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by

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Multisensory Interactions with Biophilic Flying Robots

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Thesis for the Double Doctoral Degrees

Multisensory Interactions with Biophilic Flying Robots

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谨以此博士论文献给妈妈

To mom, for the endless love and support

怀念爸爸

In loving memory of dad, who was always very proud of me and believed I would surely earn a PhD

愿自己博学审问，慎思明辨，笃定前行，继续做一个可爱的人

I hope to wander the world with knowledge and wonder, to think with depth and see the truth, to move forward with determination, and to remain always a loving and lovable person

铭

Zm̈g

Multisensory Interactions with Biophilic Flying Robots

Ziming Wang
Chalmers University of Technology and *University of Luxembourg*

Abstract

The relationship between nature and humanity has evolved throughout history and across technological epochs. This thesis advances the hypothesis that integrating natural characteristics into robot design can enrich human–computer interaction (HCI) by drawing on our deep-rooted familiarity with and affinity for the natural world. To investigate this proposition, I examined close-range interactions with flying robots under different proxemic conditions, employing a mixed-methods approach.

The thesis comprises four empirical studies, each probing a different pathway through which biophilic elements might shape human perception, interaction, and imagination. Study I examined how overlaying natural soundscapes such as birdsong and rainfall affected the perception of a noisy flying robot (N = 56). Study II explored nature narratives, particularly the conceptualization of indoor drones as animal-like companions through function framing (N = 60). Study III compared experiences with a bioinspired flapping-wing drone—foregrounding organic forms and biomimetic movement—against a similarly sized quadcopter (N = 56). Study IV staged a speculative dinner theater in which participants (N = 6) engaged with the provocative scenario of eating a biohybrid drone, highlighting hybrid living components as a design material. Across these studies, variations in spatial proximity (from very near to relatively far) and temporal framing (from near- to far-future scenarios) were integrated to reveal how context shapes engagement and experiences.

Collectively, the findings show that nature-inspired design elements can foster intuitive, relatable, and emotionally resonant interactions with flying robots, while also surfacing ethical and practical challenges. This thesis contributes empirical insights into how people respond to biophilic flying robots and argues for moving beyond surface-level biomimicry toward intentional, context-aware integration of natural elements. By treating nature not merely as aesthetic inspiration but as a lens for crafting meaningful, embodied interactions, we can design technologies that resonate more deeply with human experience—particularly in close-range, affective, and everyday settings.

Keywords: Human–Drone Interaction, Nature-Inspired Design, Proxemics, Multisensory, Interdisciplinary.

《与亲自然飞行机器人的多感官交互》

王子铭
[瑞典]查尔姆斯理工大学 & [卢森堡]卢森堡大学

摘要

自然与人类的关系历经历史长河与技术更迭而演变。本博士论文推动一假设：将自然特征融入机器人设计，可借助人类对自然世界的深层熟悉感与亲和力，丰富人机交互体验。为探究这一命题，作者采用混合研究方法，考察了不同空间距离条件下与飞行机器人的近距离交互可能方式。

本论文包含四项实证研究，分别探究亲自然元素塑造人类感知、交互与想象的多种路径。第一项研究考察了叠加自然声景（如鸟鸣与雨声）如何影响对嗡嗡作响飞行机器人的感知（样本量$N = 56$）。第二项研究探索自然叙事，特别是通过功能框架将室内无人机概念化为动物伴侣（样本量$N = 60$）。第三项研究对比了仿生扑翼无人机（强调有机形态与仿生运动）与同尺寸四旋翼无人机的体验差异（样本量$N = 56$）。第四项研究设计了一场科幻剧场晚餐，让参与者（样本量$N = 6$）体验食用生物混合无人机的情境，将混合生物元素作为设计素材加以呈现。这些研究通过整合空间距离（从极近到相对远）与时间框架（从近期到远期未来场景）的变量，揭示了情境如何塑造参与度与体验。

综合研究结果表明，自然启发的设计元素能够促进人类与飞行机器人之间直观、身临其境且情感共鸣的交互，同时也揭示了伦理与实践层面的挑战。本论文通过实证揭示人类对亲自然飞行机器人的反应机制，为该领域研究提供了新的视角与启示；并主张突破表面仿生学范式，转向有意识的、情境感知型自然元素整合。当我们不再将自然视为单纯的美学灵感，而是将其转化为构建有意义、具身化交互的视角时，便更能设计出更契合人类体验的技术——尤其在近距离、情感化及日常场景中。

关键词：人与无人机交互，自然启发设计，空间距离学，多感官交互，跨学科研究。

Preface

This thesis is the result of my PhD studies, which began in October 2020, in the interdisciplinary field of Human-Computer Interaction (HCI). It has been conducted within the framework of Double Doctoral Degrees (joint-supervision, in French: *cotutelle*), leading to the following diplomas:

- (in Swedish) ***Teknologie doktorsexamen i Data- och informationsteknik*** **[the Degree of Doctor of Philosophy in Computer Science and Engineering]** from Chalmers University of Technology in the Kingdom of Sweden, and
- (in French) ***Le Diplôme de docteur en psychologie*** **[the Degree of Doctor of Philosophy in Psychology]** from the University of Luxembourg in the Grand Duchy of Luxembourg.

In addition to my shared time between Sweden and Luxembourg, I have had the privilege of being a Visiting Researcher at Stanford University in California, USA, where part of the research work included in this thesis was conducted. I have been also an Academic Guest at the Swiss Federal Institute of Technology ETH Zurich in Switzerland, where the final part of this thesis has been written.

Furthermore, I undertook several shorter research stays at the University of Bergen in Norway, as well as lab visits and study trips to institutions in Singapore (NUS), the Netherlands (TU Delft), Denmark (Aarhus), the USA (MIT, Harvard, Cornell Tech, CMU, and UC Davis), Finland (Aalto), Japan (UTokyo and Hokkaido), and China (Tsinghua) among others. These international experiences have greatly enriched my PhD studies by broadening my academic perspective, fostering interdisciplinary collaboration, and inspiring new ideas that have shaped the direction of my research.

This is an article(paper)-based thesis, also known as a compilation thesis. I follow the *Scandinavian model*, in which the reprinted research papers are appended to an overall summary (in Swedish: ***kappa***) of their content. I am the lead author of all the papers included in this thesis, most of which have been published as full papers in premier peer-reviewed venues in the HCI field, including the prestigious CHI conference (CORE[1] A*), ACM Transactions on Human-Robot Interaction (Q1 in Robotics), and the IMWUT journal (Q1 in Computer Science, Information Systems; the publication outlet for the CORE A* UbiComp conference).

[1]Computing Research and Education: https://www.core.edu.au/conference-portal

In contrast to the included papers, which follow a highly structured format, the *kappa* summary in the Scandinavian model does not adhere to a fixed structure or require specific sections [1]. As a result, the style of a *kappa* varies from one thesis to another, even within the same institution. In the *kappa* of this thesis, I have aimed not to simply repeat the content of the included papers—as some other *kappa*s might—but rather to provide a high-level overview, articulate the connections among the studies, and share additional ideas and reflections that were not explicitly reported in the papers themselves. The goal is to offer further context and enrich the overall contribution of the thesis.

I used artificial intelligence (AI) and large language models (LLMs) to assist in improving the readability and clarity of the English language in this thesis. Every AI-suggested revision was carefully reviewed and, where necessary, further modified to ensure that the original meaning and intent were preserved. I take full responsibility for the content, including all interpretations, conclusions, and expressions presented in this work.

I have often heard people say that no one ever reads an entire PhD thesis. If you happen to be someone who made it through this one, please do let me know—via email or any other means. I would be very happy to hear from you! In any case, I hope readers will enjoy at least part of this thesis and, ideally, find it interesting, thought-provoking, or inspiring in some way. Thank you for taking the time to engage with my work.

子铭 Zǐmíng
Zürich, 2025 Summer

List of Papers

Included Papers

This compilation thesis is based on the following papers included herein:

[**Paper A**] **Z. Wang**, Z. Hu, B. Rohles, S. Ljungblad, V. Koenig, and M. Fjeld. 2023. "**The Effects of Natural Sounds and Proxemic Distances on the Perception of a Noisy Domestic Flying Robot**". *ACM Trans. Hum.-Robot Interact.*, 12, 4, Article 50. (Dec 2023), 32 pages. https://doi.org/10.1145/3579859 [Q1]

[**Paper B**] **Z. Wang**, Y. Wu, S. Yang, X. Chen, B. Rohles, and M. Fjeld. 2024. "**Exploring Intended Functions of Indoor Flying Robots Interacting With Humans in Proximity**". In *Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI'24)*, May 11–16, 2024, Honolulu, HI, USA. ACM, 16 pages. https://doi.org/10.1145/3613904.3642791 [CORE A*]

[**Paper C**] **Z. Wang**, M. Loerakker, Y. Wu, S. Yang, A. Pons, Y. Chuai, D. Sirkin, and M. Fjeld. 2025. "**In a Flap: Experiences with a Bioinspired Flying Robot**". *Proc. ACM Interact. Mob. Wearable and Ubiquitous Technol. (IMWUT / UbiComp'25)*, 9, 3, Article 138. (Sep 2025), 20 pages. https://doi.org/10.1145/3749495 [Q1 / CORE A*]

[**Paper D**] **Z. Wang**, Y. Wu, Q. Zheng, S. Zhang, N. Barker, and M. Fjeld. 2025. "**A Meat-Summer Night's Dream: A Tangible Design Fiction Exploration of Eating Biohybrid Flying Robots**". *Manuscript*, 25 pages, submitted to CHI'26. https://arxiv.org/abs/2510.06507

[**Paper E**] **Z. Wang**, N. Barker, Y. Wu, and M. Fjeld. 2023. "**Substituting Animals with Biohybrid Robots: Speculative Interactions with Animal-Robot Hybrids**". In *Designing Interactive Systems Conference (DIS Companion'23)*, July 10–14, 2023, Pittsburgh, PA, USA. ACM, 6 pages. https://doi.org/10.1145/3563703.3596641 [CORE A]

***CRediT**[2] **Statement**: For all papers, I contributed substantially to Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Project Administration, Resources, Software, Validation, Visualization, Writing – Original Draft, and Review & Editing. For Papers B, C, and D, I also made a minor contribution to Funding Acquisition.

[2] Contributor Role Taxonomy: https://credit.niso.org/

Other Papers

The following papers have been completed during my PhD studies but are not included in this thesis, as their content falls outside the thesis scope.

[a] **Z. Wang**, Z. Hu, Y. Man, and M. Fjeld. 2022. "**A Collaborative System of Flying and Ground Robots with Universal Physical Coupling Interface (PCI), and the Potential Interactive Applications**". In *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems (CHI EA'22)*, April 29-May 5, 2022, New Orleans, LA, USA. ACM, 7 pages. https://doi.org/10.1145/3491101.3519766 [CORE A*]

[b] **Z. Wang**, S. Yang, R. Currano, M. Fjeld, and D. Sirkin. 2025. "**AI Eyes on the Road: Cross-Cultural Perspectives on Traffic Surveillance**". *Manuscript*, 20 pages, submitted to CHI'26. https://arxiv.org/abs/2510.06480

[c] Y. Chuai, S. Zhang, **Z. Wang**, X. Yi, M. Mosleh, and G. Lenzini. 2025. "**Request a Note: How the Request Function Shapes X's Community Notes System**". *Manuscript*, 24 pages, submitted to CHI'26. https://arxiv.org/abs/2509.09956

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Foremost, my deepest gratitude goes to my main supervisor, Professor Morten Fjeld, who has not only selected me among many other applicants for the funded position that enabled me to start my PhD journey, but also been providing me excellent support and tremendous freedom along the way, allowing me to learn, explore, and grow. Morten, *tusen takk for alt!*

I sincerely thank my two supervisors in Luxembourg. First, Professor Vincent Koenig, who helped initiate my dual-PhD scheme and provided invaluable guidance and support. Later, Professor Pedro Cardoso-Leite, who kindly took over the supervisory role after Vincent decided to leave academia, ensuring that I could still accomplish the double doctoral programs as initially planned.

