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In a Flap: Experiences with a Bioinspired Flying Robot

ZIMING WANG*, Chalmers University of Technology, Sweden and University of Luxembourg, Luxembourg
MEAGAN B. LOERAKKER, TU Wien, Austria
YIQIAN WU, Chalmers University of Technology, Sweden
SHIWEI YANG, University of Gothenburg, Sweden
ARION PONS, Chalmers University of Technology, Sweden
YUWEI CHUAI, University of Luxembourg, Luxembourg
DAVID SIRKIN, Stanford University, USA
MORTEN FJELD, Chalmers University of Technology, Sweden and University of Bergen, Norway

While the proliferation of civil drones has led to increasingly diverse designs, research on Human-Drone Interaction (HDI) has largely focused on rotorcraft, but interacting with flapping-wing drones remain underexplored. To address this gap, we present the first study to investigate how humans experience a bioinspired flapping-wing drone compared to a similar-sized quadcopter. We conducted a mixed-methods study ($N = 56$) using a within-subject 2×2×2 factorial design to examine the effects of drone design, proxemic distance, and human posture on perceptions of safety, pleasure, discomfort, and unexpectedness. Participants had mixed feelings about the bioinspired flapper, finding it newfangled, entertaining, and inspiring, but also unsafe and unclear in its potential use cases. They also associated the flapper with animals ranging from insects to birds to bats. Our findings have important implications for HDI and future bioinspired drone development, including scaling the drone's physical dimensions to its context and purpose, enhancing control and stability, and aligning its form with familiar species archetypes, which in turn should be guided by its context and role.

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

Additional Key Words and Phrases: Human-drone interaction, bioinspired robots, flapping-wing drone, technology diversity

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*Corresponding author. The author was a visiting researcher at Stanford University while part of this work was conducted.

Authors' Contact Information: Ziming Wang, Chalmers University of Technology, Gothenburg, Sweden and University of Luxembourg, Esch-sur-Alzette, Luxembourg, ziming@chalmers.se; Meagan B. Loerakker, TU Wien, Vienna, Austria, meagan.loerakker@tuwien.ac.at; Yiqian Wu, Chalmers University of Technology, Gothenburg, Sweden, yiqianwuu@gmail.com; Shiwei Yang, University of Gothenburg, Gothenburg, Sweden, shiwei.yang@ugent.be; Arion Pons, Chalmers University of Technology, Gothenburg, Sweden, arion@chalmers.se; Yuwei Chuai, University of Luxembourg, Esch-sur-Alzette, Luxembourg, yuwei.chuai@uni.lu; David Sirkin, Stanford University, Stanford, California, USA, sirkin@stanford.edu; Morten Fjeld, Chalmers University of Technology, Gothenburg, Sweden and University of Bergen, Bergen, Norway, fjeld@chalmers.se.

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1 INTRODUCTION

> *"Nature is the source of all true knowledge. She has her own logic, her own laws, she has no effect without cause nor invention without necessity."* — Leonardo da Vinci

Drones present new opportunities in multiple fields for human-robot interaction: for example, smart construction [48], warehouse logistics [8], and co-robots for the elderly [32], and so forth (e.g. [68, 70]). Nevertheless, previous research on human interactions with drones (e.g. [16, 70, 71, 78]) has focused on a very specific morphology: rotorcraft platforms, such as quadcopters, which rely on rotating propellers to generate lift. While rotorcraft remain dominant in commercial applications, alternative morphologies are emerging.

Leonardo da Vinci conceptualized the so-called "ornithopter" in the 15th century, a type of human-controlled plane simulating the flying mechanism of a bird through its flapping wings [4]. Da Vinci's drawings are considered one of "the first serious, logical investigations of a flapping-wing flying machine" [28, p. 32]. Although da Vinci's design would not have been able to fly [28]—and especially not when the drawings were made given the resources available at the time [60]—natural inspiration has gone on to support the development of a wide range of flapping-wing drones [25, 58]. Notably, bioinspired flapping-wing drones, modeled after birds, bats, and insects, have shown potential advantages in maneuverability [2, 77], efficiency [54, 57], and safety [18].

Most flapping-wing drone research has prioritized mechanical design and flight performance, including actuators, aerodynamics, and control systems [24, 43, 66], with little focus on user interaction. Although some literature explores how humans perceive flying animals [5, 13, 41, 44], human interaction with flapping-wing drones—especially in physical environments—remains largely unexplored and mostly limited to virtual settings [59]. Yet, flapping-wing drones are now commercially realized [34, 52, 56]. A critical gap remains in understanding how people interact with these drones in physical environments, where contextual factors such as proxemics and human posture may influence perception.

Flapping-wing drones exhibit bioinspired movement patterns may be perceived as more natural or lifelike. Prior research suggests that animal-like motion and morphology can evoke positive responses [7, 26, 40]. In contrast, quadcopters tend to convey a more mechanical and utilitarian character due to their rigid symmetry and stable hover. We hypothesize that these morphological and motion differences may lead to divergent user experiences. These assumptions inform our comparative exploration of the two drone types. To this end, we aim to answer the following research questions:

- **RQ1:** *What are the differences of user experiences between interacting with a conventional quadcopter and a bioinspired flapping-wing drone?*
- **RQ2:** *How will the bioinspired robotic mechanism design affect users' perceptions of flying robots?*

Our work contributes: (i) empirical evidence from a within-subject mixed-method study with $N = 56$ participants; (ii) insights into how the drone's morphology and the user's posture and proxemic distance influence the human experience with the drone; and (iii) design considerations for further development of bioinspired flying robots serving to minimize drone discomfort while increasing user satisfaction.

2 RELATED WORK

Here, we discuss prior research and provide a basis for our study. First, we go over related work on Human-Drone Interaction, bioinspired drone designs, and user interactions with zoomorphic robots.

2.1 Close-Range Human-Drone Interaction (HDI)

Proxemics is the study of physical space between humans during various forms of interaction and activities [61]. The proxemics of HDI is of particular interest, as various studies [15, 72] show that humans may experience increased stress and discomfort in the proximity of drones. The general finding is that the closer a drone flies to a human, the more the discomfort is reported. Interpersonal distances involved can be categorized into four zones according to the framework created by Hall [31]: intimate (< 46cm), personal (46cm-122cm), social (122cm-366cm), and public (> 366cm). These four zones are widely used in human-drone and human-robot proxemics research [29]. Previous HDI research has looked into the correlations between proxemics and other factors, including drone function [70], appearance [75], sound conditions [69], and culture [23]. For instance, Wang et al. found that both proxemic distance and added nature sound conditions jointly affected participants' perceptions of drones [69]. People's comfort level with a drone in their vicinity is impacted by individual preferences [78] and culture differences [23]. Discomfort caused by such spatial relations between user and drone is reasonably well understood in the context of outdoor drones [17], indoor settings introduce unique proxemic challenges—spatial constraints, room-specific affordances, and stronger social norms. A recent study [14] explored proxemics in an indoor virtual reality setting, finding that drone height affected preferred interpersonal distance, though narrative framing had no effect. Though insightful, the simulated environment lacked the spatial and social complexity of real-world indoor scenarios.

