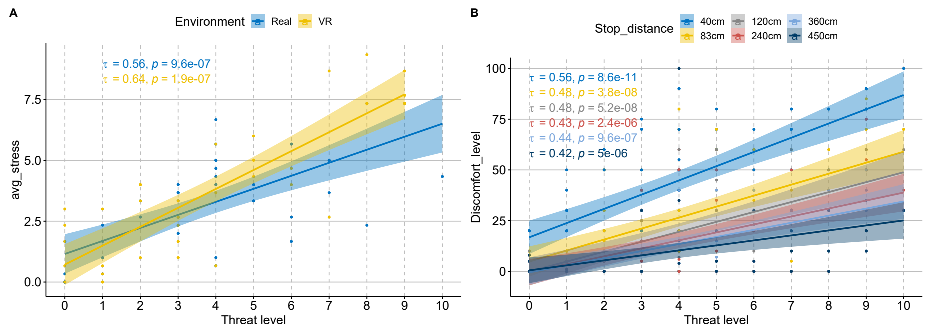

Fig. 3. A A Kendall's tau-b test revealed a significant strong positive correlation between the drone's threat level and perceived stress during the flying phases in the real (tau=0.58, $p<0.05$) and virtual (tau=0.64, $p<0.05$) environments. **B** Kendall's tau-b correlation tests revealed a significantly strong correlation between the reported drone's threat level and participants' discomfort for each stop distance. We however notice a decrease in the correlation strength when leaving the intimate space (40cm).

Environment *(No statistically significant difference)* A Kruskal-Wallis H test was conducted to determine if there were differences in perceived stress between groups that performed the experiment in a real environment (N=23) or in a virtual replica (N=18). Distributions of perceived stress were similar for both groups, as assessed by visual inspection of a boxplot. Perceived stress scores increased from the Real (Md=2.5), to the VR group (Md=2.79), but the differences were not statistically significant, $\chi^2(1) = 0.000691$, p = 0.979.

Threat Relationship *(Significant)* In both environments, Kendall's tau-b correlation was run to assess the relationship between threat level and perceived stress during the flying phases (see Figure 3). Preliminary analysis showed the relationship to be monotonic. There was a statistically significant, strong positive correlation between these two variables in the real (tau(41) = .56, $p < .0005$.) and virtual environment (tau(34)= .64, $p<0.0005$).

4.2 Proxemics

The study showed that the distance at which the drone stopped had a significant effect on participants' discomfort, with the closest stop distance being the most uncomfortable. Additionally, the study found that participants' pre-threat assessment was strongly correlated with both their discomfort and distance ratings. However, there was no significant difference in discomfort levels between the different speed conditions. These findings were consistent in both the real and virtual environments, with no statistically significant difference between them.

Stop Distance *(Significant)* A Friedman test was run for each Environment group to determine if there were differences in discomfort and distance ratings between Stop distances. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons. There was a statistically significant impact of the stop distances on **discomfort level**, in the real (χ^2(5)=70.46, p < .0001) and virtual environment (χ^2(5)=65.42, p < .0001). **In the real** environment, post hoc analysis revealed statistically significant differences in discomfort between the intimate space (40cm)(Md=41.3) and the other conditions (Md(83cm)=20.6, Md(120cm)=13.5, Md(240cm)= 9.81, Md(360cm)=8.49, Md(450cm)=6.9). The condition 83cm was also significantly different than Personal Space (120cm). **In VR**, both the intimate space(40cm)(Md=47.2) and the 83cm (Md=32.3) conditions were statistically significantly different compared to the other conditions (Md(120cm)=25.5 < Md(240cm)=20.9 < Md(360cm)=19 < Md(450cm)=14). There was a statistically significant impact of the stop distance on **distance ratings**, in the real (χ^2(5)=104.46, p < .0001) and virtual environment (χ^2(5)=89.08, p < .0001). **In the real** environment, post hoc analysis revealed statistically significant differences in distance rating between each conditions (Md(40cm)=-52 < Md(83cm)=-19.1 < Md(120cm)=-3.57 < Md(240cm)=15.1 < Md(360cm)=31.8 < Md(450cm)=46.4) **In VR**, each condition was also statistically significantly different to the others (Md(40cm)=-54.4 < Md(83cm)=-25.5 < Md(120cm)=-10.4 < Md(240cm)=13.1 < Md(360cm)=35.5 < Md(450cm)=55.2).