I am also very grateful to the other members of my supervision committees at both Chalmers and Luxembourg: my examiner, Professor Ulf Assarsson; my co-supervisor, Professor Sara Ljunblad; and my mentor, Dr. Björn Rohles, for their support—particularly Björn, for dedicating his spare time to this role. I owe special thanks to my advisor, Dr. David Sirkin, for looking after me during my time at Stanford, where I had a truly wonderful experience, and for his continued guidance and support even after I left California. I am also grateful to Professor April Wang for hosting me at ETH Zurich, where I learned a lot in various aspects while finalizing my thesis.

I want to thank my PhD defense committee: Professor Joe Paradiso for serving as my Opponent; Professors Niklas Elmqvist, Xiaojuan Ma, Florian Michahelles, Albrecht Schmidt, and Christoph Hölscher for serving on my Grading Committee; Professor Björn Johansson for serving as Suppleant; and Professor Palle Dahlstedt for serving as Chairperson. I also thank Professor Wendy Ju for serving as Discussion Leader at my half-PhD seminar.

I am grateful to all of my collaborators and co-authors, whose contributions are included in this thesis—especially Yiqian and Shiwei, who have also been good friends with whom I spent much time in Gothenburg.

To my colleagues, schoolmates, and friends across the various institutions, labs, organizations, and communities I have been part of, many of you have become an important part of my PhD journey.

Outside academia, I want to thank my dearest friends—those long-time pals who always glowed when I was in dark moments, as well as those lovely humans who brightened my days and kept me warm. To my family and relatives, thank you for always being supportive and proud of me.

There is a very long list of names I would like to include... Many of you have played multiple roles in my journey. I am truly grateful to everyone who has helped me, whether in small ways or in significant ones. 感谢大家! Thank you all! *Tack så mycket! Villmools Merci! Danke schöne! Merci beaucoup!*

Since my PhD research is in the field of human–computer interaction, I would like to make the thesis itself a little interactive:

[Please write, or I will write, your name here:] ____________, thank you!

Funding

I gratefully acknowledge the Wallenberg AI, Autonomous Systems and Software Program – Humanities and Society (WASP–HS). My PhD research was primarily funded by the Marianne and Marcus Wallenberg Foundation, and further supported by multiple smaller grants and scholarships from Chalmers Areas of Advance (AoA ICT, IDEA League), the University of Luxembourg (EPYSYLON, DHSSH, COSA), the University of Bergen (incoming mobility), and the Adlerbert Foreign Student Hospitality Foundation.

Contents

Part I

Kappa Summary

Chapter 1

Introduction

"Nature is the source of all true knowledge." — Leonardo da Vinci

Nature and humanity have always been deeply intertwined. Across historical epochs, from early agriculture and the domestication of animals to industrial automation and planetary urbanization, humans have been continuously shaping and being shaped by our interactions with the natural world. Technologies have evolved alongside us—not only as tools to harness nature's resources, but also as extensions of our will to survive, organize, and thrive. From primitive stone tools to AI-driven systems, each technological leap reflects a shift in how we relate to the environment, gradually asserting human dominance over other species and ecosystems through the exponential growth of machine power, human knowledge, and complexity.

Despite this long-standing interdependence, most man-made artifacts have remained perceptually and materially distinct from nature. The overwhelming majority of modern technologies are characterized by hard mechanical surfaces, rectilinear geometries, artificial lighting, synthetic materials, and abstract digital interfaces—qualities that clearly separate them from the natural world. Although humans have long aspired to build machines that resemble nature, the divide between the artificial and the natural has historically stemmed from limitations in knowledge, materials, and engineering paradigms, which constrained the ability to design technologies that could be realized with natural forms and behaviors. For instance, in the 15th century, Leonardo da Vinci sketched designs for a human-controlled plane simulating the flying mechanism of a bird through flapping its wings [2], see Figure 1.1. While conceptually driven by nature, the device was not feasible given the technological and material constraints of the time [3].

Yet nature continues to captivate us—not only through its aesthetic beauty, but also through its unmatched efficiency, adaptability, and intelligence. From the aerodynamic efficiency of bird wings to the decentralized intelligence of ant colonies, natural systems exhibit solutions honed by evolution over millions of years. This has long served as a wellspring of inspiration for technological innovation. A prominent example is the development of artificial neural networks, which mimic the principles of biological brains to power today's AI systems. Similarly, fields such as biomimicry and bio-inspired robotics now investigate how the principles underlying

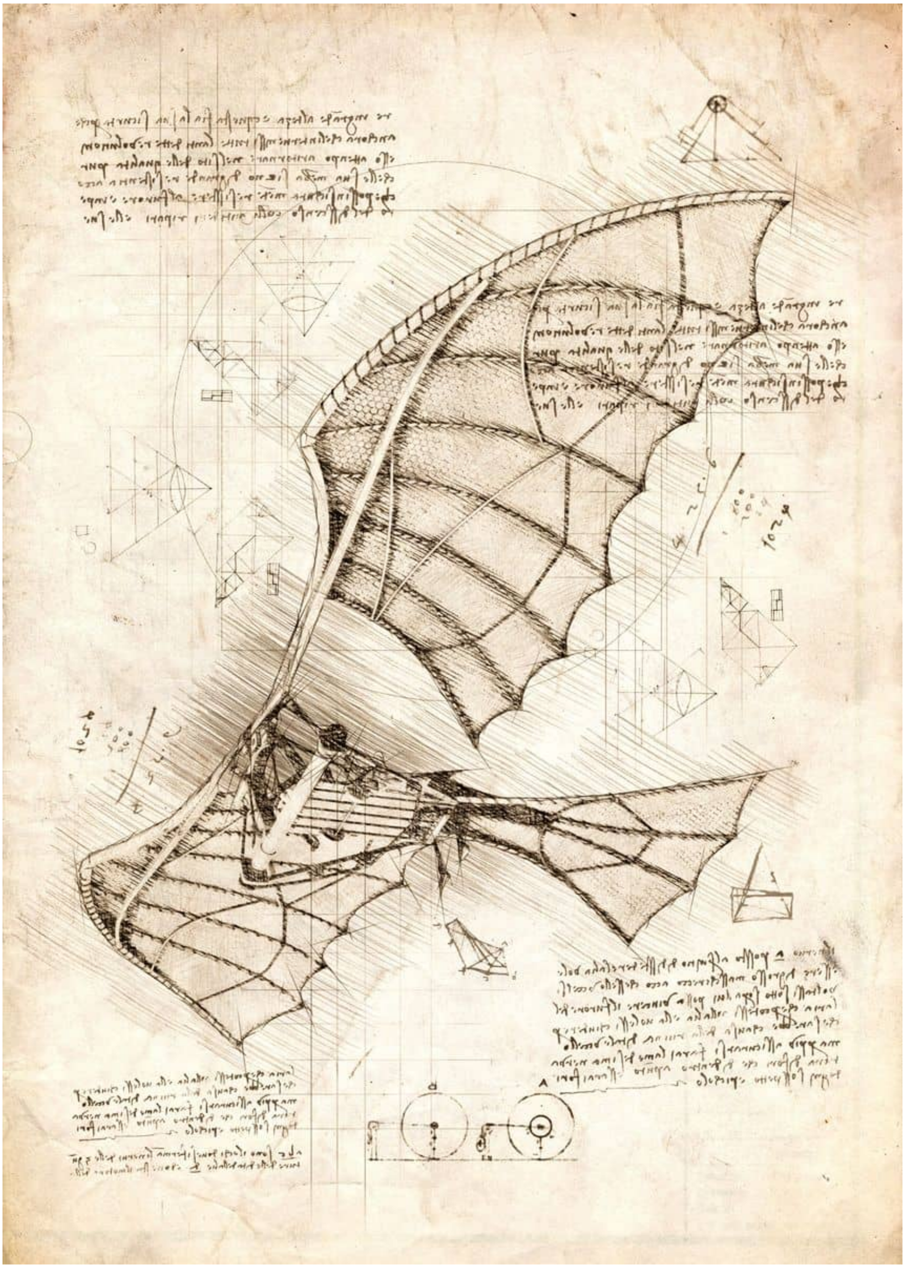

Figure 1.1: Design of a flying machine by Leonardo da Vinci. Source: [4].

natural organisms can inform the design of more efficient, adaptive, and responsive technologies.

Today, with rapid advancements in materials science, robotics, biotechnology, and artificial intelligence, the boundary between artificial and natural is beginning to blur. Researchers are now realizing biologically inspired flapping-wing drones [5]—an idea reminiscent of da Vinci's ornithopter—which, thanks to contemporary technologies, can finally achieve controlled flight. A wide range of other bioinspired and even biohybrid technologies are also emerging [6], including robots that grow like vines [7], machines with muscle-like actuators [8], and devices powered by actual biological muscle fibers [9]. These developments demonstrate how machines are increasingly adopting natural characteristics—not only in function, but also in form and behavior—and in some cases, integrating living components. However, much of this work remains focused on technical performance and engineering optimization: replicating nature to achieve greater agility, energy efficiency, and autonomy, or leveraging natural properties for improved functionality. What remains comparatively underexplored is not feasibility, but the human dimension: how people perceive, respond to, and interact with these technologies that are no longer clearly artificial, yet not entirely natural either. This shift makes the study of interaction both timely and necessary.

Flying robots, in particular, present a critical frontier for this investigation. Their ability to move dynamically in three-dimensional space, cross proxemic boundaries, and enter both public and private environments distinguishes them from other forms of technology. Indoors, where humans and robots must share close quarters, their design and behavior directly influence how people experience and accept them. Indoor drones are increasingly used in security, monitoring, entertainment, and personal assistance [5, 10, 11]—domains where intuitive interaction, trust, and acceptance are as important as technical capability. Studying them thus provides both conceptual richness and practical urgency.

Nature in design is entering an increasingly rich dialogue with Human–Computer Interaction (HCI) [12, 13], not merely as a technical or ecological concern, but also as one that is deeply cultural, philosophical, and personal [14]. Anchored in the theory of *biophilia* [15]—the hypothesis that humans have an innate preference for natural elements—this thesis explores how integrating natural characteristics into the design of flying robots can reshape the way humans engage with technology. By bringing together perspectives from HCI, nature-inspired and biophilic design, and multisensory interaction, this work seeks to understand how biophilic, multisensory flying robots can foster more intuitive, meaningful, experiential, and emotionally resonant human–robot relationships.

1.1 Overarching Research Questions

This thesis investigates how the future integration of drones into human environments—particularly within close-range, everyday contexts—can be shaped through design, with a focus on human-centered, multisensory, nature-inspired, and experimental approaches. Assuming that flying robots will become increasingly ubiquitous in daily life, the research aims to explore how design interventions can influence human–

drone interaction, perception, and experience.

A central thread throughout this work examines how incorporating natural elements—such as natural sounds, nature-evoking narratives, organic forms, biomimetic movement, natural materials, and even hybrid living components—into the design of drones might affect how people perceive and relate to these machines. Can such interventions foster pleasantness, trust, comfort, emotional connection, or entirely new types of interaction? Furthermore, how might multisensory design—engaging sight, sound, touch, smell, and even taste—mediate or enrich these experiences?