In addition, a drone's appearance or mechanism design (its morphology) influences how it is perceived—a factor extending to perceptions of the drone's intended purpose. For example, protective gear can encourage people to come closer to the drone, instilling more engaging interactions due to increased feelings of safety [1, 72]. In line with this, Yeh et al. [75] designed an oval-shaped drone with a cartoon face and a greeting voice, resulting in a significantly reduced minimum distance for people to accept the drone in their vicinity. Perceptions of the intended purpose of a drone, which may derive partly from morphological cues, can also influence comfort/discomfort—particularly when the intended purpose of the drone is unknown [70]. The design space for drone morphology is very large: despite extensive exploration [75], existing studies have focused almost exclusively on variants of quadrotor drones, with flapping-wing drones remaining unstudied.

Previous HDI research often overlooked the potential influence of the people's physical state (e.g., body posture) on their perception. It has been demonstrated that observers' body posture has a direct impact on action observation—when an observer's posture aligns with the goal posture of the action being observed, they are able to predict the action's goal more quickly [79]. In the field of human-robot interaction, research has also shown that body postures influence human's interaction with humanoid robots [55]. Moreover, a study revealed that individuals demonstrated greater comfort with drone contact when seated, with participants showing increased acceptance for drone landings on their body (especially lower torso) compared to when they were standing [6]. However, existing studies often have subjects maintain the same posture (such as sitting or standing), without comparing the effects of different postures. Hence, the impact of body posture on drone perception deserves further exploration.

2.2 Bioinspired Flapping-Wing Drone Design

Despite the continuing dominance of rotorcraft drones in the consumer drone market, advances in the fluid dynamics of flapping-wing flight have led to the development of flapping-wing drones. These platforms span a remarkable range of scales, from tiny 'RoboBees' [73], to larger mimetic seagulls capable of remote-controlled flight [47]. Flapping-wing drones have the potentials to have quieter flight [21, 45], improved efficiency at smaller scales [54, 57], higher maneuverability [2, 77], and better safety [18, 22]. They have seen applications in scientific research [56], toy industries [52], and early military reconnaissance efforts [34].

Notwithstanding this technical progress, current commercial flapping-wing drones often suffer from lower payload capacity and reduced flight endurance compared to rotorcraft of similar size [25]. Moreover, the inherent instabilities of flapping flight make achieving precise control and reliable operation substantially more challenging [65]. Consequently, existing research has largely concentrated on improving aerodynamic performance, flapping kinematics, and flight control [24, 43, 76].

However, the human-centered aspects of flapping-wing drones remained almost unexplored. To our best knowledge, the human factors of bioinspired drones have been the topic of a single study only, and this was conducted in a virtual environment [59]. Real world, embodied studies of human interaction with physical flapping-wing drones are currently missing. Given their distinct morphology, dynamic motion, and potential associations with familiar animals like birds or insects, flapping-wing drones may elicit very different human responses compared to conventional rotorcraft. Addressing this gap is essential for understanding social acceptance and comfort in close-range HDI settings.

2.3 Human Interaction with Zoomorphic Robots

While the study of human interaction with bioinspired flapping-wing drones is only nascent, studies of human responses to other zoomorphic robots offer valuable insights. A key question raised by this broader literature is how biomimetic features—such as appearance, morphology, or behavior—affect people's perceptions of robots and their feelings of comfort or discomfort during interaction.

Evidence suggests that the relationship between biomimicry and user response is complex and not always intuitive. For example, Löffler et al. [46] observed that the uncanny valley effect also applied to zoomorphic robots, where robots that are either very realistic or very unrealistic in their animal likeness are preferred over those that are in between. In the studies on quadrupedal robot dogs, Jones et al. [33] found that incorporating biomimetic morphological and behavioral features did not significantly enhance user satisfaction with robot performance. In contrast, other studies show that specific animal-like behaviors can foster social bonding: people spontaneously attributed emotions to robot dogs that exhibited familiar canine behaviors [30]; and children, in particular, are likely to conceptualize and interact with a robot dog in ways that they would with a real dog [49]. In the context of bioinspired flapping-wing drones, there is less research directly related to human responses. A study by Reiter and Moore [59] on a virtual butterfly-inspired drone further highlights these complexities. Participants preferred unrealistic wingbeat and flight parameters over realistic ones.

Some scholars advocate an *ethological* and *ethorobotic* approach to interpreting these findings, arguing the shared evolutionary history of dogs and humans informs human interaction with, and attachment to, robotic dogs and other social robots [39, 50, 67]. This perspective suggests that similar principles could apply to bioinspired drones, particularly those modeled after familiar flying animals. For example, humans typically form positive associations with butterflies and honeybees, while negative associations are more commonly linked to mosquitoes [35, 42, 63]. For birds, perceived aesthetic value can be high [44], whereas bats remain widely stigmatized [13, 38]. Whether the perspective of canine ethorobotics translates to bioinspired drones remains unclear. In this study, we provide evidence that can help explore this translation.

3 METHODOLOGY

In this section, we outline the methodology employed for our study.

3.1 Pilot Study

We first conducted a pilot study with 10 participants in various individual/group configurations (3×1 + 2×2 + 1×3) to explore initial reactions to the bio-inspired flapping-wing drone and inform the main study design. Participants generally found the flapper's design to be obviously zoomorphic, describing it as a novel and intriguing technology, though some expressed mild safety concerns. These insights guided the selection of dependent measures. The pilot also revealed the richness of qualitative feedback, reinforcing our decision to complement quantitative measure with semi-structured interviews. Furthermore, participants remained focused on the drone regardless of group size, supporting our choice to group three participants per session in the main study for greater efficiency without compromising data quality.