Speed *(No statistically significant difference)* A Wilcoxon signed-rank test was conducted for each Environment group to determine the effect of Speed on discomfort level and distance rating. **In VR**, there was a median decrease in discomfort (Md(0.25)=25.5 < Md(1)=27.6) and a median increase in distance rating (Md(0.25)=2.4 > Md(1)=2.36) between 0.25m/s compared to 1 m/s, but these differences were not statistically significant (Discomfort: z = 30.5, p = .311, Distance rating: z = 63, p = .53). **In the real** environment, there was a median increase in discomfort (Md(0.25)=18.7 > Md(1)=15) and a median decrease in distance rating (Md(0.25)=-2.51 < Md(1)=8.22) between 0.25m/s compared to 1 m/s, but these differences were not statistically significant (Discomfort: z = 99.5, p = .0.556, Distance rating: z = 54.5, p = 0.0619).

Environment *(No statistically significant difference)* A Kruskal-Wallis H test was conducted to determine if there were differences in discomfort or distance ratings between groups that performed the experiment in a real environment (N=23) or a virtual replica (N=18). Distributions were similar for both groups, as assessed by visual inspection of a boxplot. Distance ratings increased from the VR (Md=2.38), to Real group (Md=2.92), and discomfort decreased from the VR (Md=26.5) to the Real group (Md=16.8), but the differences were not statistically significant, (Discomfort: $\chi^2(1) = 1.04$, p = 0.308. Distance ratings: $\chi^2(1) = 0.0118$, p = 0.913).

Threat Relationship *(Significant)* In both environments, Kendall's tau-b correlation was run for each stop condition to assess the relationship between threat level and discomfort level. Preliminary analysis showed the relationship to be monotonic. There was a statistically significant, strong positive correlation between these two variables as shown on Figure 3.

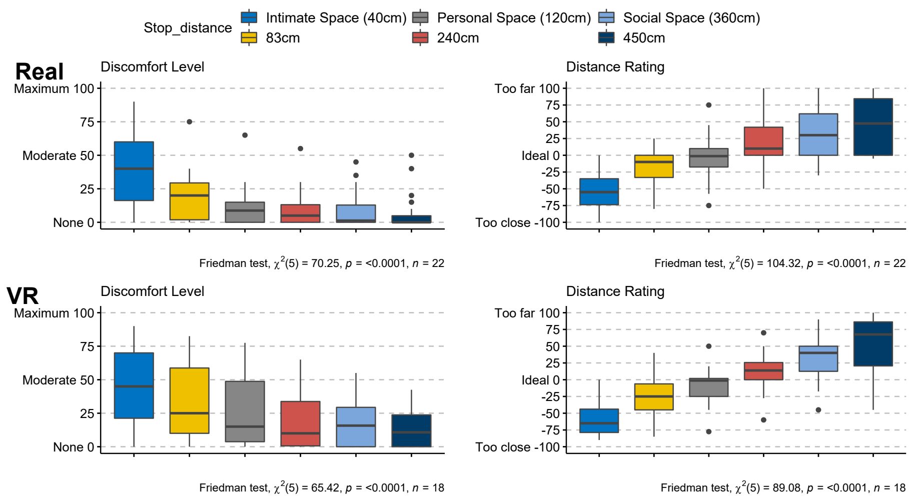

Fig. 4. Discomfort level (left) and stop-distance ratings (right) in the real (top) and virtual (bottom) environments for each stop condition. Friedman tests revealed a statistically significant effect of the drone stop distance on participants' discomfort and distance rating in both environments. We can observe an increase in discomfort when entering the personal space (below 120 cm). Overall, the personal space frontier (120cm) was rated the closest to participants' ideal distance (rating of 0) in the real (Md=-3.570) and virtual environment (Md=-10).

