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# Expanding the Interaction Repertoire of a Social Drone: Physically Expressive Possibilities of a Perched BiRDe

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**Abstract**

The field of human–drone interaction (HDI) has investigated an increasing number of applications for social drones, all while focusing on the drone's inherent ability to fly, thus overpassing interaction opportunities, such as a drone in its perched (i.e., non-flying) state. A drone cannot constantly fly and a need for more realistic HDI is needed, therefore, in this exploratory work, we have decoupled a social drone's flying state from its perched state and investigated user interpretations of its physical rendering. To do so, we designed and developed BiRDe: a Bodily expressIons and Respiration Drone conveying Emotions. BiRDe was designed to render a range of emotional states by modulating its respiratory rate (RR) and changing its body posture using reconfigurable wings and head positions. Following its design, a validation study was conducted. In a laboratory study, participants ($N = 30$) observed and labeled twelve of BiRDe's emotional behaviors using Valence and Arousal based emotional states. We identified consistent patterns in how BiRDe's RR, wings, and head had influenced perception in terms of valence, arousal, and willingness to interact. Furthermore, participants interpreted 11 out of the 12 behaviors in line with our initial design intentions. This work demonstrates a drone's ability to communicate emotions even while perched and offers design implications and future applications.

**Keywords** Human–drone interaction · Affective computing · Interaction design · Prototype · User study

## 1 Introduction

Over the past decade, the human–drone interaction (HDI) community has been investigating an increasing number of applications for social drones [1], related to their innate ability to fly. However, drones cannot operate in a constant flying state since this can be bothersome to people and unrealistic from a technological perspective (e.g., battery life). Therefore, in this work, we propose investigating how drones could present social abilities while in a non-flying state. This perched state has the potential to use and explore new interaction opportunities with drones, as well as take advantage of naturally occurring communication methods that cannot be applied to a flying drone. For example, a drone using propellers for aviation purposes may not be able to also use them for communication when flying. Further, we argue that for some social drone applications, the perched state (i.e., at rest) will have its own unique benefits to users.

We posit that, beyond in-flight human–drone interaction (HDI), which is already being studied, interaction should be considered when the drone is perched (see Fig. 1). *We define a drone as perched when it is non-flying, ready to interact, and either perched on an object or a person or grounded on a surface (e.g., a table, on the ground)*. In this state the drone is still operational, thus, distinguishing it from it being turned off (i.e., inanimacy).

We propose that with regards to perched drones, some domains would particularly benefit from interaction in a perched state, such as Help/Assistance [1]. Imagine a Search-and-Rescue drone, which upon encountering an injured person, approaches them and offers them support while waiting at their side for the rescue team– instead of leaving the person alone without knowledge of when help will be coming. Similarly, in the Companionship domain, where drones are envisioned in the home environment [2], most likely, most of the time spent interacting with the drone will be in

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a perched or inanimate state (as opposed to when the drone will perform various tasks while flying around).

While flying will generally be fundamental to the social drone's significant functions, its non-flying time is a substantive and overlooked interaction opportunity. During these periods, it can be quiet, does not generate dust or pollution, reducing attentional demands on both operator and local interactor, and also reducing battery drain. Interaction with an object *able* to fly, which is *currently* perched, opens possibilities that are masked by movement given current technology, such as affectionate pet-like behavior and even physical contact. Prior work has been successful in designing such social ground robots [3], but drones (i.e., aerial robots) present different affordances and form factors compared to their ground counterparts, which need to be studied in their own right. Furthermore, prior findings show that ground robotics research does not necessarily translate to aerial robots [4, 5].

Social drones (and other social robotic systems) need to be accepted by their potential users. Prior work shows that acceptability and intention to use technology are tightly bound to perceived usefulness and ease of use [6]. Additionally, a robot's ability to present emotions was also found to have an effect on the robot's acceptance [7]. A recent review covering the last 20 years of robots' emotions in HRI [8] has shown that robots presenting emotion (via facial or body expressions) are not only highly recognized by people but that a robot expressing emotions is more accepted than one that does not.

This research presents a drone design aimed at conveying emotional information while perched, a feature useful in scenarios such as Help and Companionship, and which could further enable ambient HDI [9]. Drones have been shown to successfully express emotions using their flight path [10, 11], head movement, and facial features [12, 13]. Yet, these expressions of emotions rely on the drone flying or positioned at a certain distance and angle from the user.