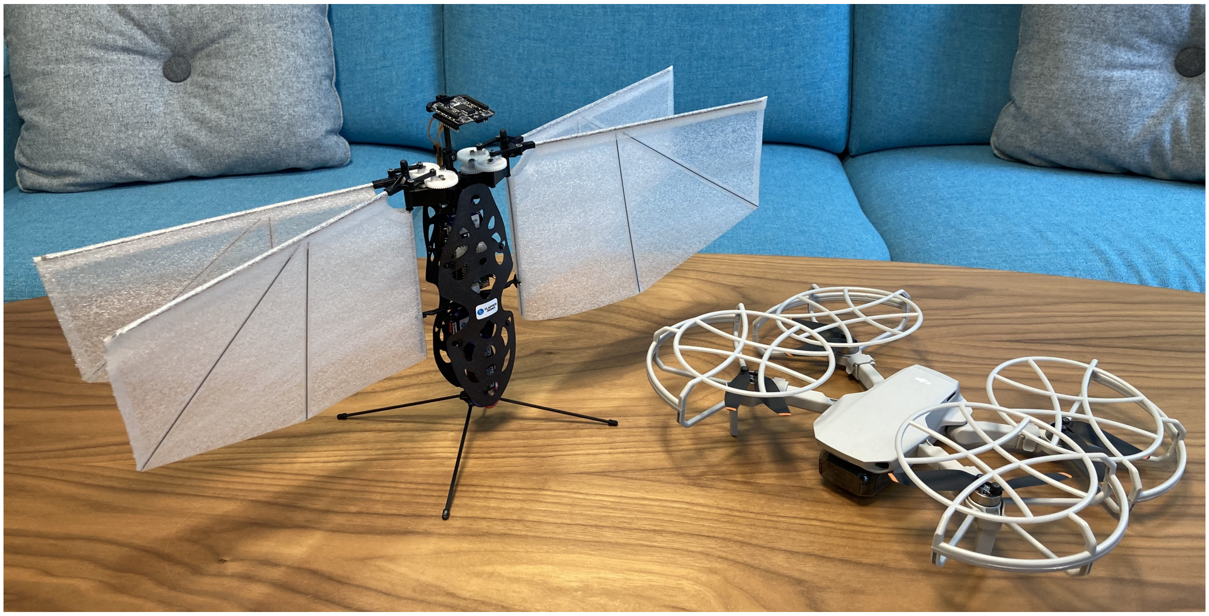

Fig. 1. The two flying robots used in this study showed radically different morphology at a similar scale: a bioinspired flapping-wing drone (*left*) and a conventional quadcopter drone (*right*).

3.2 Drone Selection and Prototyping

Figure 1 shows the two drones we used in this study: a commercially available Flapper Nimble+ drone with a wingspan of 50 cm, sourced from Flapper Drones[1], and a DJI Mini 2[2] for its similar size to the flapper and added propeller guards for safety during indoor flights. We integrated a set of Lighthouse extension module and positioning system provided by Bitcraze[3], which allowed the flapper to fly in a controlled and repeatable trajectory, ensuring better reliability and repeatability in our setup. The flapper and quadcopter inherently differ in motion characteristics: the flapper's flapping flight introduces more erratic movement, whereas the quadcopter exhibits more stable and linear motion. This mismatch made precise control of drone velocity challenging, but the short demo duration likely minimized any resulting impact. Both drones followed a fixed linear trajectory defined by preset waypoints to ensure consistency across trials. Figure 2 illustrates the complete flight path, and supplementary videos[4] visually document this setup.

3.3 Experimental Design and Conditions

We employed a mixed-methods approach using a within-subject 2×2×2 factorial design to study participants' perceptions through questionnaire scales and semi-structured post-experiment interviews. We examined the effects of three factors, namely drone design (flapping-wing, quadcopter), human posture (sitting, standing), and proxemic distance (near, far), on four measures: perceived safety, pleasure, discomfort, and unexpectedness. We also monitored participants' heart rates during the experiment. Each participant experienced all eight conditions

[1] https://flapper-drones.com/wp/
[2] https://www.dji.com/mini-2-se
[3] https://www.bitcraze.io/documentation/system/positioning/ligthouse-positioning-system/
[4] Available in the ACM Digital Library.

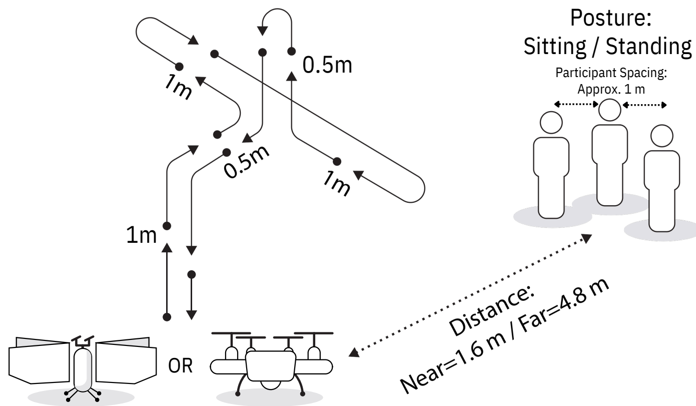

Fig. 2. Overview of the experiment setup, including outline of flight trajectory of either drone that hovers for five seconds before changing direction each time.

(2 drones × 2 distances × 2 postures) in a counterbalanced order to avoid potential ordering effects. Figure 2 provides an overview of the study setup. Supplementary materials include demonstration videos[4] along with examples showing variations in setup across conditions. We reflect on the study design and suggest improvements for future work in subsection 5.3.

3.4 Participants and Study Procedure

A total of 56 adults fluent in English residing within the European Union, with 24 females (42.9%) and 32 males (57.1%), aged 19 to 59 (M = 29.36, SD = 8.51), were recruited through snowball sampling. Each participant received a 20-euro gift voucher for their involvements. Each session involved three participants (except one session with two), who simultaneously experienced the drones. The participants were spaced approximately one meter apart and all faced toward the drone. They did not interact with each other during the experiment.

Experiments took place in a controlled, soundproof room at the university. Participants were given a pseudoanonymized ID for use in questionnaires and provided with a wearable heart rate (HR) sensor to put on. The HR sensor was connected to the Wahoo app[5] to record the data for analysis. Researchers explained the experiment process, and participants were instructed on their positions. After a 1-minute drone demonstration, participants completed a questionnaire digitally. This process was repeated eight times for each condition. The questionnaire remained the same throughout. After the final drone demonstration, HR data was saved and sensors were removed. After the experiment, each participant was interviewed individually.

3.5 Measures

For each experimental condition, we collected quantitative data using a *Qualtrics XM* questionnaire. This questionnaire included 5- or 7-point scale statements measuring participants' perceived safety, pleasure, discomfort, and unexpectedness. Table 1 lists all subscale question items for each measure. We chose the measures for the following reasons: (i) Safety is considered as the key issue in robot interacting with humans [9]. In this study, **Perceived Safety** was assessed using the questionnaire of Akalin et al. [3], consisting of eight items on a 5-point semantic differential scale. (ii) Perceived pleasantness has been demonstrated to have an influence on usefulness, ease of use and enjoyment, and has been ascertained as an essential hedonic factor affecting

[5] https://eu.wahoofitness.com/

HCI [19, 20]. Adapted from Kim and Mutlu [37]'s *User Experience* scale, we measured the **Pleasure** with eight items and the **Discomfort** with six items, both on a 7-point Likert scale. (iii) Meeting expectations is crucial for technologies to offer a positive first impression [74]. To capture the **Unexpectedness**, we applied six items from Wozniak et al.'s *Perceived Creepiness of Technology Scale* (PCTS) [74].

Table 1. The chosen measures and their corresponding question items.