4.3 Qualitative Results & Guidelines

After the experiment, we ran semi-directed interviews to unveil the factors contributing to perceived danger of drones, explore participants' defensive behaviours and examine the potential impact of VR on these aspects.We present the main themes from our affinity diagrams, with participant responses annotated (P + participant ID) and "VR" for virtual group participants.

How to Decrease the (Perceived) Danger? Based on our discussions with participants regarding the drone's perceived dangerousness in this experiment, we outline high-level guidelines to reduce the drone's threat level and enhance acceptability of proximity.

1) Positive associations: Beyond its loudness, the drone's sound and design are negatively connoted in participants' minds. (P1) said "this drone looks a little bit like a huge insect", (P41-VR) "it looks like a military thing". (P33-VR) said "It's like, constantly like a mosquito" and (P18) "Like something chop your head." Although it is hard to predict what associations might emerge in people's minds, fostering positive ones may orient participants' framing [74] towards an optimistic interpretation of the situation. Modifying the nature of the sound or the drone's design ((P15) "maybe like birds", (P3) "have some cute sticker" or (P13) "bright colours") could help. Wojciechowska et al. [91] have investigated the multifaceted people's perception of existing drones' design, Yeh et al. [92] showed that using a round shape and displaying a face helped decrease personal space, and Cauchard et al. [17] have found that radical drone forms strongly affects the perception of drones and their interactive role.

2) Communicate its intention: As in prior work [93], the drone's unpredictability was reported as an important source of perceived danger. (P9) suggested to "Add things to indicate what it does before doing it. Like a sensory cue." and (P37-VR) said, "there could be like a voice, alerting people that it's coming". Researchers explored drone's movements to communicate emotions [19] or intents [10,84,22] and preferred acknowledgment distances [46].

3) Reduce threats' saliency: The propellers, camera, and sound are prominent threatening components of the drone. As threat assessment relies on the perception and interpretation of sensory inputs, decreasing their salience might help orient participants' focus on other components and reduce the resulting perceived threat. (P13) and (P21) suggested it would be better "not being able to see" the propellers, remove the lights (camera) or "reduce the sound" (P1). The reduced visibility of propellers has already been mentioned as a factor for decreased threat perception in favour of other components (sound) [93]. Similarly, participants in Yeh et al. [92] social proxemic experiment reported not thinking about the propellers because they focused instead on the displayed face.

4) Increase drone's safety: It was also suggested to objectively decrease the threats. From a design perspective, (P12) "increase the size of the guard propellers" or (P14) "if the propellers were at the back I know that there's no chance of it interacting with my hair." But also its size "because bigger drone means bigger propellers and a more dangerous object closer to me" (P36-VR). While (P7) proposed soft material for the propellers, Nguyen et al. [62] recently presented safer deformable propellers. On a flying behaviour side, its position in space with regards to the participants' position, and flying speed has also been reported as critical. (P23) said "If it was higher (not in the eyes' line) it would not be a problem" which is congruent with previous HDP findings [15]. Some participants revealed being much more alert when it was close compared to when it was far. Indeed, as illustrated by (P2), "you never really know what happens if it's close to you." Finally, (P0) said that "more speed. It could be terrifying".

5) Limit sensory inputs: The annoyance resulting from the overwhelming sensory inputs (sound, air) following the drone's approach has been reported as a major concern by participants. It is congruent with previous findings [18]. The space people maintain with others also serves at maintaining an acceptable level of arousal stimulation [65,3,50], which is compromised by sensory overload. Reducing the sound level and produced air would probably greatly improve the drone's proximity acceptability. While the noise from rotors and downwash generated are not negotiable with the available state of technology of consumer drones, we argue that there is a need to push the boundaries to minimize the drawbacks of today's drones. VR can help investigate features that are unfeasible today, to guide the manufacturing of future drones.