This inquiry spans both near-future scenarios and more speculative, long-term visions, addressing how drones might operate within varying spatial proximities and cultural contexts. It also reflects on the implications of these insights for researchers, designers, and engineers working at the intersection of robotics, design, and HCI. Based on these aims, the thesis is guided by the following overaching research questions:

- **ORQ1:** How can the integration of nature-inspired or nature-based elements in drone design influence human perception, emotional response, and trust in close-range interactions?
- **ORQ2:** In what ways can multisensory design strategies—visual, auditory, tactile, olfactory, and gustatory—shape the quality and character of human–drone interaction experiences?
- **ORQ3:** What implications do these human-centered design approaches have for envisioning and developing future scenarios of drone integration into everyday human environments, both near and long-term?

1.2 Brief Overview of the Studies

The overarching research questions (section 1.1) were translated into four focused empirical investigations, each examining a different facet of how biophilic elements can be integrated into flying robot design and experienced through multisensory interaction. All studies were conducted in physical environments where participants could engage with real drones in staged scenarios through multiple sensory modalities. Figure 1.2 shows the functional drones used in the four studies.

Each study incorporated a distinct intervention—namely, natural sounds, nature-evoking narratives, organic forms with biomimetic movement, and natural materials with hybrid living components—chosen to probe different pathways through which nature-inspired qualities might shape human perception, interaction, and imagination. These four studies are:

- **Study I (Natural Sounds):** Examined how overlaying natural soundscapes such as birdsong and rainfall onto the noise of a flying robot influenced human responses and perceptions (N = 56).
(**Paper A**, reprint of [11])

Figure 1.2: Drones used in the studies presented in this thesis

- **Study II (Nature-Evoking Narratives):** Explored potential roles for indoor drones, including the conceptualization of a "pet drone" as an animal-like presence in domestic environments with participants (N = 60).
(**Paper B**, reprint of [10])

- **Study III (Organic Forms and Biomimetic Movement):** Compared human experiences (N = 56) with a bioinspired flapping-wing drone to those with a similarly sized quadcopter.
(**Paper C**, reprint of [5])

- **Study IV (Hybrid Living Components):** Staged a design fiction in the form of an experiential dinner theater, where participants from the creative industry (N = 6) engaged with a speculative scenario of eating a biohybrid drone.
(**Paper D**, preprint (see [16]) + **Paper E**, reprint of [17])

Across all studies, the research also examined how spatial proximity (ranging from very near to relatively far distances) and temporal framing (from near-future to far-future scenarios) influenced participants' perceptions and experiences. These dimensions were integrated into each study's design to explore how context, distance, and time horizon shape the potential role of biophilic flying robots in human lives. A fuller discussion of the overarching narrative connecting these studies, along with detailed summaries of their designs, methods, and findings, is provided in Chapter 4: The Four Studies.

1.3 Thesis Structure

As mentioned in the Preface, this compilation paper-based thesis follows the *Scandinavian model*, where Part I, the *Kappa* Summary, provides an overview and synthesizes the research presented in the appended papers as Part II. *Kappa* chapters generally do not follow a fixed structure and may vary in style [1]. Nevertheless, this *kappa* aims to offer a comprehensive overview, along with supplementary information and reflections not explicitly or fully addressed in the individual papers.

The remainder of Part I continues with Chapter 2: Motivations and Key Concepts, which further elaborates on the contextual foundations of the thesis. This is followed by Chapter 3: Research Philosophy and Methodological Considerations, which outlines the often-overlooked metatheoretical underpinnings of the research and the rationale behind key methodological choices. Chapter 4: The Four Studies presents a detailed overarching narrative with summaries of each study. Chapter 5: Discussion offers broader thematic discussions on the research as a whole.

Part II includes five papers: four original research articles (Papers A, B, C, and D) and one discussion paper (Paper E). Papers A, B, C, and E have been peer-reviewed and published; they are reproduced here as exact reprints of the versions published in their respective venues, with copyright retained by me as the lead and corresponding author, shared with my co-authors. Paper D, which is currently under review, is included as a preprint.

Chapter 2

Motivations and Key Concepts

This chapter outlines the contextual foundations of the thesis and situates the contributions of the appended papers within the context, introducing the overarching motivations and key concepts that unify the research. It serves as a conceptual backdrop rather than an exhaustive literature review. Detailed, domain-specific discussions of related work are presented in the appended papers in Part II, each addressing background material relevant to its specific research questions.

Herein, we first examine the context of human–drone interaction and the core factors explored in this thesis, followed by an overview of nature inspiration approaches and technologies, where bioinspiration and biophilia are seen as complementary. We then consider multiple senses, their spatial ranges, and their relationships and significance to human experiences. Lastly, we discuss the value of imagining and studying possible futures as an important approach in HCI research, and outline the future-oriented aspects of the studies in this thesis across different time scales.

2.1 Human–Drone Interaction (HDI)

Recent market analyses indicate a steady rise in consumer drone sales, with miniaturized drones emerging as one of the fastest-growing segments [18]. Human–Drone Interaction (HDI) is an emerging research domain within human–computer interaction (HCI) that investigates how people perceive, respond to, and collaborate with flying robots. As drones become increasingly present in everyday environments, designing interactions that are both functional and meaningful has become a pressing challenge. Unlike ground-based robots, drones introduce distinct opportunities and constraints arising from their three-dimensional mobility, proxemic dynamics, acoustic signatures, and morphological diversity [19, 20]. Applications now span search and rescue, inspection, and delivery, as well as education, entertainment, and companionship—each with unique human factors and design requirements [10, 21, 22]. While early research concentrated on technical performance, the field increasingly addresses the social, perceptual, and experiential aspects of human–drone encounters.

Interaction Context in HDI: Indoor vs. Outdoor

The context in which drones operate critically shapes HDI design. Although most commercial and research deployments have focused on outdoor environments, the anticipated growth of drones in human-inhabited spaces demands careful consideration of indoor scenarios. Indoor drones are typically smaller, lighter, and less powerful than outdoor counterparts, with limited payloads, endurance, and different noise profiles [10, 23]. These characteristics create distinct affordances and constraints: confined spaces intensify proximity effects, noise is more perceptible, and privacy concerns are heightened. At the same time, indoor settings enable sustained close-range interaction for applications such as guidance, education, and companionship [10, 21, 22]. Outdoor contexts, in contrast, allow greater range and payload but require strategies for visibility, safety, and adaptation to variable environmental conditions. Across both settings, in-situ studies—conducted with real drones in relevant environments—are essential for understanding authentic user experiences [5, 10, 11].

Although many HDI studies have taken place indoors for practical reasons, purposefully designed research on indoor, close-range, embodied interaction remains limited [10]. This thesis addresses that gap by focusing on close-range interactions, primarily in indoor environments, while deriving insights applicable to outdoor scenarios where similar conditions apply.

Core Factors in HDI

As drones expand from specialized outdoor uses to indoor and other human-inhabited, close-range settings, questions of proxemics, sensory attributes, function legibility, and morphology become central to user acceptance and experience.

Proxemics. Hall's theory of proxemics [24], which divides interpersonal space into intimate, personal, social, and public zones, has been used to study how people react to nearby drones. Research consistently finds that distance, trajectory, and speed influence perceptions of safety and trust [20, 25, 26]. While closer approaches can foster engagement, they often increase perceived risk, with acceptable thresholds varying by context and individual differences [27, 28]. This thesis further investigates how proxemics interacts with other modalities—such as sound or functional framing—to shape experience and suggest that spatial configuration should be treated as a deliberate design parameter rather than a fixed constraint.

Sensory Attributes. The acoustic presence of drones—particularly rotorcraft, where propulsion noise and aerodynamic turbulence dominate—is one of the most salient perceptual factors in HDI [11]. Engineering solutions such as propeller optimization or active noise cancellation remain limited for small indoor drones [29]. Consequently, this thesis explores alternative approaches, including perceptual strategies (e.g., masking noise with natural sounds) and mechanical redesign (e.g., adopting flapping-wing mechanisms) to address the sensory challenges of "consequential sound".

Function Legibility. A drone's intended function—whether for delivery, surveillance, assistance, or play—strongly influences user perceptions and acceptance.Ambiguity or hidden functions can evoke discomfort and perceptions of creepiness [30], whereas transparent and socially meaningful roles foster trust [10]. Functional intent can be conveyed through motion patterns [31, 32], symbolic indicators, or environmental cues, with the most effective designs combining multiple communication channels. The studies in this thesis emphasize the role of function legibility in shaping interaction outcomes.

Morphology. Physical form affects how people interpret a drone's capabilities, safety, and purpose. While quadrotors dominate current HDI research, alternative forms—such as fixed-wing, hybrid, or bioinspired flapping-wing drones—offer distinct perceptual and functional characteristics [5, 33, 34]. Novel forms can spark curiosity and engagement but may also introduce perceptions of unpredictability or risk [35]. This thesis also examines morphology as a factor in close-range HDI, particularly in relation to perceived safety and user experience.

2.2 Nature Inspiration and Technologies

Nature has been a source of inspiration for centuries, shaping both the arts and sciences. In interactive technologies, this inspiration has evolved into two intertwined trajectories: **bioinspiration**, which adapts principles from natural organisms and ecosystems to improve technological form, function, and behavior; and **biophilic design**, which incorporates the qualities of nature to enrich human experiences. Together, these approaches hold distinctive potential for HCI, where both technical performance and experiential acceptance are critical. They motivate a design agenda that supports human flourishing, ecological awareness, and more-than-human coexistence [13, 15, 36]. This requires moving beyond performance optimization alone toward cultivating experiential authenticity, ecological empathy, and social acceptance across contexts [5, 6, 14].

Biophilia posits an innate human tendency to affiliate with life and "life-like processes", a claim supported by evidence of stress reduction, attentional restoration, and emotional well-being [15, 37, 38]. Contemporary HCI extends this legacy by asking how interactive systems can surface natural dynamics (light, airflow, soundscapes, growth), foster embodied and multisensory engagement, and give agency to more-than-human stakeholders (e.g., plants, pollinators) [13, 14]. This involves moving beyond token greenery or simulated landscapes on digital displays toward ecological authenticity, multispecies flourishing, and equitable access to meaningful nature experiences [13]. Visual-centric approaches risk neglecting smell, touch, movement, and temporal variation, and overly "sanitized" representations can undermine genuine connection [13]. More embodied and multisensory approaches are therefore needed. This thesis explores how drones can integrate biophilic qualities—through morphology, motion patterns, acoustic tuning, and multisensory cues—to become more approachable, restorative, and socially acceptable.

Bioinspiration and biomimetics, in turn, translate biological strategies into robotic design [6]. For flying robots, this includes flapping-wing designs that emulate the flight mechanics of birds or insects [5]. While these designs often originate from engineering goals such as maneuverability, efficiency, or autonomy, they also carry perceptual and symbolic weight. The way a drone looks and moves can evoke familiar species archetypes (butterflies, birds, bats), shaping emotional responses and social interpretation [35].

Recent advances in biohybrid robotics and animal–robot analogies [39] extend this inspiration further: machines are increasingly adopting natural characteristics—not only in function, but also in form and behavior—and, in some cases, integrating living components. Biohybrid designs may incorporate muscle tissue, plant matter, or microbial systems; others simulate lifelike gestures, self-repair, or growth. Much of this work still focuses on technical performance: replicating nature to improve agility, efficiency, and autonomy, or leveraging natural properties for functional gains [6].

What remains comparatively underexplored is the human interaction dimension—how people perceive, respond to, and relate to machines that are no longer entirely artificial yet not entirely natural. These "living machines" occupy an ontological grey zone that can provoke fascination, empathy, or discomfort. They challenge established mental models of technology, agency, and life, raising new questions about trust, proxemics, ethics, and social norms.