Perceived Safety	Pleasure	Discomfort	Unexpectedness
While interacting with the robot, I felt {...}	**Interacting with the robot is {...} to me.**		UE1: Using this system in public will make other people laugh at me.
PS1: Insecure <—>Secure	PL1: enjoyable	DC1: uncomfortable	UE2: I would feel uneasy carrying this system in public.
PS2: Anxious <—>Relaxed	PL2: entertaining	DC2: uneasy	UE3: The system looks bizarre to me.
PS3: Uncomfortable <—>Comfortable	PL3: exciting	DC3: difficult	
PS4: Lack of control <—>In control	PL4: fun	DC4: annoying	
I think the robot is {...}	PL5: interesting	DC5: confusing	UE4: The system looks as expected. (R)
PS5: Unsafe <—>Safe	PL6: pleasurable	DC6: disappointing	UE5: I don't know what the purpose of the system is.
PS6: Unfamiliar <—>Familiar	PL7: happy		UE6: The system has a clear purpose. (R)
PS7: Unreliable <—>Reliable	PL8: satisfying		* (R = reversely coded)
PS8: Scary <—>Calming			

3.6 Post-Experiment Interviews

The post-experiment individual interviews were conducted in English using a semi-structured format. Researchers followed a prepared set of questions, with follow-ups asked when relevant. The interview explored participants' perceptions of the two drone designs (flapper vs. quadcopter), focusing on differences in appearance, flight movement, sound, airflow, and size. Participants also reflected on how posture (sitting vs. standing) and proximity (near vs. far) affected their feelings and reactions. They were encouraged to share ideas for potential drone applications, especially for the flapper, and to imagine designing their own drone with both functional and aesthetic considerations. Interviews concluded with participants identifying preferred or disliked demonstrations and sharing any final thoughts. All sessions were audio-recorded with participant consent.

3.7 Data Analysis

3.7.1 ***Statistical Analysis.*** For data cleaning, we removed duplicated answers (a few participants submitted the same questionnaire multiple times), fixed structure errors (a few put wrong participant IDs), and the responses from one session of three participants were excluded due to technical failures.

For each measure, a three-way repeated measures ANOVA was used to examine the three main effects of each factor, three two-way interactions, and one three-way interaction. The assumptions of sphericity and normality were checked and all met. Post-hoc pairwise comparisons were conducted following significant main effects. To gain a more nuanced understanding of participants' responses, we analyzed the subscales of each measure by conducting pairwise comparisons of item ratings across three factors. Recognizing the longstanding controversy over parametric versus non-parametric analysis of single Likert item data [51, 62, 64], we adopted parametric methods, given our adequate sample size and the greater statistical power and more in-depth analyses parametric tests offer compared to non-parametric alternatives [51, 64].

3.7.2 ***Interview Analysis.*** To analyze the qualitative data from the interview transcriptions, the first, second and third authors each open coded two interviews individually following Blandford et al.'s guidelines [11], resulting in six open-coded interviews. Based on this, they collaboratively developed a coding tree, which was then used to code the remaining interviews. Previously coded transcripts were revisited and revised as needed..

After completing the full dataset, the same authors performed thematic analysis to gain detailed insights into the participants' opinions, perceptions and thought patterns regarding the drone designs, as well as the influence of user posture and proxemic distance.

4 RESULTS

In this section, we present the results from the analysis of questionnaires and the heart rate data, and interviews.

4.1 Quantitative Results

Table 2 presents a summary of the overall results. Significant interaction effects were barely found. Significant main effects of three factors differed across four measures. As shown in the Main Effects Plots of Figures 3, 4, 5, and 7, drone type has overall the most substantial impact on measures, except for the pleasure scale. While drone type showed a dominant effect, posture and distance had comparatively minor influences. This imbalance likely reduced the chances of detecting significant interaction effects involving drone type. Subscale plots are also presented in the figures respectively. In all plots, the red dashed line refers to the overall mean, error bars indicate 95% confidence interval, and significance levels are indicated with asterisks: * for $p < .05$, ** for $p < .01$, *** for $p < .001$, and n.s. for non-significant. We present detailed results for each measure and their subscales in the following subsections.

Table 2. Summary of statistical results of four measure scales.

Measure	Main Effects			3-way Interaction	2-way Interaction		
	Drone	Posture	Distance	Dro×Pos×Dis	Dro×Pos	Dro×Dis	Dis×Pos
Perceived Safety	Flap < Quad	Sit > Sta	N < F	n.s.	n.s.	n.s.	n.s.
Pleasure	n.s.	n.s.	N > F	n.s.	n.s.	n.s.	n.s.
Discomfort	Flap > Quad	Sit < Sta	n.s.	n.s.	n.s.	n.s.	p = .04
Unexpectedness	Flap > Quad	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

All effects listed are significant at p < .05.
N = *near*; F = *far*; Flap = *Flapper*; Quad = *Quadcopter*; Sit = *Sitting*; Sta = *Standing*; n.s. = Not significant.

4.1.1 ***Perceived Safety Scale***.

No significant two-way or three-way interactions were found ($p > .05$ for all interactions). Thus, the main effects can be interpreted straightforwardly. The main effects for all three factors were significant on the perceived safety scale: specifically, drone type ($F(1, 52) = 50.09$, $p < .001$, $\eta_P^2 = 0.49$), posture ($F(1, 52) = 5.38$, $p = .024$, $\eta_P^2 = 0.09$), and distance ($F(1, 52) = 9.26$, $p = .004$, $\eta_P^2 = 0.15$). Respectively, quadcopter scored significantly higher than flapper (MD = 0.90, SE = 0.13), sitting scored higher than standing (MD = 0.06, SE = 0.03), and near distance scored lower than far (MD = 0.20, SE = 0.06). As shown in Figure 3(a), the steeper slope from quadcopter to flapper indicates a stronger effect, while both distance and posture have weaker effects as their slopes are less steep. Thus, among the three factors, drone type has the most substantial impact on perceived safety.

For the subscale questions (listed in Table 1), quadcopter was rated significantly higher than flapper across all eight items. Notably, as shown in Figure 3(b), PS6 and PS7 have obvious larger magnitudes of differences, implying participants found the flapper particularly unfamiliar and unreliable compared to the quadcopter. In contrast, the effect of posture and distance on perceived safety mainly came from participants' interactive experience with the drones (PS1~4). This suggests that the drone's inherent design and behavior maintain a consistent level of perceived safety across varying spatial and postural configurations.

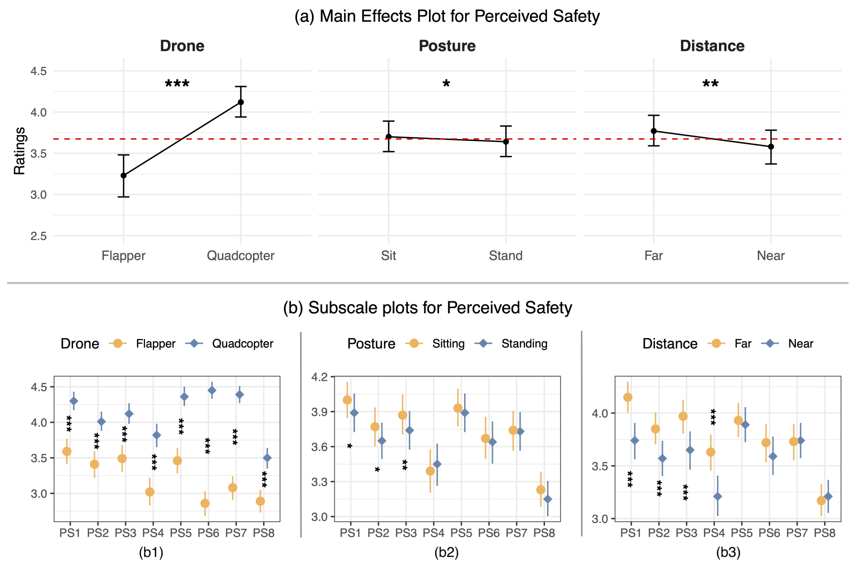

Fig. 3. (a) Main effects plots for perceived safety; (b) Subscale plots for perceived safety.