Defensive Behaviours In a scenario where the drone would have continued approaching participants until impact, they reported reactions that perfectly fit with the "3 Fs" of defensive behaviours: fight, freeze, or flight [11]. **Flight** - Some participants would have tried to avoid the drone with more or less intensity such as (P34-VR) "I would have left the chair definitely." or (P6) "I would have bent." **Fight** - Some others said they would have attacked, like (P33-VR) "I would hit it with my hands like I would do to a mosquito." or (P18) "My instinct was to hit it away." **Freeze** - Finally, some participants reported they would not have moved away, as (P36-VR) "I would have closed my eyes and step back a little bit." or (P9) "There's a strong chance I would be sitting here whispering is it going to stop, is it going to stop?”. Their reactions are of different natures and intensities and might be representative of the interaction between the perceived threat level, the moment at which they would have intervened (the shorter, the more intense and instinctive the response) [12], and their personality [67]. It is no doubt that the experimental context has influenced these responses. When asked whether they would react similarly in a real situation, participants generally reported more intense and precocious defensive reactions suggesting larger defensive spaces. (P20) reported that “in the real life, I wouldn't let the drone approach me that close". (P19) “would most probably punch it.” if it came as close as the intimate frontier. During the experiment, some participants believed the drone could not hurt them because they were in a controlled environment and they trusted the experimenter. But all these certainties fall out when leaving the experimental context. (P1) said "If it's outside, it's more like someone intends to attack me or something.”, (P19) “I don't know who is behind that. I don't like it", (P9) “It's like what is happening and why is it happening?”. But also (P16) "with a known person, I think I would be fine.” It is congruent with previous research linking risk assessment with danger ambiguity [11]. It also highlights the impact of a controlled experimental environment on participants' risk assessment (and therefore ecological validity) even without visible safety mechanisms.

Virtual Reality The real group, having experienced a real drone, reflected on what affected their reactions and provided valuable feedback to make the VR experience of HDP more ecologicaly valid. Responses fit into five categories (visual, sound, haptic, distances, environment) and emphasize the importance of **1)** the sensory inputs dynamic's accuracy, indicating the drone's location relative to the participant and **2)** the replica of threatening components. For the visual category, (P20) said "It would have the propellers as that's how I would distinguish the drone from something else.", for the sound (P14) said “If you can control the sound [relative to my] position, it's a bit more real because I would be able to associate the distance with the sound” and (P19) "The noise as well, I mean these components that felt threatening.” For the distances, (P19) said it was important to replicate “how close it came to my face.” and (P18) "it needs to come to me at my eye line, I think.” Apart from the air induced by the drone's propellers, our virtual environment matched these requirements as supported by participants' feedback. When asked what made the environment feel not real, (P29-VR) said "No nothing at all. Everything was accurate." Some participants reported missing objects (e.g., their bag), poor resolution, and avatar mismatch (e.g., skin color).

5 Discussion

We found that a drone's state and location can induce significant stress among participants, and that these factors also correlate with the drone's perceived level of threat. We found no significant effect of the drone's speed or the environment on participants' stress, discomfort, and distance ratings. This section provides a discussion of these results.

5.1 Threatening Drones

Unnoticed Speed While participants reported the drone's speed as an important factor for the threat assessment, it had no significant effect on stress, threat perception, or discomfort. Participants had not been informed that speed would vary and we asked them during the interview whether they noticed the velocity variation. Less than 50% of them noticed the drone going 4 times faster or slower between the conditions. We expect the way the experiment was designed (5 minutes of resting period between conditions) and presented (focused on the drone's stop distance) distracted participants from the drone's speed in favor of its proximity. Ultimately, most participants did not perceive the speed variation and interpreted both conditions as the same. According to the Situational Awareness model, filtered perception and interpretation of sensory inputs are the first steps in the process of understanding current and future states of a given situation [30]. This means an input that exists but is not processed should not impact the situational evaluation process. Nonetheless, it does not necessarily mean the input is not important. It emphasizes the subjective nature of threat perception and supports the proposed guideline "Reduce threat's saliency".