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In this thesis, the notion of a "grey zone" is framed primarily as phenomenological rather than ontological for Studies I–III: natural cues (sound, form, motion) may make machines feel more lifelike in experience without rendering them biologically living. The ontological boundary is probed most directly in Study IV, where biohybrid imaginaries raise questions of material integration and ethics. Accordingly, claims about "new mental models" are grounded in how participants interpret and relate to such systems across the studies, rather than in any blanket assertion that biophilic drones are inherently partly alive.

2.3 Multisensory Experiences and Spatial Ranges

In close-range HDI, multiple sensory channels are typically engaged simultaneously due to the reduced separation between human and drone and the tangible nature of the encounter [11]. This proximity makes sensory integration especially relevant: visual cues from the drone's movement and form; auditory cues from its consequential sound; tactile cues from airflow or vibration; and, in certain contexts, olfactory cues—such as the smell of construction materials or odors from overheating components in cases of malfunction or short circuit. Designing for such multisensory experiences is therefore not optional—it is fundamental for creating interactions that are natural, comfortable, and ecologically valid.

Human perception and interaction with the environment are inherently multisensory. People experience the world not through a single channel, but by integrating information from multiple sensory modalities—vision, hearing, touch, smell, and taste—each contributing unique capabilities and constraints. This integration is fundamental to human existence: senses work together to create experiences that are immersive, affective, and embodied. In the context of HDI, leveraging multiple sensory channels can make interactions not only more engaging but also more intuitive and meaningful, aligning with the ways humans naturally perceive and interpret their surroundings.

Different senses operate over distinct spatial ranges and directional sensitivities, influencing how people detect and respond to stimuli in space:

- **Vision** allows humans to perceive objects over long distances, but only within the field defined by gaze direction.
- **Hearing** operates in all directions but over a shorter spatial range compared to vision.
- **Touch** depends on direct physical contact or the perception of forces on the skin, limiting its range to the body's immediate reach.
- **Smell** is effective over relatively short distances, depending on airflow and the presence of airborne particles.
- **Taste** is restricted to direct contact with the tongue.

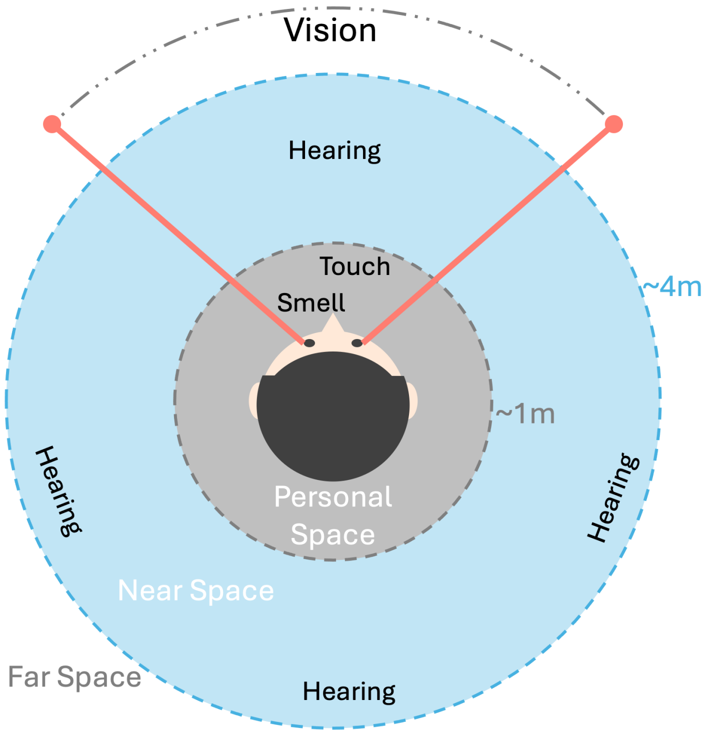

Figure 2.1: Hall's concept of extra-personal space, with schematic spatial ranges of the visual, auditory, and somatosensory modalities that contribute to spatial perception, based on[40]; ranges are approximate and context-dependent.

These spatial and directional characteristics mean that different sensory cues become salient at different interpersonal distances, as reflected in Hall's proxemic zones [24]. For instance, visual cues dominate in public and social zones, whereas tactile and olfactory cues are more relevant in intimate or personal space. Figure 2.1 illustrates the spatial ranges of these senses in the context of Hall's extra-personal space definition. In Hall's framework, taste falls largely outside the scope of proxemics, as it occurs primarily inside the mouth or body. This is consistent with its limited presence in HCI research, given that edible technologies remain far less common than other sensory modalities. Nevertheless, this thesis explores taste and smell in Study IV through a speculative design approach, demonstrating how even underrepresented senses can expand the boundaries of HDI by provoking new perspectives on multisensory engagement [16].

In real life, multiple factors interplay to shape sensory experiences. For instance, hearing spans all directions, and its effective range varies substantially with frequency and environmental conditions (e.g., enclosures, terrain, wind). Lower frequencies attenuate more slowly and may travel farther in some settings, whereas high-frequency components diminish more rapidly. The practical implication for HDI is that drone acoustics are perceived differently across rooms, corridors, and outdoor spaces, rather than functioning as a uniform short-range channel. Critically, the realism of sensory input determines the quality of multisensory integration and the authenticity of human responses. Ecologically valid stimuli—those that preserve the natural timing, intensity, and congruence of cues—enhance perceptual coherence, support trust, and reduce cognitive load during interaction [41, 42]. In HDI, this means that real-drone experiments capture richer and more reliable user data than simulations or video-based studies, which often fail to reproduce tactile forces, low-frequency noise components, or airflow effects [43, 44]. Crossmodal effects depend heavily on the synchrony and spatial congruence of cues—delays or mismatches between, for example, motion and sound can break immersion and even cause discomfort [45].

Close-range drone encounters are particularly sensitive to these factors because they naturally involve multiple overlapping sensory channels—sight, sound, airflow, vibration, and sometimes smell. Realistic, congruent stimulation across these channels is essential for designing HDI experiences that feel authentic, immersive, and comfortable. By considering both the capabilities of each sensory modality and their spatial ranges, HDI design can better orchestrate multisensory cues to enrich interactions, support functional communication, and ensure positive experiences across different interaction distances [11].

2.4 Imagining Futures

"The future interests me – I'm going to spend the rest of my life there."
— Mark Twain

In Human–Computer Interaction (HCI), a significant body of frontier research investigates possible interactions ahead of product realization or implementation [46]. Such work employs methods that allow researchers to study potential experiences and implications without fully functional systems. One widely used technique is the *Wizard-of-Oz* method (e.g. [47]), in which system behaviors are simulated or "faked" by a human operator to prototype future capabilities. This approach enables early exploration of user responses, design affordances, and ethical questions, even when the underlying technology is not yet mature. Such speculative exploration spans a continuum—from **near-future scenarios**, in which existing technology could feasibly evolve within a few years, to **far-future visions**, where the imagined interactions may depend on breakthroughs in materials, energy, artificial intelligence, or policy frameworks.

Within HCI, speculative design and design futures frameworks provide structured ways to craft and evaluate imagined futures. These approaches push beyond incremental improvements to envision radically different configurations of technology, use, and social meaning. By treating design as a form of inquiry, they allow researchers to interrogate cultural narratives, challenge implicit assumptions, and provoke debate about desirable technological trajectories [48, 49].

In this thesis, explorations of interactive drones are situated along a future timeline under the assumption that flying robots will become increasingly ubiquitous in daily life. Most studies (Studies I, II, and III) adopt a near-future orientation, envisioning plausible deployments based on current trends, while one study (Study IV) adopts a far-future lens to probe more radical possibilities. This temporal range enables the research to address both imminent design challenges and longer-term speculative questions.

A futures-oriented approach makes it possible to move beyond immediate technological constraints, opening space to imagine alternative interaction paradigms and values for human–drone coexistence. This work considers not only functional capabilities but also the aesthetic, behavioral, and sensory dimensions of drones, questioning normative assumptions about their roles in everyday environments. By engaging participants and readers in acts of imagination, reflection, critique, and dialogue, this thesis aims to shape discourse around drones toward outcomes that are socially beneficial, ethically responsible, and experientially rich.

Chapter 3

Research Philosophy and Methodological Considerations

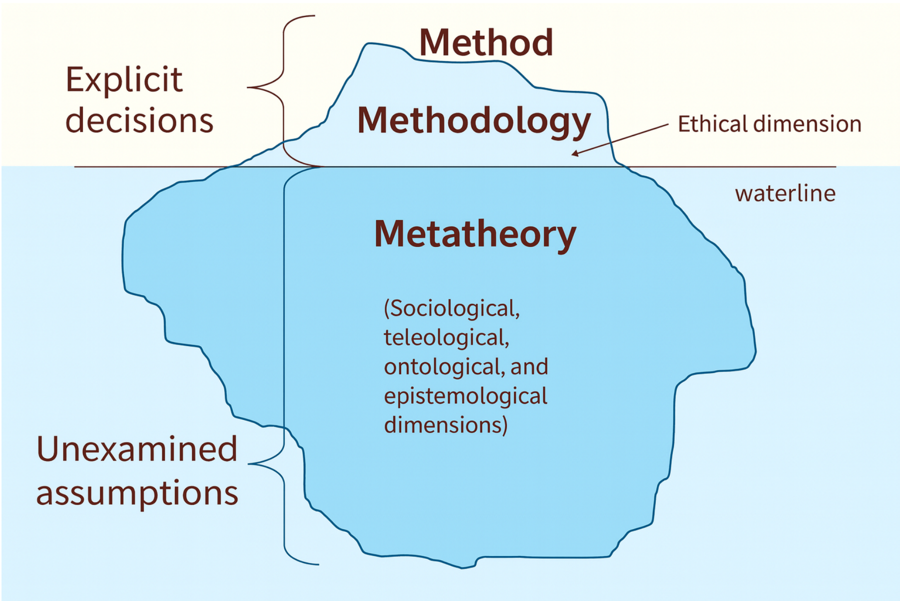

Figure 3.1: "Iceberg model", based on [50].

Regarding research philosophy, there is a hierarchy of precedence from ontology to epistemology, followed by methodology and methods. While methodology and methods are routinely reported in scholarly works, metatheoretical considerations including ontological and epistemological positions are often left unstated [50], remaining implicit and largely hidden beneath the surface. Figure 3.1 uses the "iceberg model" to illustrate this relationship.

Although less frequently discussed, ontology and epistemology provide the conceptual foundation for methodology and methods, shaping the coherence, scope, and interpretation of research outcomes. For this reason, I consider it valuable and important to make these underlying assumptions more explicit.

In this chapter, I share my worldview by reflecting on the metatheoretical assumptions that have, at times explicitly and at times implicitly, guided my work. I also discuss the relevant methodological considerations at a general level that unify the whole research. The specific methods employed in each study are detailed in the appended papers in Part II.

3.1 Metatheoretical Considerations

"The brain is merely a meat machine." — Marvin Minsky

At the ontological level, my position is firmly grounded in materialism, also commonly referred to as physicalism [51]. I hold that all existence is dependent upon matter, and that consciousness is not an immaterial essence but a physical phenomenon arising from the material processes of the brain. Marvin Minsky's metaphor of the brain as a "meat machine" vividly expresses this view, underscoring the idea that, in principle, there is no barrier to replicating a brain within an artificial substrate. Extending this reasoning, I maintain that humans can eventually replicate all natural phenomena through technological means—although the time required for such achievements may extend far beyond present foreseeability. In the meantime, we are already creating entities that blur the boundary between the natural and the artificial, such as biohybrid robots [6]. The idea that artificial creations can progressively become more "natural" therefore constitutes a foundational premise of this thesis.