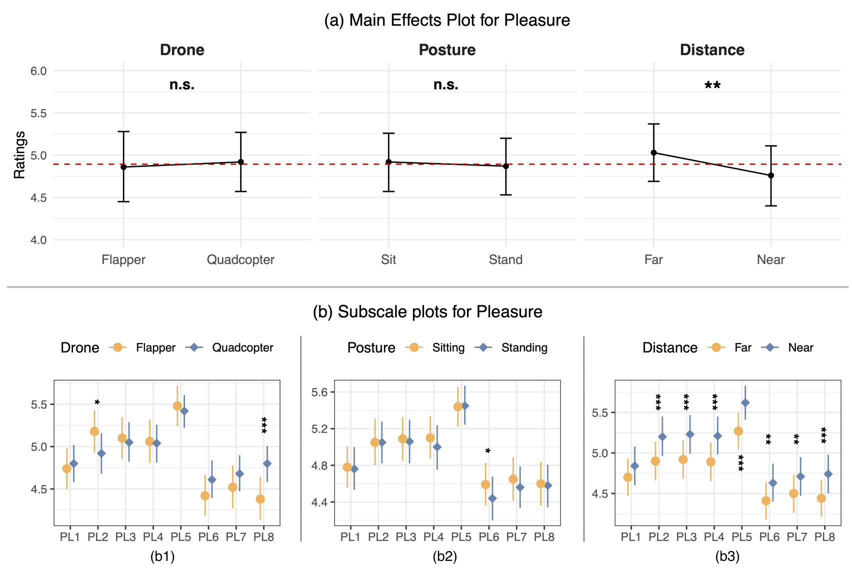

Fig. 4. (a) Main effects plots for pleasure; (b) Subscale plots for pleasure.

4.1.2 ***Pleasure Scale.*** No significant two-way or three-way interactions were found. Hence, we interpret the main effects straightforwardly. As shown in Figure 4(a), the main effects for both drone type and posture were not significant on the pleasure scale, but the effect of distance was significant (F(1, 52) = 10.12, p = .002, $\eta_P^2 = 0.16$), with near distance scoring significantly higher than far (MD = 0.27, SE = 0.09).

Even though there was no significant main effect of drone type, significant differences between the quadcopter and the flapper were found in terms of PL2 and PL8 of the subscale questions (listed in Table 1), see Figure 4(b). The flapper was rated notably higher on PL2 but lower on PL8 compared to the quadcopter, indicating participants found the flapper more entertaining but less satisfying than the quadcopter.

4.1.3 ***Discomfort Scale.*** Except for a significant two-way interaction between posture and distance (F(1, 52) = 4.45, p = .040, η_P^2 = 0.08), no other significant two-way or three-way interactions were found. Simple effects analysis of posture and distance were thus performed. As shown in Figure 6, for near distance, the ratings of the participants while sitting were lower than when they were standing (MD = 0.19, SE = 0.07), p = .009, d = 0.15.

As shown in Figure 5(a), significant main effects on the discomfort scale were found for drone type (F(1, 52) = 16.86, p < .001, η_P^2 = 0.25) and posture (F(1, 52) = 4.63, p = .036, η_P^2 = 0.08); but the effect of distance was not significant. Specifically, the quadcopter scored significantly lower than the flapper (MD = 0.75, SE = 0.18) and sitting scored lower than standing (MD = 0.11, SE = 0.05). Drone type has a visually obvious substantial impact on discomfort.

For the subscale questions (listed in Table 1), the flapper was rated significantly higher than the quadcopter across all six items. Notably, as shown in Figure 5(b), DC5 has the largest magnitude of difference, while DC6 has the smallest. This implies participants found the flapper particularly confusing but not as disappointing compared to the quadcopter.

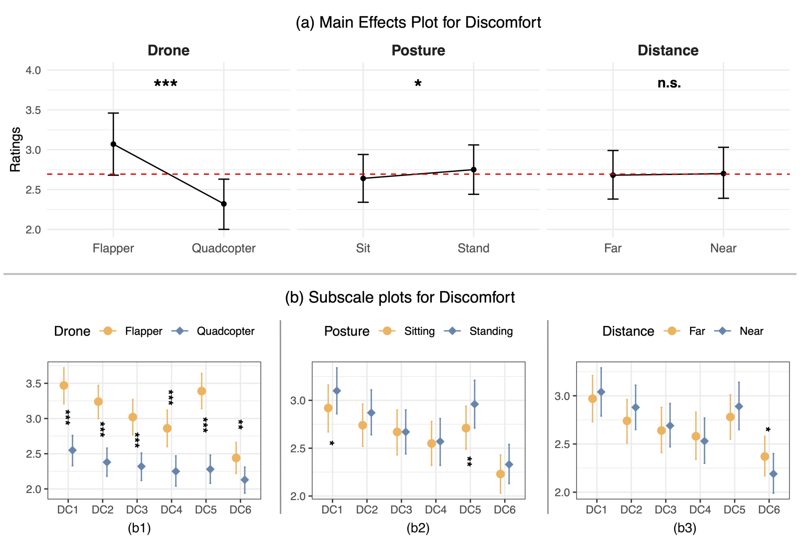

Fig. 5. (a) Main effects plots for discomfort; (b) Subscale plots for discomfort.

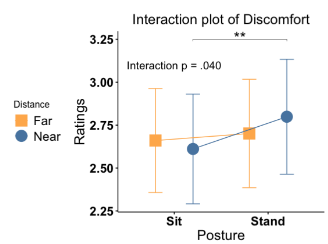

Fig. 6. Interaction plots of Posture×Distance.

4.1.4 ***Unexpectedness Scale.*** No significant two-way or three-way interactions were found. Thus, we interpret the main effects straightforwardly. As shown in Figure 5(a), the main effect for drone type was significant on the unexpectedness scale (F(1, 52) = 82.71, p < .001, η_P^2 = 0.61), with the quadcopter scoring significantly lower than the flapper (MD = 1.69, SE = 0.19); but the main effects of both posture and distance were not significant.

For the subscale questions (listed in Table 1), the flapper was rated significantly higher than the quadcopter across all six items. Notably, as shown in Figure 5(b), UE3 and UE4 have the largest magnitude of differences, implying participants found the flapper in particular looked bizarre and unexpected.