Proximity, Behaviour and Defensive Space The drone's proximity was associated with greater stress and discomfort amongst participants. We explain these results considering the cognitive appraisal theory [32], risk assessment process [12,11], defensive peripersonal space [87,73], and protective function of proxemic [3,27]. The drone's presence triggers a vigilance behaviour (increased watchfulness) associated with the detection of a potential threat [11,32]. Hence participants reported shifting their attention from the environment towards the drone when it took off, but drifted away after some time. Then, we argue that there is a threshold distance (defensive space) below which participants' perceived ability to avoid the drones' threat becomes significantly compromised (ratio demand/available resources) [32] and that defensive behaviours occur to reduce the threat level. Such defensive reactions would increase in intensity with the magnitude of the perceived danger [73] and as the distance from the threat decreases (from escape, hiding, to defensive threat, to defensive attack [11]). Within this space (defensive space), attention is focused on the threat and the body gathers resources to face it (inducing stress). The measured perceived stress supports this explanation and participants reported being much more alert when the drone was close compared to far. (P16) said "here (close) it can attack me anytime and there (far) it wouldn't matter. It was too far." (P22) added that "The weaving was less disconcerting when it was further away" suggesting an interacting effect between proximity and drone's behaviour on the interpretation of sensory inputs and risk assessment. Intruding the defensive space in a non-natural way or when defensive reactions are not possible (e.g., experimental context, crowded environment, social norms) would induce discomfort in that it triggers a physiological need that cannot be fulfilled (i.e., reduce the threat level). Considering the approach, as the distance decreased perceived danger might have increased in parallel with the changing uncertainty that the drone would stop, and higher demand/ability ratio. Hence, even though the looming of visual stimuli instinctively triggers defense mechanisms, we believe this induced more stress than the other phases as the highest perceived situational danger occurred right before the drone stopped.

5.2 Other Carrier Mechanisms: *Arousal Regulation, Communication, Goal-oriented*

While this study primarily focuses on the proxemic protective function [27,73], we acknowledge that other carrier mechanisms may have been involved during the experiment and in HDI more broadly. In fact, we believe HDP behaviours to be the result of a weighted mean of the active spaces surrounding the individual in the given situation. For instance, a sound can be at the same time annoying and threatening, generating a distance above which its annoyance becomes acceptable, and another to maintain the threat to an acceptable threshold. It might have been exactly the case during this experiment, as the drone's sound has been characterized as very annoying and sometimes threatening. We have identified cues of the arousal regulation function [65,3] linked to the sensory overload due to the sound loudness when approaching. Some participants' feedback also suggest that the communicative function [3,39] came into play. (P20) explained their distance preference saying "that's how I talk to people" and added "I've never encountered a thinking drone so, it's like meeting a new person." and (P13) said, "My brain still kind of thinks it's a living creature, so I still kind of try to look into its eyes (camera)." It suggests that the implementation of anthropomorphic features (e.g., faces [42,92], eyes[63]) brings benefits but also adds design considerations. The way we presented the experiment may have impacted participants' proxemic preferences as we believe some participants picked their preferred distance with regards to the task the drone had to perform (face detection) which would involve the goal-oriented proxemic function [87].

5.3 Validity of Virtual Reality

In readiness for the use of VR as a valid methodological tool for the HDI field, this study investigated the impact of VR on people's perception near drones. We found no significant differences between the real and virtual environments and similar results in both. As mentioned earlier (see section 4.3), these results might be explained by the sensory inputs dynamic's accuracy, indicating the drone's location with respect to participants' position and the replica of the threatening components. In other words, the elements involved in the evaluation of the situation with regards to participants' position. However, VR can impact critical factors such as the perception of distances [45,59], motor abilities [31], or threat perception [33,26]. We, therefore, expected each measure to be significantly different between the two environments. Regarding the perception of distances, we believe the transfer of depth markers (chairs, tables, experimenter) of the same size and position from the real world to VR helped participants develop an accurate distance estimation. For motor abilities, we used a wireless headset, hand-tracking, and participants' position was calibrated to be the same between the two environments. They were able to use their hands, freely get up from the chair and move without worrying to collide with anything (even though it never happened in the study). Then for the threat perception, we noted an impact of VR, as some participants reported not being afraid of the drone due to the virtual context. Yet similar comments have been reported by participants from the real-world setting, replacing "virtual" with "experimental" context. Threat perception might have been equally biased between both environments.This study shows that VR is extremely promising and can successfully replicate real-world results. Beyond the regular considerations of VR designs (maximize immersion), new recommandations for researchers willing to use VR for Human–Drone Proxemics include 1) identifying the relevant underlying mechanisms linked to the variables under investigation, 2) acknowledging the extent to which VR can alter these elements, and 3) limiting VR's impact through accurate replication of these elements. In our case, the relevant underlying processes are linked to threat perception and situational appraisal but it depends on the focus of the proxemic experiment.