Philosophically, this position aligns with ontological monism—the conviction that reality is of a single kind, namely material. Yet ontological monism need not entail epistemological monism. Here I adopt a form of epistemological pluralism, which resonates with both pragmatist traditions (where truth is seen as what proves useful in practice) and critical realism (where different methods capture distinct aspects of a stratified reality). From this perspective, no single epistemic framework—be it empirical science, computational modeling, or artistic exploration—can claim exhaustive authority. Instead, each constitutes a partial but valuable mode of disclosure, revealing different facets of phenomena that are themselves materially grounded.

Practically, this metatheoretical stance provides the foundation for the methodological diversity that characterizes my work. While a materialist ontology inclines me toward scientific and technical accounts, the embrace of epistemological pluralism enables me to employ a wide range of approaches—from the rigorous and repeatable methods of empirical science to more speculative and exploratory artistic practices. I regard empirical rigor and creative exploration not as antagonistic but as complementary, each illuminating aspects of phenomena that the other cannot fully capture. This conviction reflects a broader belief that epistemological pluralism enriches inquiry, allowing for a more comprehensive and nuanced engagement with complex problems than any single methodology alone could provide.

3.2 Methodological Diversity and Mixed Methods

In practice, the orientation toward methodological diversity outlined above has led me to adopt a **mixed-methods approach** in the majority of my studies. Specifically, in the three more conventional studies presented in this work (Studies I, II, and III), I combined quantitative and qualitative methods of data collection and analysis. This approach yields a richer understanding of the research questions than would be possible through reliance on either method alone [52]. Quantitative methods contribute generalizability and statistical validation, while qualitative methods provide contextual depth, interpretive insight, and sensitivity to emergent phenomena. By integrating these approaches, I can leverage their respective strengths, cross-validate findings, and construct a more complete picture of the phenomenon under study. These methodological choices are not arbitrary but are grounded in appropriate sample sizes (approximately 50–60 participants), sound study designs, and controlled study conditions.

At the same time, I recognize that not all research questions are best addressed through mixed methods. For example, Study IV in this thesis took the form of an artistic exploration to a large extend, for which a qualitative approach was both more suitable and more meaningful. Likewise, in separate projects I worked on (Papers b and c listed in Other Papers, see [53, 54]), a purely quantitative approach was employed. For instance, Paper b was through a large-scale online survey, which allowed for the collection of broader demographic data at scale [53]. These choices reflect not only methodological openness but also a guiding principle: methods should be determined by the demands of the research question, the study design, and the specific context.

This stands in contrast to more rigid methodological orientations, where researchers may consistently rely only on quantitative or qualitative methods. Such specialization often stems from disciplinary training or comfort within a particular paradigm. While expertise in a single method brings depth, it can also impose limitations on the range of research problems one is prepared to tackle. By contrast, embracing methodological diversity expands the scope of inquiry and fosters flexibility in addressing complex, interdisciplinary questions. In my view, methodological decisions should not be constrained by convention or personal comfort, but rather should be responsive to the requirements and suitability of each individual study. This principle of methodological fit underlies the research presented in this thesis and reflects my broader commitment to a pluralist and integrative approach.

3.3 Arts & Sciences and Design Research

> *"Arts and sciences are branches of the same tree."* — Albert Einstein

Einstein's metaphor suggested that the arts and sciences, while seemingly distinct, are bound by a common human impulse: the desire to understand, express, and make meaning of the world. Sciences traditionally focus on explaining phenomena—discovering principles, laws, and causal relationships that account for how the world works. Arts, in contrast, explore human experience—giving form to emotions, values, and perspectives that shape how the world is lived and understood. What unites them is a shared pursuit of knowledge and expression, albeit through different methods and outputs.

Modern design research sits precisely at this intersection. As Buchanan explains, its roots can be traced to Galileo Galilei's *Two New Sciences*, which began not with physics but with observations of artisans and mechanical inventions in the Venetian Arsenal, linking practical making with systematic inquiry. Likewise, Francis Bacon's *Great Instauration* envisioned our ability to command nature through the creation of "artificial things", essentially positioning design as central to human progress [55]. Yet design was once long dismissed in academic circles as merely "servile" artisan, outside the legitimate intellectual pursuits of the university. Today, however, design is re-emerging as a neoteric form of learning, one capable of bridging the fragmented domains of arts and sciences and reuniting knowledge with practice [55].

A prominent example of this re-emergence is **Research through Design (RtD)**, particularly visible in HCI. RtD treats design practice itself as a method of inquiry: knowledge is generated by making, with artefacts serving not only as outcomes but also as carriers of insight. Herriott's critique, however, underscores that RtD mirrors the logic of conventional research—posing questions, creating experimental prototypes, collecting and analyzing data, and building theory [56]. Its novelty lies less in inventing a new epistemology than in foregrounding making as a legitimate research act. Standard experimental science often studies pre-existing phenomena; RtD, by contrast, constructs phenomena to study. Both, however, depend on systematic inquiry, iteration, and the production of communicable knowledge [56].

This perspective helps clarify an enduring tension in design research: tacit versus explicit knowledge. Proponents of RtD argue for a "designerly way of knowing", yet, as Herriott notes, designers do not know in a fundamentally different way from scientists. What matters is not mystical intuition but the ability to articulate insights embedded in artefacts and translate them into communicable knowledge [56]. Seen this way, RtD is not radically different from experimental science—it is another form of it, one that retains its practice-based flavor while being securely situated within the broader research tradition.

In this thesis, my work reflects this bridging of arts and sciences. Studies I–III adopt a scientific orientation, using controlled experimental design to generate testable findings. Study IV, in contrast, leans toward the artistic side, emphasizing designerly knowledge expressed through artefacts. Yet both orientations share the same fundamental principle: systematic inquiry aimed at creating knowledge that is communicable, meaningful, and impactful.

3.4 Research Design: Quasi-Experiments and Internal vs. External Validity

In HCI, the majority of studies fall into the category of quasi-experiments. To situate this, it is useful to distinguish between the three major families of research design [57]. **Experimental studies** are highly controlled, relying on random assignment and systematic manipulation of independent variables to test causal relationships. **Non-experimental studies**, by contrast, involve observations, surveys, or case studies in which variables are not manipulated, making causal inference weak but ecological realism stronger. **Quasi-experimental studies** occupy the space in between: they involve some manipulation and structured comparison but lack full randomization or complete control over conditions. Figure 3.2 illustrates the general tendency across study designs.

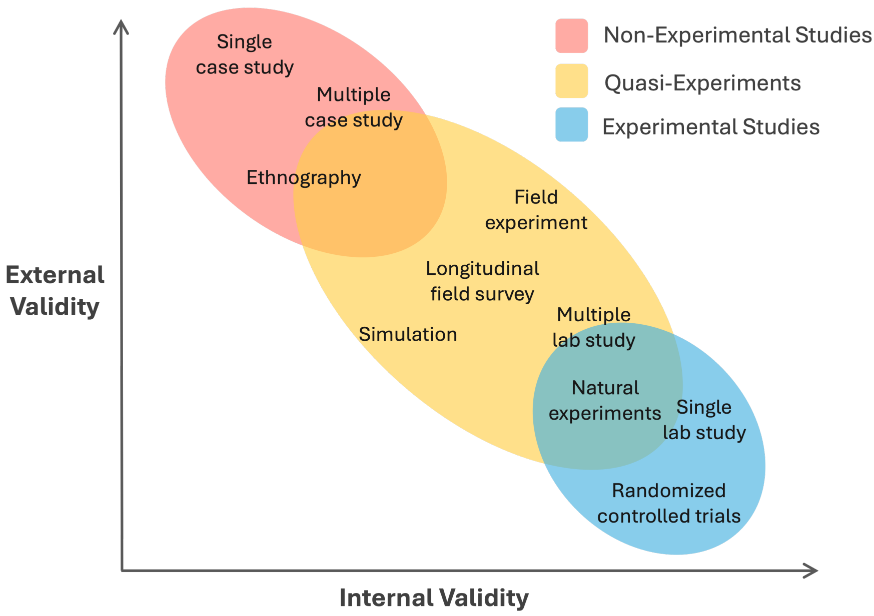

Figure 3.2: An illustration of the trade-off between internal and external validity across different research designs; the figure is intended to convey overall patterns in study designs rather than provide a strict classification; based on [57, 58]

These designs are often discussed in terms of a trade-off between internal and external validity [58]. **Internal validity** refers to the credibility of causal inferences within a study—whether observed effects can be confidently attributed to the manipulated variables rather than to confounds. **External validity** concerns the extent to which results generalize across populations, contexts, and times. A closely related notion is **ecological validity**, which emphasizes whether the research situation reflects the complexity and realism of the real world, and is generally treated as a subtype of external validity. Experimental designs, with their tight controls, maximize internal validity but often sacrifice external validity. Non-experimental designs, by contrast, tend to maximize external validity at the cost of weaker causal claims. Figure 3.2 also shows how internal and external validity vary across research designs.

Quasi-experiments are particularly well suited to HCI because they provide a pragmatic balance: enough structure and control to support reasonable causal inference, but enough flexibility to retain relevance to real-world contexts. This balance is especially important in studies of multisensory experience, which are central to this thesis, where ecological validity is indispensable. Traditional psychological and behavioral research often isolates a single sense—for example, exposing participants only to sound or visual stimuli—but such reductionist control is poorly aligned with multisensory inquiry. Studying vision or hearing in isolation may ensure internal validity, but it neglects ecological validity by stripping away the real-world interplay of multiple senses

For this reason, in the studies included in this thesis, I exposed participants to physical environments within the constraints of a controlled laboratory setting. This research design choice reflects an intentional attempt to balance internal and external validity: maintaining experimental rigor while preserving ecological realism. My studies, therefore, fall under the broad category of quasi-experiments.

It is worth noting, however, that quasi-experiments span a wide spectrum of methodological control. As shown in Figure 3.2, some quasi-experiments may be highly structured, overlapping with true experiments, while some others may be more naturalistic, bordering on non-experimental studies. Even within this thesis, the degree of control varies: Study IV employs the least control, whereas Studies I–III share a more comparable and controlled structure.

Chapter 4

The Four Studies

4.1 Story Line—The Avian Robots

> *"The human bird shall take his first flight, filling the world with amazement, all writings with his fame, and bringing eternal glory to the nest whence he sprang."*
>
> — Leonardo da Vinci

Da Vinci's prophetic words capture the timeless human aspiration to rise into the skies. Fascinated with flight, he referred to flying machines as the "*human bird*". In his time, birds represented both the mystery of flight and the most obvious natural model for how flight might be achieved. The language of "aviation" itself preserves this connection: the word derives from the Latin *avis* (bird) [59], and "avian" in modern English continues to mean bird [60]. Birds are not only biological inspirations but also cultural symbols of freedom, transcendence, and the crossing of boundaries.

Following da Vinci's legacy, I adopt the bird metaphor to frame the biophilic flying robots studied in this thesis (shown in Figure 1.2). Each robot draws inspiration from a specific bird, not only in form or sound but also in the qualities they evoke in human perception and imagination. Across four studies, I designed distinct interventions—namely, natural sounds, nature-evoking narratives, organic forms with biomimetic movement, and natural materials combined with hybrid living components—that each probe different pathways through which nature-inspired qualities can shape human interaction with technology. Taken together, I refer to these systems as the "**Avian Robots**".

- **Study I (Natural Sounds)** employed the birdsong of the great tit (***talgoxe*** in Swedish, as the study was conducted in Sweden). This auditory intervention emphasized *hearing*, situating the drone with an acoustic add-on intended to mask its mechanical noise.
- **Study II (Nature-Evoking Narrative)** explored the concept of the indoor "pet drone", conjuring up the parrot (***papageien*** in Luxembourgish, as the study was conducted in Luxembourg). This intervention invited a sense of *petting*, exploring potential affective qualities of interaction.