In this paper, we present the design and development of *BiRDe: Bodily expressIons and Respiration Drone conveying Emotions*, whose design is inspired by prior work in robotics and existing flying creatures. BiRDe can express its emotional state through breathing (as in [14]) and through bodily expressions using its wings and head. The respiration was created by using a laser-cut wooden ribcage [14] and the wings and head were designed and 3D printed in PLA, as well as a frame to connect the parts together. To animate BiRDe, three servo motors were connected so that the ribcage movement can represent respiration rate, the wings can rotate between positions, and the head moves in a linear motion. We then implemented three Respiratory Rates (RR) meant to represent different levels of *Arousal* (i.e., deactivated-activated emotion), and two head and two wing positions meant to convey *Valence* (i.e., negative-positive emotion) through bodily expressions. These resulted in twelve combinations of emotional behaviors that we validated in a user study designed to answer the following research questions:

- RQ 1.a: How do BiRDe's components (i.e., RR, Wings, Head) affect peoples' interpretations of its Arousal and Valence?
- RQ 1.b: Can people recognize a perched drone's behaviors (i.e., the combinations of RR, Wings, and Head) into emotional states?
- RQ 2: Which of BiRDe's emotional states increases users' willingness to interact with it?

Participants ($N = 30$) were first asked to rate a series of emotional labels from the Positive And Negative Affect Schedule (PANAS) scales [15] in terms of valence and arousal. For each of BiRDe's twelve behaviors, they then had to interpret and label each behavior into emotional states, as well as rate their willingness to interact with BiRDe. Our results demonstrate BiRDe's effectiveness in conveying arousal through RR, and head position, and valence through RR, wings, and head positions. Our results further describe which of BiRDe's emotional states foster the participants' willingness to interact with it. Overall this paper introduces three key contributions to the field of HDI:

- A novel approach to drones conveying information when perched via BiRDe: bodily expressions and respiration drone that conveys emotions.
- Results of a user study validating the degree and manner in which BiRDe can convey emotional valence and Arousal.
- Design implications and examples of possible applications for perched drones.

## 2 Related Work

The main focus of prior HDI research focuses on drones while flying. To present prior works on perched drones, we describe instances from performance arts where drones have been presented perched, although most of this body of work did not explore interaction per se. We further propose examples from prior literature where interacting with a perched drone would create novel opportunities. In the next subsections, we report prior works on first social drones, and then on social ground robots, designed to convey emotions since both technologies helped guide our design rationale.

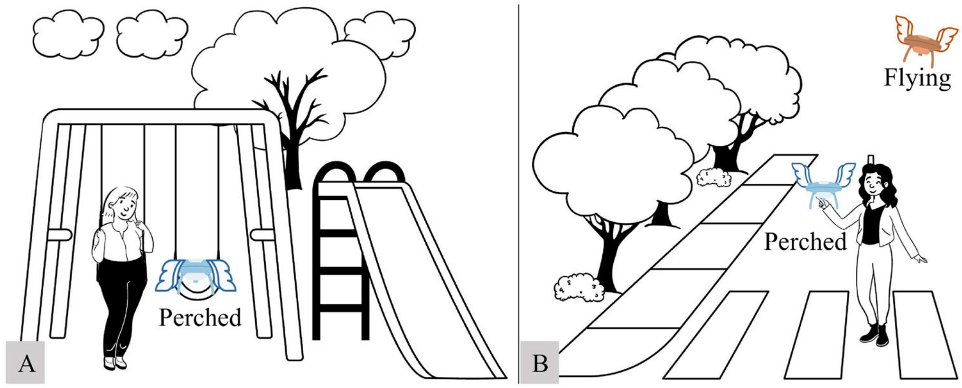


**Fig. 1** Example scenarios for perched drones (in blue): (**A**) the drone is perched next to the user; (**B**) the drone is perched on the user, as opposed to traditional human–drone interaction (flying; in orange). (Colour figure online)

## 2.1 Towards Interaction with Perched Drones

In performance arts, drones have been used as props, as well as lighting mechanisms. In "SPARKED",[1] for example, drones have been fitted with LED lights and used as flying lampshades. Yet, before taking off and switching to a flying state, the drones are perched and go from turned off to lit up. A similar example can be found in "Shadow"[2] where drones are used as directional flying flashlights. Here also, the show starts with the drones grounded on the stage (i.e., perched) and starting their illumination before taking off. We describe both examples as instances of perched drones, although in neither example, the drone is used for collocated interaction.