6 Conclusion and Future Work

This study confirms our concerns regarding the potential negative impact of integrating drones into close social spaces on people's well-being. Participants' reactions during passive interaction with a drone aligned with expected responses to perceived threats. Stress levels increased based on situational risk and were strongly correlated with the intensity of the perceived drone's threat level. Participant discomfort significantly varied within their personal space and was also correlated with the drone's threat level. In sensitive cases such as in policing scenarios where individuals may already feel anxious or threatened, or in search and rescue operations, where they may be in distress or vulnerable, it is essential to ensure that drone interactions do not further escalate their discomfort or distress. By incorporating the insights and guidelines from our research, drone designs can be tailored to prioritize user well-being and minimize any potential negative effects on individuals' emotional states. Moreover, we believe that significant shifts in drone designs, beyond slight variations such as changing colors, would be beneficial. The current design spectrum, largely dominated by the default four-propellers model, offers limited alternatives. This study also contributes to the development of VR as a proxy for HDI experiments, enabling researchers to explore possibilities beyond the constraints of reality. Recent work by Cauchard et al., utilizing VR to explore disruptive drone forms, aligns with this ongoing movement [17].

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A Summary statistics

Table 1. Direct comparison of Real-world and Virtual-Reality measures. This table presents a direct comparison of measures between the real-world and virtual-reality experimental settings. The measures are defined in the Measure subsection of the Method section in the paper. The table includes means, and statistical tests conducted to assess the differences between the two settings. No significant differences were found between the real and virtual experimental settings.

Measure	Variables	Real-World	Virtual Reality	Environment difference
Perceived Stress	*Baseline*	1.35	1.17	**Kruskal-Wallis H test** $\chi 2(1) = 0.000691$, $p = 0.979$. No statistically significant difference between the real and virtual environment.
	Static Far	1.89	2.64	
	Approach (0.25 m/s)	4	4.39	
	Approach (1 m/s)	4.74	4.61	
	Static Close	3.39	4.14	
	Resting	1.52	1.5	
	Overall	**2.5**	**2.79**	
Perceived Threat	*0.25 m/s*	3.76	3.56	**Kruskal-Wallis H test** $\chi 2(1) = 0.00168$, $p = 0.967$ No statistically significant difference between the real and virtual environment.
	1 m/s	3.86	4.28	
	Overall	**3.81**	**3.92**	
Discomfort Level	*40 cm*	41	47.2	**Kruskal-Wallis H test** $\chi 2(1) = 1.04$, $p = 0.308$ No statistically significant difference between the real and virtual environment.
	83 cm	19.8	32.3	
	120 cm	13.4	25.5	
	240 cm	9.59	20.9	
	360 cm	8.11	19	
	450 cm	6.59	14	
	Overall	**16.5**	**26.5**	
Distance Rating	*40 cm*	-51.5	-54.4	**Kruskal-Wallis H test** $\chi 2(1) = 0.0118$, $p = 0.913$ No statistically significant difference between the real and virtual environment.
	83 cm	-18	-25.5	
	120 cm	-1.59	-10.4	
	240 cm	17.8	13.1	
	360 cm	34.7	35.5	
	450 cm	48.9	55.2	
	Overall	**4.87**	**2.38**	

Table 2. Friedman Test for Perceived Stress differences between phases in each environment group, with bonferroni correction for multiple comparisons.