- **Study III (Organic Forms and Biomimetic Movement)** tested a flapping-wing drone inspired by the hummingbird (***kolibrier*** in Swedish, as the study was conducted in Sweden). This emphasized *encountering*, as participants engaged with a novel machine whose hovering movement elicited both excitement and unease.

- **Study IV (Hybrid Living Components)** investigated a bird–robot hybrid incorporating elements of the ortolan bunting (***ortolaan*** in Dutch, as the idea was first conceived in the Dutch-speaking region of Belgium). This study emphasized *eating*, interrogating multisensory and ethical dimensions of future human–nature–technology entanglement.

Although all studies were conducted in physical multisensory settings, each emphasized a distinct sensory channel and a particular mode of human activity. By coupling the bird metaphors with verb actions ("hearing", "petting", "encountering", and "eating"), a coherent narrative thread emerges across the four interventions. Moreover, the studies unfolded across different proxemic spatial ranges and temporal contexts, as discussed in preceding chapters (see section 2.3: Multisensory Experiences and Spatial Ranges and section 2.4: Imagining Futures), thereby situating the Avian Robots within a varied ecology of human–machine relations. Table 4.1 provides an overview of these dimensions.

Table 4.1: Overview of the studies

Study	Engaged Sense(s)	Timescale	Spatial Proxemics
I: Hearing *Talgoxar*	Hearing, (sight, touch)	Near future	Near, middle, far
II: Petting *Papageien*	Sight, (touch, hearing)	Near future	Near, far
III: Encountering *Kolibrier*	Sight, (hearing, touch)	Near future	Near, far
IV: Eating *Ortolaan*	Taste, (smell, sight, touch, hearing)	Far future	* Inside mouth/body

The storyline of the Avian Robots is coherent in that all four studies revolve around the unifying metaphor of birds as symbols of flight and nature, and each intervention explores how biophilic qualities can be embedded into flying machines. Nevertheless, not all studies relied exclusively on bird references. In Study I on natural sounds, for example, rain was examined alongside birdsong. Birdsong directly reinforces the avian metaphor, whereas rain represents a broader class of biophilic auditory cues. In Study II, functions such as camera use and education were explored in addition to the pet-like framing. These roles were deliberately chosen to foreground other socially meaningful domains for potential drone applications: photography as perception and memory-making, and education as learning and knowledge transfer. Such breadth introduces some tension with the unifying metaphor, a characteristic common to compilation theses where individual studies extend beyond a single storyline. By foregrounding the avian metaphor while acknowledging these extensions, the thesis maintains narrative coherence while demonstrating broader relevance.

The storyline is also multifaceted because the studies approach the theme from different sensory angles, interactional modes, spatial and temporal dynamics, and cultural contexts. This combination ensures that the work does not reduce biophilic flying robots to a single dimension, but instead opens up multiple perspectives on how they may affect perception, imagination, and lived experience. Ultimately, the Avian Robots storyline invites readers to see these flying machines not merely as functional artefacts, but as cultural and symbolic mediators—connecting past visions of flight, present explorations of design, and future possibilities through which humans might renegotiate our relationship with nature, technology, and ourselves.

4.2 Study I: Hearing *Talgoxar* [Paper A]

Figure 4.1: Participant in the experimental setup of Study I: Hearing *Talgoxar*.

Paper A – The Effects of Natural Sounds and Proxemic Distances on the Perception of a Noisy Domestic Flying Robot

Z. Wang et al., 2023 – published in ACM THRI

Motivation & Method: This study asks a simple but important question: Can **natural sounds** make noisy domestic drones feel more acceptable—especially up close—and does proxemic distance change the answer? To investigate, I conducted a mixed-methods, within-subjects 3×3 study ($N = 56$), overlaying birdsong of the great tit (*talgoxar*), heavy rain, or no sound onto a noisy flying robot at three proxemic distances (near, middle, far) in a domestic-like, sound-controlled lab. Figure 4.1 shows a participant in the experimental setup. We measured perceived loudness, sharpness, pleasantness, safety, relaxedness, and attractiveness, and conducted interviews to explore participants' reasoning.

Findings: Sound and space both matter. Distance strongly shaped perceptions of safety and relaxedness (near = worse; far = better), while natural sounds shifted affective appraisals. Birdsong significantly boosted pleasantness and attractiveness at far, but was least liked at near; rain was generally preferred at near and middle ranges. Interestingly, birdsong also increased perceived loudness and sharpness, yet still enhanced appeal at far—showing that affective meaning can outweigh acoustics. Preference data underline the point: at far, birdsong scored about twice as high as rain and three times higher than none added sound (see Figure 4.2). Participants' prior associations and experiences played a strong role, explaining divergent reactions to the same stimulus.

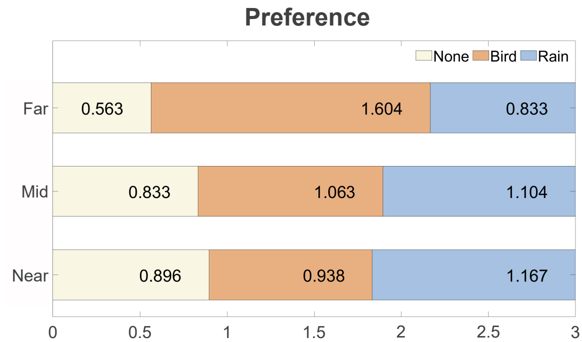

Figure 4.2: Mean preference ratings by sound and distance

Contributions & Implications: Paper A leverages embodied evaluation—using an actual flying platform—thereby achieving higher ecological validity than audio/video-only approaches common in prior work; this better captures HDI's multisensory character. The results show that sound preferences depend on both acoustic content and spatial context, underscoring the need to co-design audio cues in tandem with flight dynamics and proxemic patterns. More broadly, the work contributes: (i) a real-robot, full-sensory study that overcomes the ecological limitations of prior audio- and video-only methods; (ii) evidence that sonic design should be tuned to distance and meaning, not just decibels; and (iii) six design recommendations for making close-range drone interaction more enjoyable by combining natural sound overlays with proxemic awareness. In short: add nature, but mind the range.

4.3 Study II: Petting *Papageien* [Paper B]

Paper B – Exploring Intended Functions of Indoor Flying Robots Interacting with Humans in Proximity

Z. Wang et al., 2024 – published in CHI'24

Motivation & Method: Previous HDI research suggested that participants might prefer a pet-like metaphor for a drone at close range, but no prior studies had empirically evaluated this concept. This study explored how framing a drone as a pet—through **nature-evoking narratives**—shaped user experience. In addition,

Figure 4.3: Participant and experimenter in the experimental setup of Study II: Petting *Papageien*.

indoor drone functions remain largely underexplored compared to outdoor use. What happens when drones move into our living rooms? To investigate, I conducted a within-subjects 2×4 study (N = 60) with a real indoor drone to test how intended function (camera, education, pet, unknown) and distance (near: 60 cm; far: 180 cm) shape people's experiences. Figure 4.3 shows the experimental setup with both a participant and the experimenter. In a domestic-like lab, participants were engaged in functional narratives through storytelling and observed carefully scripted drone flights. Here, "petting" in the title referred more to a conceptual or imaginative frame, as only a few participants physically touched the drone during the study. Participants rated noisiness, pleasantness, usefulness, stress, attractiveness, and safety, and then took part in interviews. This study was also an embodied, proxemics-aware evaluation rather than an audio/video simulation.

Findings: Function mattered greatly, and distance still played a role. Education was the clear winner (highest pleasantness, usefulness, attractiveness, and safety; lowest noise and stress). Camera was perceived as useful but also annoying and stressful, often raising privacy concerns. Pet was rated as pleasant but useless, with most participants rejecting a genuine "pet" bond and instead framing it as more toy-like. Unknown was the least preferred on nearly every measure (low pleasantness, usefulness, attractiveness, and safety; high stress), underscoring how ambiguity near people is unsettling. Near vs. far consistently influenced safety and stress, with far distances feeling safer and less stressful. Quantitative patterns aligned with interview language (e.g., "useful/useless," "pleasant/annoying"). Figure 4.4 illustrates the key results from the study.

Contributions & Implications: (i) Communicate function explicitly through cues (form, lights, sounds, playful affordances for camera; soft coverings or "cute" cues for pet). (ii) Treat privacy and transparency as first-class concerns: clarify who is operating, what is being recorded, and where data goes. (iii) Reduce noise and manage

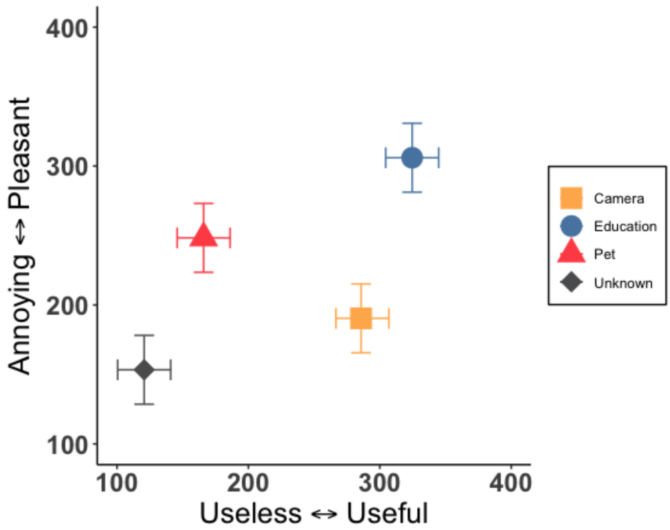

Figure 4.4: Rank means between perceived *usefulness* and *pleasantness*, with error bars (95% confidence interval).

risk (e.g., guards, sensors, fail-safes), while respecting proxemic distance indoors. (iv) Recognize that nature-related effects can be multi-faceted, sometimes involving trade-offs between qualities (e.g., the pet function was rated pleasant but useless). (v) Balance pragmatic (usefulness, safety) and hedonic (enjoyment, engagement) user experience—the education function excelled here by supporting both. Overall, the findings show that intent and distance co-shape indoor drone user experience: make intent legible, and mind the range.

4.4 Study III: Encountering *Kolibrier* [Paper C]

Paper C – In a Flap: Experiences with a Bioinspired Flying Robot

Z. Wang et al., 2025 – published in IMWUT/UbiComp'25

Motivation & Method: What if a drone didn't buzz—but flapped? This study presents the first embodied, side-by-side comparison of human experiences with a bioinspired flapping-wing drone featuring **organic forms and biomimetic movement** versus a similarly sized quadcopter (N = 56). Conducted in a controlled indoor setting, three participants took part in each session for practical and logistical reasons. Figure 4.3 shows the experimental setup with three participants in one session. Using a within-subjects 2×2×2 design, the experiment varied drone type (flapper vs. quad), distance (near vs. far), and posture (sitting vs. standing), measuring perceived safety, pleasure, discomfort, and unexpectedness, along with heart rate, followed by in-depth interviews.

Figure 4.5: Participants in the experimental setup of Study III: Encountering *Kolibrier*.

Findings: Results show that participants prized novelty but penalized instability and unpredictability, with perceived safety and functional legibility often outweighing the abstract effects of nature. The flapper was consistently described as novel, entertaining, and inspiring, yet also rated less safe, more uncomfortable, and more unexpected than the quadcopter (strong main effects of drone type). Distance reliably boosted safety (far > near), while pleasure was sometimes higher at near range, as participants found closer encounters more engaging. Posture also mattered: sitting reduced discomfort, while standing raised heart rate. Table 4.2 summarizes the statistical results. Qualitative accounts revealed associations of the flapper with insects, birds, or bats—a mix that sparked fascination with its mechanics but also unease about instability and unclear purpose.

Table 4.2: 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.