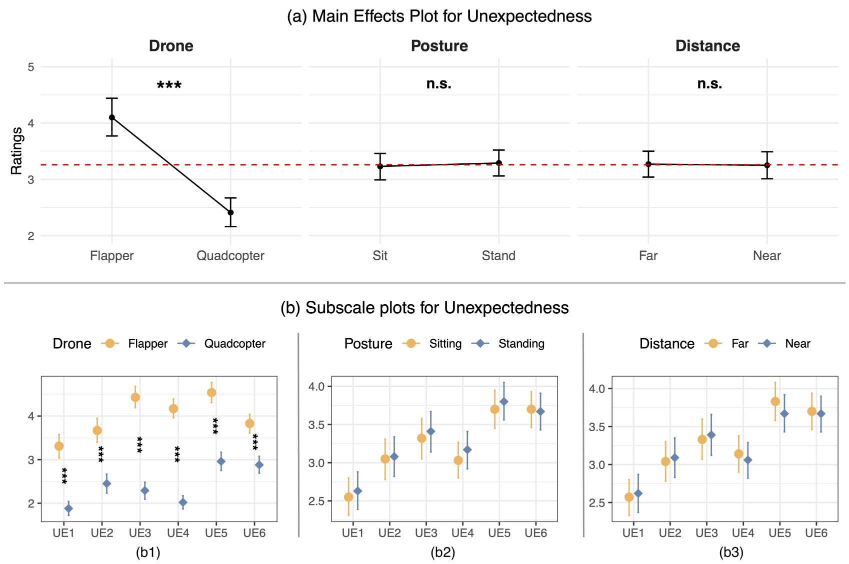

Fig. 7. (a) Main effects plots for unexpectedness; (b) Subscale plots for unexpectedness.

4.1.5 ***Heart Rate Trends.*** We calculated the average heart rate for each demonstration of each participant. A three-way ANOVA was conducted to examine the effects of posture, drone type, and distance to the drone on participants' heart rates. The analysis revealed a significant main effect of posture, F(1, 45) = 100.23, p < .001, η_P^2 = 0.69. Additionally, a significant interaction effect between posture and drone type was observed, F(1, 45) = 4.17, p = .047, η_P^2 = 0.09. Post hoc comparisons indicated that participants' heart rates were significantly higher while standing compared to sitting (MD = 4.82, SE = 0.48). This effect was consistent for both the flapper (MD = 4.32, SE = 0.45) and the quadcopter (MD = 5.32, SE = 0.62) drones. No other main effects or interaction effects were found. These findings suggest that the observed differences in heart rate were primarily attributable to postural changes, with standing consistently eliciting higher heart rates than sitting. The type of drone and distance to the drone did not have a significant effect on participants' heart rates. Furthermore, an analysis of the order effect revealed no significant effect on heart rates, indicating consistent heart rates throughout the whole experiment.

4.2 Qualitative Results

Here, we illustrate the identified themes with detailed descriptions of the trends found in the interview data, and excerpts from the transcripts.

4.2.1 ***Brand New Experience.*** Incontrovertibly, the flapper drone appeared to be completely new to participants, most of whom commented they had never seen this type of drone before and were unaware of its existence. Their reactions varied from excitement to uncertainty. For instance, P3 and P36 described the surprise and excitement of encountering the flapper drone for the first time as an eye-opening and amusing experience that exceeded their expectations. P40 described it as, "It was a very bittersweet moment, you know. Super fun, but oh my god, what's going to happen?" P22 also expressed appreciation for witnessing such advanced technology, noting, "It is really cool to see how we actually are in an era where an ordinary person can witness the existence of such advanced technology like the flapper."

The flapper drone consequently drew significant attention from participants, sparking curiosity and interest. Participants expressed a desire to understand its mechanics, particularly the wings — inquiring about their materials, quantity and other details. As P22 stated, "I wanted to know the engineering behind it, like how it managed to actually get it to lift stuff, so fascinating." P30 wondered how many wings there were and what kind of materials could enable its movement. This level of interest was also evident in informal conversations after the interviews, where many participants expressed an interest to interact more closely with the flapper.

In contrast, most participants showed more familiarity with the quadcopter, having encountered them through media, friends, relatives, or even personal ownership. They had already developed expectations regarding its characteristics. For instance, P4 said, "For the quadcopter, I was kind of expecting that kind of noise since I've experienced my friend's drone." Conversely, the flapper was perceived as intimidating and nerve-wracking due to its novelty. P10 noted, "The flapper was new to me. The sound of the flapping was a bit intense. It was making me anxious and tense." However, several participants, including P24 and P55, initially felt startled or unsettled by the flapper drone but later grew accustomed to it and became more relaxed.

4.2.2 ***Prominent Physical Features and Associations.*** Among all the physical characteristics of the drones, the flapper's wings were mentioned most frequently. Specifically, P3 noted that the movements of the flapper's wings reminded them of someone waving their hands, and could associate the sound it made with these movements. Additionally, the wings' material appeared fragile and soft to most participants. While this fragility made the flapper seem less dangerous to some, it also raised concerns about its durability. As expressed by P45 and P40, they worried more about damaging it and perceived it as less sturdy.

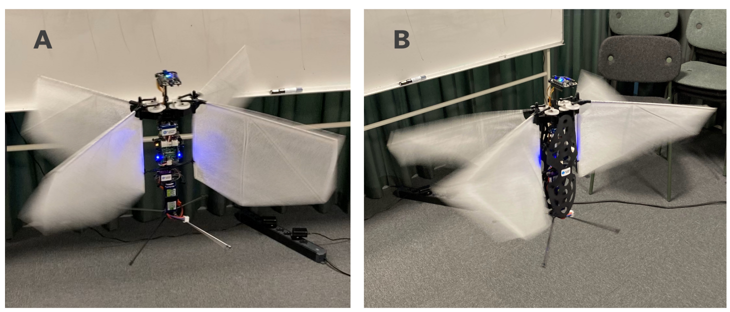

Fig. 8. Flapper flying in motion: (a) Body without casing; (b) With casing.

In the pilot study, the flapper lacked a cover, which made it appear visually slimmer, leading participants to associate it with dragonflies, see Figure 8(a). However, during the primary study, a cover was added to the flapper, see Figure 8(b). As a result, most participants began to compare the flapper to insects such as butterflies, moths, and bees. P19 noted, "The way the flapper flies is similar to how bees fly. Especially the mechanism, how the wings go down and go up." P37 remarked, "When I saw the shadows of the wings from the flapper, it reminded me of a moth flying under the light. Moths are drawn to light." P8 commented that the flapper's movement resembled a moth shaking off dust. The second most common association was with birds, particularly hummingbirds and pigeons. P1 highlighted, "The shape and the movement are very similar to hummingbirds." P10 commented, "I felt it was something similar to pigeons when it passed by. It was similar in terms of the size too." Some participants even drew parallels to the ornithopters from sci-fi movies. P4 said, "It really looks like the ships in the air in *Dune*."