Environment	n	statistic	df	p.value	Kendall's W effect size
Real	23	51.1	4	2.09e-10	0.556 (large)
Virtual	18	53.1	4	8.25e-11	0.737 (large)

Comparison	Environment	p value adjusted	Significance
Baseline vs Static Far	Real	0.496	ns
	Virtual	0.025	*
Baseline vs Approach	Real	0.000941	***
	Virtual	0.000308	**
Baseline vs Static Close	Real	0.05	ns
	Virtual	0.000472	**
Baseline vs Resting	Real	1	ns
	Virtual	0.341	ns
Static Far vs Approach	Real	0.000607	***
	Virtual	0.003	*
Static Far vs Static Close	Real	0.077	ns
	Virtual	0.004	*
Static Far vs Resting	Real	1	ns
	Virtual	0.014	ns
Approach vs Static Close	Real	0.028	*
	Virtual	0.228	ns
Approach vs Resting	Real	0.000613	***
	Virtual	0.000471	**
Static Close vs Resting	Real	0.015	*
	Virtual	0.00031	**

Table 3. Friedman Test for Discomfort levels and Distance ratings Differences Between Stop distances in Each Environment Group, with Bonferroni Correction for Multiple Comparisons.

Measure	Environment	n	statistic	df	p.value	Kendall's W effect size
Discomfort	Real	22	70.3	5	9.09e-14	0.639 (large)
	Virtual	18	65.4	5	9.15e-13	0.727 (large)
Distance Ratings	Real	22	104	5	6.49e-21	0.948 (large)
	Virtual	18	89.1	5	1.05e-17	0.990 (large)

Comparison	Measure	Environment	p value adjusted	Significance
40 cm vs 83 cm	Discomfort	Real	0.001	**
		Virtual	0.013	*
	Distance Ratings	Real	0.000633	***
		Virtual	0.003	**
40 cm vs 120 cm	Discomfort	Real	0.001	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000644	***
		Virtual	0.003	**
40 cm vs 240 cm	Discomfort	Real	0.002	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000639	***
		Virtual	0.003	**
40 cm vs 360 cm	Discomfort	Real	0.004	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000640	***
		Virtual	0.003	**
40 cm vs 450 cm	Discomfort	Real	0.006	**
		Virtual	0.007	**
	Distance Ratings	Real	0.000640	***
		Virtual	0.003	**
83 cm vs 120 cm	Discomfort	Real	0.007	**
		Virtual	0.013	*
	Distance Ratings	Real	0.001	**
		Virtual	0.007	**
83 cm vs 240 cm	Discomfort	Real	0.062	ns
		Virtual	0.011	*
	Distance Ratings	Real	0.000947	***
		Virtual	0.003	**
83 cm vs 360 cm	Discomfort	Real	0.072	ns
		Virtual	0.007	**
	Distance Ratings	Real	0.000948	***
		Virtual	0.003	**
83 cm vs 450 cm	Discomfort	Real	0.078	ns
		Virtual	0.016	*
	Distance Ratings	Real	0.000956	***
		Virtual	0.003	**
120 cm vs 240 cm	Discomfort	Real	0.444	ns
		Virtual	0.412	ns
	Distance Ratings	Real	0.003	**
		Virtual	0.003	**
120 cm vs 360 cm	Discomfort	Real	0.444	ns
		Virtual	0.141	ns
	Distance Ratings	Real	0.001	**
		Virtual	0.003	**
120 cm vs 450 cm	Discomfort	Real	0.444	ns
		Virtual	0.160	ns
	Distance Ratings	Real	0.001	**
		Virtual	0.003	**
240 cm vs 360 cm	Discomfort	Real	0.444	ns
		Virtual	1	ns
	Distance Ratings	Real	0.003	**
		Virtual	0.005	**
240 cm vs 450 cm	Discomfort	Real	0.444	ns
		Virtual	0.414	ns
	Distance Ratings	Real	0.003	**
		Virtual	0.005	**
360 cm vs 450 cm	Discomfort	Real	0.444	ns
		Virtual	1	ns
	Distance Ratings	Real	0.007	**
		Virtual	0.007	**