Contributions & Implications: The study challenges the assumption that "nature-like" form automatically improves acceptance. Instead, it highlights the need to: (i) introduce and familiarize people with new technology to minimize unexpectedness; (ii) improve control and stability to reduce unpredictability; (iii) scale size to context (smaller indoors, larger outdoors); and (iv) align morphology with familiar species archetypes to avoid uncanny blends. The upshot: bioinspired drones can delight through novelty, but that same novelty may hinder the effects of nature. To earn trust, they must feel predictable, legible, and context-fit—insights that emerge only through real-robot, multisensory evaluation.

4.5 Study IV: Eating *Ortolaan* [Papers D + E]

Figure 4.6: Participants in the experimental setup of Study IV: Eating *Ortolaan*, with *ortolaan* flying in motion.

Paper D – A Meat-Summer Night's Dream: A Tangible Design Fiction Exploration of Eating Biohybrid Flying Robots

Z. Wang et al., 2025 – manuscript submitted to CHI'26

Paper E – Substituting Animals with Biohybrid Robots: Speculative Interactions with Animal-Robot Hybrids

Z. Wang et al., 2023 – published in DIS'23 Companion

Motivation & Method: What if "meat" were a biohybrid robot? Study IV drew on the speculative concept introduced in Paper E, which proposed assembling animal–robot hybrids that could be harvested for edible meat products. Each hybrid combines an AI-controlled artificial "brain" with a living body grown from animal stem cells; crucially, the design is cerebrumless (no sentience), thereby claiming "slaughter-free" meat. The body functions as a mobile bioreactor capable of growing structured flesh and organs with authentic textures—potentially overcoming the limitations of current lab-grown or cultured meat. In principle, cells from any species could be used (including endangered or even extinct lineages), and such hybrids might also produce eggs and milk, all under tighter biosecurity and environmental control.

Paper D narrowed this broader vision to a specific case: a biohybrid drone modeled after the ortolan bunting. It extended the discussion beyond speculative writing to a real-world, multisensory dinner theater experience.

The study staged a tangible design fiction: a Paris restaurant in 2052 where diners consume a biohybrid flying robot with **living components** as an ethical, sustainable stand-in for the banned French delicacy, the ortolan bunting. Rather than a video or vignette, we hosted a “dinner-in-the-drama” with six participants ($N = 6$), blending theatre and tasting. The experience featured a feathered drone (Wizard-of-Oz) flying in motion (see Figure 4.6), a 3D-printed biohybrid prototype (see Figure 4.7(A)), and a roasted quail served under napkins to mirror the historic ritual (see Figure 4.7(B))—together creating a fully multisensory encounter that transformed speculation into embodied experience.

Findings: Attendees found the experience plausible, fun, and thought-provoking, yet it surfaced key tensions: curiosity versus caution about AI-biocomputing, uncertainty about sentience and moral status, ambivalence over sustainability claims (energy use, supply chains), and questions about cultural rituals, access, and economics if such food were ever mass-produced. Several participants argued that understanding our relationship to animal–robot hybrids may matter more than their potential environmental benefits.

Contributions & Implications: (i) Artifact: a vivid world in which eating biohybrid flying robots becomes thinkable, reframing human–food and human–robot relations. (ii) Empirical insight: nuanced public reactions across ethics, sustainability, identity, and culture—elicited through real tasting and touch rather than abstract speculation. (iii) Method: a scalable tangible design fiction format—“dinner-in-the-drama”—that deepens engagement beyond texts or VR and enables HCI to probe controversial futures through embodied experience.

Bottom line: By letting people see, touch, hear, smell, and eat a speculative future, this work turns debate about food-tech ethics from the head to the senses—and demonstrates how design can stage complex questions that the lab alone cannot.

Figure 4.7: (A) *Ortolaan* (3D-printed prototype) presented on a plate; (B) participants were eating “biohybrid flying robots” (*ortolaan* simulated by edible roasted quail) in the traditional French manner.

Chapter 5

Discussion

This chapter synthesizes the overall findings, implications, limitations, and directions for future work, unifying the research as a whole. While the included papers discuss their specific results in detail, here the focus is on higher-level insights, cross-cutting themes, and contributions that emerge when the studies are viewed collectively. By connecting the individual studies, this chapter also identifies opportunities for future inquiry and outlines how the research may evolve. For study-specific discussions, readers are encouraged to refer to the respective papers in Part II.

5.1 Overall Findings and Implications

Revisiting the overarching questions (see section 1.1), the studies show that: (**ORQ1**) Nature-inspired design can enhance the appeal and emotional resonance of drones, making them feel more approachable, but in close-range interactions trust rests on clarity of purpose, stability, and predictability; when nature cues create ambiguity or erratic motion, they risk evoking discomfort. (**ORQ2**) Multisensory strategies shape interaction by layering meaning across senses: auditory overlays can soften mechanical harshness, visual and kinesthetic cues can frame drones as expressive or lifelike, and tactile, olfactory, or gustatory engagements can provoke cultural and ethical reflection; their effectiveness depends on calibration to context and distance. (**ORQ3**) Drone acceptance depends on combining clear purpose and safe, context-aware multisensory design with long-term imaginaries of drones as companions, tools, or cultural agents—decisive for acceptance yet still requiring societal and human-centered exploration.

Together, these questions show how nature cues, multisensory design, and contextual clarity jointly shape human–drone interaction and its future acceptance. The following subsections examine each dimension in more detail.

5.1.1 The Effects of Nature Cues

Across the four studies, a recurring theme emerges: when flying robots adopt cues from nature—whether through sound, form, movement, or embodied interaction—human experiences are profoundly shaped. These cues evoke familiarity, spark imagination, and sometimes raise ethical questions, ultimately influencing acceptance, comfort, and meaning-making in human–computer interaction.

Nature as a mediator of acceptance and comfort. Study I demonstrated that overlaying natural sounds such as birdsong or rain on the consequential noise of domestic drones significantly affected user perceptions, though in nuanced ways depending on proxemic distance. Birdsong was preferred when the drone flew farther away, yet disliked at closer ranges. This ambivalence highlights that nature cues do not function as simple "add-ons" but are context-dependent mediators: they can soothe annoyance, but may also amplify associations—for instance, evoking a bird that feels uncomfortably close. Similarly, in Study II, participants' acceptance of drones varied depending on intended functions and distance, with pet-like metaphors (implicitly tied to nature) being rated more pleasant but less useful. These results suggest that nature cues can alter perceptions of technological artifacts in both positive and negative ways, but their effectiveness hinges on alignment with proxemic norms and contextual expectations.

Bioinspiration and the evocation of the living. When morphology and movement embody biological archetypes, drones are no longer perceived as mere machines—at least not in the traditional sense. Study III found that participants attributed lifelike qualities to a flapping-wing drone, associating it with insects, birds, or bats. While this inspired awe and entertainment, it also evoked feelings of unpredictability and unease. The findings resonate with broader research on zoomorphic robots [61, 62]: nature-inspired motion fosters recognition and empathy, but also invites critical reflection on safety, control, and purpose. This duality illustrates the unique power of nature cues: they bridge the mechanical and the animate, drawing users into a liminal space where technology becomes uncanny, playful, or even threatening.

Nature as a site of imagination and ethics. Nature cues not only shape proxemic comfort and sensory perception but also open speculative and ethical dimensions. Study IV staged a future in which people consume biohybrid flying robots as sustainable delicacies. Participants grappled with questions of sentience, sustainability, and cultural tradition, interpreting the hybrids simultaneously as food, technology, and to some degree living beings. Here, nature cues in the form of hybrid living tissue and animal-robot analogies did not merely enhance experience; they provoked reflection on human responsibility in a post-natural world [63, 64]. This highlights a deeper effect: by borrowing from nature, technology can stimulate critical imagination, compelling us to reconsider our place in ecological and technological systems.

Taken together, these studies reveal that nature cues exert their influence across multiple levels: sensory comfort, proxemic mediation, affective resonance, and speculative ethics. Designing with nature cues therefore requires sensitivity to context, distance, and cultural framing. Rather than treating such cues as superficial embellishments, we should recognize them as powerful mediators of meaning—able to transform drones from noisy machines into companions, desirable tools, or even ethical provocations.

The effects of nature cues remind us that technologies do not exist in isolation; they are interpreted through the lenses of memory, culture, and imagination. Birdsongs may soothe or irritate, a pet drone may be perceived as pleasant but useless, flapping wings may charm or unsettle, and edible biohybrids may amuse or disturb—but in all cases, they invite us to negotiate boundaries between the artificial and the natural. As designers and researchers, embracing these tensions offers a pathway toward richer, more human-centered technological futures—where interaction with machines is not just about utility, but about cultivating empathy, reflection, and a renewed awareness of our entanglement with the natural world.

5.1.2 Proxemics and Multisensory Experience Matter

A central insight across the studies is that proxemics [24] and multisensory experience are not peripheral design factors but foundational to how humans perceive and make sense of flying robots. Physical distance, sound, and embodied cues shape not only comfort and acceptance but also deeper affective and ethical responses.

First, proxemics consistently emerged as a key determinant of experience. Study I showed that the same birdsong overlay could be soothing when a drone was distant yet irritating when it was near. Similarly, in Study II, intended functions shaped comfort in relation to proximity: drones framed as pets or educational tools were welcomed at closer distances compared to drones with unknown or camera functions. In both cases, proxemic distance modulated how users interpreted sensory and functional cues, revealing that spatial negotiation is inseparable from meaning-making in human–drone interaction.

Second, multisensory design [65] amplified these effects. The overlay of natural sounds provided not only auditory masking of consequential noise but also evoked associations from prior experiences with birds, rain, and related occasions. In Study III, the morphology and motion profile of a flapping-wing drone further engaged vision and embodied perception, producing lifelike impressions that were inspiring yet at times unsettling. In the speculative dining with biohybrid robots of Study IV, the multisensory richness of taste, smell, touch, and ritual provoked reflections extending beyond utility to questions of ethics and culture. These findings highlight that multisensory engagement is not merely additive but transformative, shaping both affective responses and broader imaginaries.

Collectively, these studies suggest that proxemics and multisensory experience form a coupled system that fundamentally mediates human–robot interaction. Distance modulates how sensory cues are interpreted, while multisensory richness deepens emotional and ethical engagement. Designing future flying robots thus requires more than optimizing performance or reducing noise; it requires attentiveness to how bodies, senses, and spaces co-produce meaning. By embracing proxemics as a dynamic negotiation and multisensory design as a catalyst for reflection, we can move toward human–computer encounters that are not only acceptable but also culturally resonant and experientially profound.

5.1.3 Purposes, Contexts, and the Need for Customization

For all studies, purpose and context consistently emerged as critical factors, shaping how people interpret, accept, and value flying robots [66, 67]—and pointing to customization as a design imperative rather than an optional flourish. In the controlled indoor trials of Study II, the intended function of a small drone was the primary driver of experience: for an otherwise identical drone, different functional narratives strongly influenced user perceptions. When the drone's purpose was unknown or unclear, it became the least preferred, underscoring how ambiguity erodes acceptance. This finding was consistent with Studies I and III, where functions were not deliberately emphasized, yet participants nonetheless raised questions and concerns about the drones' purposes, noting that the absence of clear framing diminished their experience.

Context extends beyond distances and surroundings to social meaning and ritual. In Study IV, a tangible design fiction of eating biohybrid flying robots made the "purpose" of a drone—as food, not tool—salient, prompting participants to weigh sustainability, sentience, cultural continuity, and value. The same artifact elicited curiosity, delight, and discomfort, illustrating how culturally loaded contexts can amplify ethical reflection while still supporting engagement. In other words, the scene defines the sense: when purposes are culturally legible, people can locate their stance; when they are not, uncertainty dominates.