Compared to the flapper, some noted that the quadcopter's visible propellers contributed to a sense of unease, and safety concerns of the fast-moving blades were raised, with P8 fearing potential harm and P42 specifically worried it could cut their finger. Additionally, many participants like P19 specifically noticed the camera on the quadcopter, whereas no camera was observed on the flapper. Overall, participants perceived the quadcopter as more mechanical and artificial, associating it with robots and machines.

4.2.3 ***Exploratory Prototype: Limitations and Future Potentials.*** The vast majority of the participants described the flapper's movements as unstable, shaky and unpredictable, which triggered a sense of discomfort and fear. P6 expressed concerns about the drone's instability and potential danger in public use. Similarly, P44 reported its unpredictability, which made the drone feel more threatening when facing it directly. In contrast, many participants found the quadcopter to be more stable and controllable. P1 compared the two, stating, "The flapper drone was shaking all the time. But the quadcopter was extremely stable. The control was very precise." P5 also claimed, "The quadcopter looked so good and controlled. I felt secure and comfortable with the show."

Regarding the drones' appearances, many participants felt that the flapper resembled a work-in-progress or an unfinished product due to its exposed components. P30 and P37 noted its exposed wires, flashing diodes, and minimal casing gave the impression that it was in an earlier stage of development,. In contrast, participants generally found the quadcopter's appearance to be mature, reliable, and familiar, making it less surprising. P12 and P30 noting it seemed like a well-refined design and professional product. P55 mentioning that its familiarity made it felt more safe but less exciting.

Several participants highlighted limitations they perceived in the flapper. For instance, P8 noted that finding a suitable landing surface outdoors would be challenging. P7, P16, P17, and P47 believed that weather conditions, such as strong winds and rain, would significantly impact the flapper's outdoor performance. Some participants were also concerned that the flapper's shaky movements might affect the quality of its photographs. Conversely, P16 pointed out that the flapper's unique structure might offer better cooling due to its open design, potentially allowing it to stay airborne longer compared to the compacted and closed quadcopter. Many participants also expressed positive attitudes towards the flapper's future potentials, believing there is room for improvement. P25 and P26 mentioned that they would prefer experimenting with the flapper, as it offers more room for optimization, while the quadcopter's design felt more fixed.

4.2.4 ***Ambiguity in the Flapper's Purpose and Potential Applications.*** Most participants struggled to understand the purpose of the flapper. For instance, P2, P25, P26 and P41expressed uncertainty about the flapper's practical applications, highlighting its unfamiliarity and admitting difficulty in imagining specific use cases. Moreover, levels of stability might have influenced participants' perceptions of drones' potential uses. As P35 noted, while the quadcopter's stability made its use for observation or exploration clear, the flapper's instability made its purpose more ambiguous.

Furthermore, the participants brainstormed possible scenarios and use cases for the flapper, which varied widely. A common suggestion was using the flapper as a toy for children. For example, P3 mentioned, "It could be used to keep babies happy. They cry a lot, and the flapper could distract them." P20 also noted, "The flapper almost looks like a bird. It could be used as a toy for kids, so they wouldn't be scared." Some participants believed that the flapper could be a tool for pets to chase. For example, P24 and P44 envisioned playful interactions between the flapper and pets, suggesting it as a tool to engage animals in exercise. Additionally, many participants suggested that the flapper could be useful for nature-related outdoor activities, such as field investigations, agriculture, and bird watching. P1, P13 and P15 highlighted how its natural, bird-like movements could help it blend into the environment and observe wildlife without disruption.

4.2.5 ***Impact of Posture and Distance on Perceptions.*** Participants' posture preferences and perceptions varied significantly due to individual differences. Many participants believed standing was safer and more flexible as it allowed for quicker reactions and movements. For instance, P6 and P20 remarked that standing was less stressful due to the ability to step back, but sitting created more difficulty in reacting quickly. Interestingly, P30 offered a unique perspective, interpreting standing as providing greater "freedom of movement," saying, "While standing, the drone felt more threatening because I felt more ready to defend myself." Conversely, some participants found sitting more preferable. P3 and P26 noted that while standing felt tiring, sitting allowed for greater relaxation and focus, making the experience more immersive, like watching a performance.

The most notable difference in participants' perceptions regarding distance was their sense of safety. The majority felt safer when the drone was farther away. For instance, P24 and P27 both expressed feeling safer at a distance, noting concerns about potential technical issues and increased worry about the drone crashing into them when closer. However, this increased sense of safety at a distance was not without drawbacks. Many participants found the drone less engaging when it was farther away. Proximity to the drone contributed to a more interactive, personal, and immersive experience. As reflected by P11, P15 and P17, they found the experience more immediate and immersive, allowing them to become more familiar with the drones. Several believed that being closer to the drone provided a better opportunity to observe and understand its behavior, which in turn made them feel safer. As P10 stated, "When I was near the drone, I could notice its presence. I would feel much safer knowing what is happening inside and what it is doing."

5 DISCUSSION

Our study advanced understanding of human experiences with bioinspired flapping-wing drones, a domain that remains underexplored compared to the well-studied rotorcrafts in HDI. Here, we discuss our findings, their implications, limitations, and directions for future work.

5.1 Relevance and Extension to HDI Literature

We found that the unclear perceived purpose of the flapper negatively impacted human experiences, aligning with prior research showing that ambiguity in drone function can cause discomfort and reduce positive engagement [70]. This finding underscores the importance of clearly communicating a drone's intended purpose and functionality, particularly for novel designs like flapping-wing drones. Consistent with previous work [6], we found that participants reported feeling more comfortable encountering drones while seated rather than standing. Furthermore, we observed a significant interaction effect between posture and proxemic distance, suggesting that human posture and spatial dynamics jointly shape perceptions of drones. Future HDI studies should consider these contextual factors to better reflect real-world interactions. Moreover, we also found that personal preferences varied widely, often shaped by individuals' prior experiences with drones or familiarity with animals. This finding aligns with previous work emphasizing how individual experience influences proxemic comfort and interpretability in HDI [59, 69, 70].

Interestingly, while prior studies consistently reported increased discomfort with closer drone distances [15, 17, 72], we found no significant discomfort differences across distances. Instead, closer proximity often fostered greater engagement and curiosity, likely because participants were intrigued by the novel flapping-wing mechanics. This indicates that perceptions of proximity may be context- and novelty-dependent. Although previous HDI studies have shown that nature-related cues (e.g., added natural sounds [69] or pet-like framing [70]) enhance pleasantness, we found no significant difference in reported pleasure between the bioinspired flapper and the conventional quadcopter. This suggests that natural morphology alone does not guarantee a more positive experience. A potential explanation is the *novelty effect*: the flapper's unfamiliar and unstable behavior may have overridden positive associations typically evoked by natural designs. Similarly, while earlier studies indicated that users often envisioned rotorcraft drones as pets or preferred animal-like behaviors [10, 16, 36], none of our participants suggested pet-like interactions with the flapper. Despite its zoomorphic appearance, the lack of perceived stability and familiarity may have hindered relational or companionable interpretations. Moreover, robotics researchers and the flapper manufacturer have claimed that flapping-wing drones are safer than conventional rotorcraft drones due to their soft wings, which tolerate minor collisions better than propellers [18, 22]. However, this safety benefit was not perceived by participants, likely due to unfamiliarity and the lack of direct contact experiences during the study. Overall, these findings highlight that to successfully leverage *nature effects* in HDI, designers must ensure not only experiential biomimicry but also interaction qualities such as predictability, familiarity, and perceived safety that support user acceptance.

5.2 Implications for Bioinspired Drone Design and Engineering

5.2.1 Improving Experiences through Enhanced Control. Participants who described the flapper as "uncomfortable", "scary", and "unsafe" often linked this to its unstable movement. Precise orientation and position control of flapping-wing drones remains a broad open technical challenge: the challenges of precise wing actuation, combined with the inherent flight dynamic instability of these drones, necessitates advanced and customized control strategies [53, 65]. The flapper used in this study used cascading proportional-integral-derivative (PID) control, of the same form as in a range of quadrotor platforms [27]. It is well known that this control architecture can be improved for flapping-wing drones [12, 65]—though, practically, this requires an in-depth modification of the drone firmware. While the development of improved control systems for flapping-wing drones is typically motivated by operational concerns (precise positioning, imaging, etc.), our study provides a new motivation: human experiences of these flapper drones will also likely be improved by improvements in control.

5.2.2 Tuning Physical Dimensions According to Context and Purpose. Our interviews reveal that drone size and morphology play a critical role in shaping user perceptions of appropriateness across contexts. Participants consistently indicated that the flapper should be more compact indoors to feel less disruptive and more manageable, while the current or larger sizes were considered acceptable outdoors, matching broader expectations of durability and utility in open environments. This reflects how physical scale can signal functional intention [70]. Notably, participants found it more difficult to imagine specific use cases for the flapper than for the quadcopter, and some described its motion or behavior as confusing. This likely stems from a lack of clear affordances in the flapper's design, which made it harder to infer function from form. Ultimately, our findings suggest that tuning drone size and morphology to match specific environments and user expectations could foster greater social acceptance and a richer ecosystem of applications of bioinspired drones.

5.2.3 Aligning Form with Familiar Species Archetypes. Participants in our study expressed discomfort and confusion when the flapping-wing drone's form blended traits from multiple animals (e.g., insect-like movement, bat-like wings, bird-like size), making it hard to categorize. This ambiguity likely contributed to unease, echoing findings in zoomorphic robot research where inconsistent biomimicry leads to negative reactions or uncanny perceptions [33, 46]. While creative hybrid forms may still have a place, they should be designed with care to avoid uncanny or confusing impressions. Notably, a casing-free version of the flapper in the pilot study was more often seen as dragonfly-like, illustrating how even small changes in design details (e.g., wing transparency, body slimness) can influence perceived biological resemblance. Bioinspired drone designs should align more clearly with recognizable and culturally accepted animal forms, since familiar and positively perceived species—such as butterflies, birds, or bees [44, 63]—may provide more intuitive design templates than those evoking stigmatized animals like bats or large insects [13, 35, 38, 42]. Grounding drone morphology in coherent and recognizable species archetypes could foster greater emotional comfort, interpretability, and social acceptance of bioinspired drones.

5.3 Limitations and Future Work

While our study offers novel insights into human interactions with bioinspired drones, several areas warrant further investigation and methodological refinement. The study was conducted in a controlled environment, which, while necessary for consistency, created an artificial context that may have influenced participants' perceptions. For instance, wearing heart rate sensors might have heightened participants' awareness of being observed, subtly altering their behavior. Future work conducted in more naturalistic, context-rich settings could help elicit more authentic responses that better reflect real-world scenarios. Our use of heart rate sensors was exploratory. These consumer-grade devices recorded data at one-second intervals and occasionally suffered from signal dropouts. As a result, our physiological data analysis was limited. Future work should employ higher-fidelity biometric tools and explore additional stress and emotion indicators, such as electrodermal activity (EDA) or facial expression analysis, to gain deeper insights into users' emotional and physiological responses. Given the within-subjects design, participants' responses may have been influenced by exposure to all conditions, due to practice and/or fatigue effects, although the conditions were counterbalanced. Future research could compare within- and between-subjects designs to evaluate how repeated exposure influences perceptions in HDI.

The spatial design included only two distance conditions, selected for practical and cost-effective reasons. However, this limited our ability to capture finer-grained sensitivities to proxemic variation. Incorporating a broader and more nuanced range of distances—especially more extreme or subtly varied ones—could enrich our understanding of how physical proximity mediates HDI across different morphological types. Although the lack of strict velocity control likely had minimal impact due to the short demos, differing motion profiles—such as velocity, smoothness, and oscillation—raise questions about their effect on perception. Future studies should systematically investigate these qualities, especially in bioinspired drones, to better understand their role in shaping human experience.

We considered that the novelty of the flapper may have overshadowed the effects of its bioinspired morphology. Participants' unfamiliarity with such technology may have diminished their sensitivity to the effects of nature-cue—that is, the extent to which the drone's zoomorphic qualities influence perception. Future studies could include a familiarization phase, where participants spend time to get familiar enough with flapper before the main experiment, in order to disentangle novelty responses from nature-cue-driven perceptions. This study only explored a specific type of flapping-wing drone, but participants often commented on attributes like shape, size, color, and material—all of which may influence acceptance and emotional response. Future research should systematically explore how different bioinspired morphologies and surface aesthetics affect perception. Investigating interactive flapper swarms, rather than individual drones, may also offer fresh perspectives, especially in social or performative contexts.

Grouping three participants in the same session in this study was done solely for practical reasons. While we did not observe major issues, group dynamics might have influenced individual reactions. Future studies should consider individual sessions to better isolate personal experiences. Rigorously investigating interactions between flappers or drones and humans within group settings may also provide valuable insights into social dynamics in HDI. Furthermore, expanding the participant pool to include individuals from diverse cultural backgrounds could reveal how cultural factors influence the perception of bioinspired drones. And finally, although we did not formally study children's experiences with the flapper drone, participants suggested that using bioinspired flying robots for educational or recreational purposes with children is a promising niche. A dedicated future study should investigate how children interact with these robots and explore potential applications in education, especially for STEM learning.

6 CONCLUSION

In conclusion, we conducted a within-subject experiment in a controlled environment, exposing participants to a bioinspired flapping-wing drone and a similar-sized quadcopter, in different postures (sitting vs standing), and positioned at different distances (near vs far). The results showed that participants rated the flapper drone significantly lower in perceived safety and higher in discomfort and unexpectedness compared to the quadcopter.

However, participants unanimously agreed on its novelty, finding it exciting, inspiring, and entertaining. Future design recommendations include scaling the drone size to its role and environment, enhancing control and stability, and focusing on familiar biological shapes or behaviors. Our work advances the field of HDI by offering insights into how people perceive bioinspired drones and how their presence and behavior shape human experience. The flapper drone's unique design has sparked conversations about technology diversity and how we might reshape our interactions with drones in the future. Its potential as an educational tool and yet-to-be-discovered applications opens exciting directions for future exploration.

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