Form and sensing further modulate purpose–context fit. A bioinspired flapping-wing drone was perceived as novel and lifelike but also unpredictable. The study's takeaways recommend aligning morphology with familiar species archetypes, scaling size to role, and improving control and stability—each a lever of customization that can render purpose more legible in context. Likewise, altering the soundscape reshaped perceptions of the same domestic drone, with effects flipping depending on distance (birdsong preferred when far, disliked when near). This demonstrates that auditory customization must be proxemics-aware rather than static. Across studies, participants also varied individually, sometimes holding opposite views of the same feature. These differences highlight the importance of personalization and respecting individual preferences alongside broader contextual framing [68].

As a whole, these findings argue for adaptive, purpose-forward design: (i) make purpose explicit through transparent cues (icons, light patterns, flight postures) rather than leaving intent ambiguous; (ii) bind morphology and motion to the intended purpose; (iii) personalize multisensory profiles that adapt to spatial context and user preference; and (iv) incorporate cultural and ethical framing when purposes cross into sensitive domains (e.g., food, surveillance), using participatory and multisensory methods to surface norms prior to deployment [69].

Purpose and context do not merely influence experience—they co-produce it. Designing for this co-production through thoughtful customization can transform drones from generic gadgets into situated partners that feel appropriate, trustworthy, and meaningful.

5.2 Potential Improvements and Future Work

5.2.1 Limitations and Potential Improvements

While the four studies in this thesis adopt different framings and methods, the variation across them should not be read as inconsistency but rather as a deliberate strategy to broaden the scope of inquiry into biophilic flying robots. Still, several areas merit reflection for improvements in future studies.

Temporal scale. The research engaged both near-future and far-future imaginaries [70], leaving less attention to the "middle ground" of plausible mid-term scenarios. This focus was intentional: by working at the extremes, the studies highlight immediate technical challenges on the one hand and long-term cultural implications on the other. Nevertheless, mid-term futures could complement this work in future research, providing a bridge between speculative visions and practical deployment.

Range of quasi-experiments. Although all studies can be situated as quasi-experiments [71], they span a wide spectrum—from more conventional, controlled designs to artistic and speculative interventions. Rather than being a weakness, this breadth reflects the heterogeneity of quasi-experimental research itself, where methodological flexibility is key to addressing different facets of human–technology interaction. Still, one might argue that the resulting portfolio appears polarized. Future work could consider situating studies more evenly across the continuum, though the present spread has the advantage of covering both rigor and imagination.

Proxemic granularity. Distances were operationalized in a relatively small number (2 or 3) of categories. This simplification was necessary to balance other study conditions and to keep comparisons systematic and manageable. While more fine-grained proxemic distinctions [24] could yield richer insights into nuanced interactions, the chosen levels provided a robust foundation for uncovering the most salient contrasts. Future research could build on this foundation by exploring additional gradations or dynamic spatial trajectories.

In short, while the research designs inevitably involved strategic choices and trade-offs, these were made to maximize the exploration of diverse aspects across studies. Addressing temporal middle grounds, expanding quasi-experimental diversity, and refining proxemic resolution are promising avenues for improvements; however, they do not undermine the overall coherence or contributions of this thesis.

5.2.2 Research Ideas For Future Exploring

Interactive Swarm in Proximity

Most HDI studies, like HRI research more broadly, have focused on single robots, with investigations of swarms remaining rare and even reduced to abstract dot-based simulations [72]. Yet nature offers abundant inspiration for collective intelligence—for instance, bees coordinating hive activities, ants organizing trail foraging, geese synchronizing flight formations, or group-living mammals such as wolves cooperating in hunts. These examples demonstrate how coordinated groups can achieve complexity and resilience beyond any single agent.

Studying interactive swarms in proximity therefore presents a compelling opportunity for HRI. It invites us to go beyond single-agent paradigms and consider how humans might perceive, interpret, and respond to multiple autonomous agents acting together in shared spaces. This line of inquiry is especially relevant to the concerns of this thesis, which emphasizes multisensory experiences in physical settings. Extending this approach to real robot swarms could open new directions for understanding proxemics, sensory integration, and the design of swarm behaviors that are not only efficient but also intelligible and meaningful to humans.

Interacting with Bioinspired Intelligence and On-Board Computing Drones

Most HCI studies, including this thesis, adopt a future-oriented perspective, exploring how emerging technologies could be experienced rather than how they are fully realized today. Prototypes and wizard-of-oz techniques are often used to showcase and study potential interactions, with technical implementation left for later. For example, many lab-based drone studies rely on external positioning systems and off-board computation, where a separate computer calculates trajectories and sends commands to the drone. While suitable for controlled settings, such approaches are impractical outside the lab. In real-world environments, drones must operate with on-board computing, processing sensor input and making decisions autonomously in real time. This shift imposes significant physical constraints: limited payload, compact sensors and actuators, restricted energy supply, and cost efficiency all shape what on-board systems can achieve. The difference between off-board and on-board control is therefore profound—not only in technical capability but also in how people may experience and interpret a drone's behavior. Robotics research has long addressed the engineering challenges of on-board autonomy, but the human side of the interaction—how users perceive, trust, and engage with drones that compute and decide locally—remains largely unexplored.

Here, bioinspiration offers a promising lens. Nature shows that intelligence can thrive under constraint: animals, particularly insects, demonstrate how relatively simple brains and primitive biological sensors can enable complex tasks. For instance, bees navigate landscapes with tiny brains, while ants coordinate collective foraging with minimal sensory input. Translating these principles, drones with modest sensors (e.g., low-resolution cameras), lightweight actuators, and simple on-board neural networks with highly limited computing power have already been commercialized for research (see [73]), showing that "good enough" intelligence can support autonomous flight. Such bioinspired intelligence could make drones more affordable, scalable, and adaptable to real-life contexts.

Yet little is known about how people will interact with and interpret these bioinspired, resource-constrained machines. Will their simplicity make them more transparent and trustworthy, or more frustrating? Will their animal-like behaviors feel familiar and legible, or uncanny and alien? Exploring interaction with on-board computing drones thus represents not only a technical but also a cultural and experiential challenge. It invites us to imagine futures where autonomy is modest yet widespread, where machines learn from nature's frugality and adaptive intelligence, and where human–drone relationships are shaped by the interplay of constraint, adaptation, and imagination.

Interacting with Plant/Fungus–Robot Hybrids

In this thesis, I examined a speculative case of animal–robot hybrids, focusing on how such machines might challenge cultural and ethical norms around food. Looking ahead, plant– and fungus–robot hybrids may represent a more immediate and tractable step, occupying the middle ground between near- and far-futures. Compared to animals, plants and fungi pose fewer ethical concerns and technical constraints. It is arguably easier for people to imagine cutting a branch or leaf from a plant–robot hybrid, or harvesting a portion of fungal mycelium, than butchering meat from an animal–robot system. Technically, integrating living plant or fungal components into machines may also be more feasible than hybridizing animal tissues, given their relative resilience and compatibility with environmental conditions. Moreover, plants and fungi offer distinct advantages as design materials: they can grow and regenerate (enabling self-healing structures), are renewable (supporting sustainable upkeep), and are biodegradable at end-of-life, allowing organic waste to be decomposed or composted.

This direction builds on emerging explorations of human–plant and human–fungus symbiosis in design and engineering research. For example, LivingLoom integrates living plants into e-textiles to create interactive systems that foreground care, growth, and sustainability in human–technology relations [74]. In parallel, other projects employ fungi as computational substrates for robotic control [75], blurring the boundary between machine and organism. Together, these strands illustrate the potential of plant and fungal integration to enable new forms of biophilic interaction and reciprocal engagement.

Plant–robot and fungus–robot hybrids extend this vision further. A robot integrated with living plants could not only move or sense but also grow, bloom, and bear fruit, while fungal hybrids might self-assemble mycelial networks, repair themselves, or adapt to their substrates. Their regenerative capacity and renewable growth cycles make them technically robust and ecologically sustainable, reducing long-term maintenance and waste through biodegradable end-of-life pathways. These capabilities may transform interaction from purely functional exchanges to relationships grounded in cultivation, care, and shared ecological presence. They could blur the boundaries between technology, ecology, and daily life, offering both practical benefits (e.g., renewable food sources, adaptive environments, sustainable material cycles) and rich experiential dimensions. Exploring human interaction with plant– and fungus–robot hybrids therefore presents an exciting research avenue, one that brings together questions of ethics, sustainability, and biophilic design. Taken together, these approaches point toward futures where machines not only compute and act but also grow and live alongside us.

Biophilic Technology in Group and Social Contexts

Thus far, much of the research on biophilic and bioinspired technologies has focused on individual interactions, yet many real-world encounters with technology occur in group settings. Investigating how people interact with biophilic technologies collectively could provide valuable insights into social dynamics in HCI. For instance, could such technologies support collaboration in workplaces, team-based learning in education, or shared aesthetic experiences in museums, performances, and public installations? Studying proxemics, attention, and communication in multi-user scenarios would help uncover whether bioinspired designs can not only engage individuals but also enhance group interaction, cooperative work, and collective meaning-making.

At the same time, it is important to recognize that responses to biophilic technologies are not universal. Cultural background shapes how people perceive, interpret, and assign meaning to nature-inspired designs and interactions. Expanding research to include participants from diverse cultural contexts could therefore reveal significant differences in how biophilic qualities are understood and valued. Festivals, rituals, and local practices related to nature and animals may deeply influence how biophilic technologies are experienced. While this thesis already touched on some of these aspects, a more systematic investigation is still needed.

Exploring group and cross-cultural interactions thus represents an important step forward. It would allow biophilic technologies to be studied not only as individual experiences but also as social and cultural artefacts, embedded in shared practices and collective values. This broader perspective could help ensure that biophilic design in HCI contributes to technologies that are both socially meaningful and globally relevant.

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Part II

Included Papers

Paper A

The Effects of Natural Sounds and Proxemic Distances on the Perception of a Noisy Domestic Flying Robot

Z. Wang, Z. Hu, B. Rohles, S. Ljungblad, V. Koenig, and M. Fjeld

ACM Transactions on Human-Robot Interaction, Volume 12, Issue 4, Article 50.
(December 2023), 32 pages.

https://doi.org/10.1145/3579859

Paper B

Exploring Intended Functions of Indoor Flying Robots Interacting with Humans in Proximity

Z. Wang, Y. Wu, S. Yang, X. Chen, B. Rohles, and M. Fjeld

In Proceedings of the CHI Conference on Human Factors in Computing Systems (CHI'24), May 11–16, 2024, Honolulu, HI, USA. ACM, New York, NY, USA, 16 pages.

https://doi.org/10.1145/3613904.3642791

Paper C

In a Flap: Experiences with a Bioinspired Flying Robot

Z. Wang, M. Loerakker, Y. Wu, S. Yang, A. Pons, Y. Chuai, D. Sirkin, and M. Fjeld

Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies (IMWUT / UbiComp'25), Volume 9, Issue 3, Article 138. (September 2025), 20 pages.

https://doi.org/10.1145/3749495

Paper D

A Meat-Summer Night's Dream: A Tangible Design Fiction Exploration of Eating Biohybrid Flying Robots

Z. Wang, Y. Wu, Q. Zheng, S. Zhang, N. Barker, and M. Fjeld

Manuscript submitted to CHI'26, 25 pages.

https://arxiv.org/abs/2510.06507

Paper E

Substituting Animals with Biohybrid Robots: Speculative Interactions with Animal-Robot Hybrids

Z. Wang, N. Barker, Y. Wu, and M. Fjeld

In Designing Interactive Systems Conference (DIS Companion'23, July 10–14, 2023, Pittsburgh, PA, USA. ACM, New York, NY, USA, 6 pages.

https://doi.org/10.1145/3563703.3596641