In the HDI literature, we find works that acknowledge the usefulness of non-flying drones (i.e., perched). One example is Drone Chi [16], where lotus-inspired drones are docked on a vine-like charging station waiting for people to pick them up. In this work, the drone is turned off (i.e., inanimate) and therefore does not meet the criteria to be considered perched as per our definition. We propose that, instead, Drone Chi could be used while on the vine to display information in an ambient manner, becoming a drone at rest, and therefore perched. Furthermore, Herdel et al [1] "wonder[ed] whether drones should always be flying, and which use cases could benefit from drones that alternate between flying and grounded states". This further brings the question of whether drones in perched states would be considered more as ground robots or whether they remain considered as aerial robots (drones), especially since prior work described that aerial and ground robots present different design characteristics and are perceived differently by people [4]. We then further identify two prior research works that investigated acceptable on-body locations for companion robots [13] and for drones [17]. Although the chosen companion robot was in the shape of an owl, the two studies led to different results in which body parts would be acceptable for positioning such technologies. This hints at the fact that there is a continuum between aerial and ground robots and that the perched state may be positioned somewhere along that continuum. Yet, apart from the work on companion robots, all prior work presented here focuses on flying drones. We here propose to go further and investigate a perched drone that displays emotions.

## 2.2 Drones Conveying Emotions

Social drones [18] expand drone usage from being used merely as tools to becoming social creatures [19], such as pets and companions [20], with one main construct, their emotional capacity. Prior HDI works have shown that drones can display emotional states that can be recognized by people, using the drone's flight path [10, 11], anthropomorphized features such as head movement and eye color [12], and even facial expressions [21]. When looking deeper into how emotions are conveyed and assessed, we find that Sharma et al [10] used the drone's flight path to communicate affect to people via the Laban Effort System, a methodology from the performing arts for describing expressive motion. To assess participants' perception of the drone's affective state, they used the SAM instrument [22] for valence and arousal. In their work, Cauchard et al [11] defined an emotional space and personality model for drones and showed that humans can accurately associate a drone's movements and behavior with an emotional state using labels. More recently, Herdel et al [21] used facial expressions of emotions on drones and investigated whether these could be identified as basic emotional label categories. These prior works demonstrate that, while interest in conveying a drone's emotional state is growing, there is no best practice yet in conveying or assessing these emotional states. Since conveying emotions with a perched drone is a space not yet explored, we turn to another technology that can convey emotions: social robots.

1 https://thekidshouldseethis.com/post/cirque-du-soleil-sparked.

2 https://elevenplay.net/project/shadow.

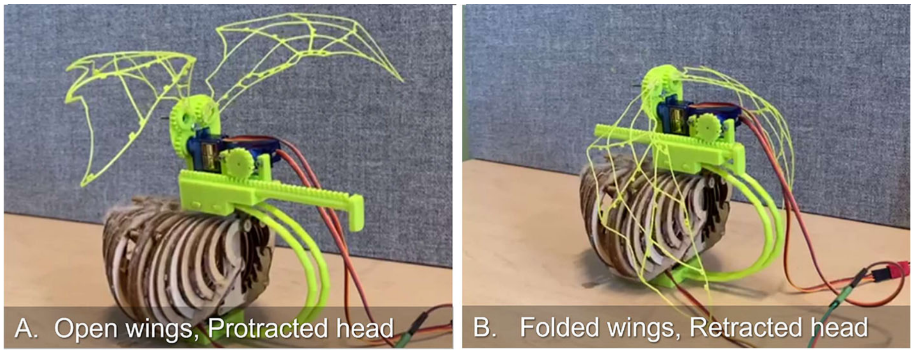


**Fig. 2** The Bodily expressIons and Respiration Drone conveying Emotions. It is composed of a ribcage representing its respiratory rate (RR), a pair of wings, and a head that can reconfigure its position, changing the overall body postures. Figures (**A**) and (**B**) describe two body postures, respectively open wings, protracted head, and folded wings and retracted head

### 2.3 Social Robots Conveying Emotions

A variety of methods and mechanisms have been developed for ground robots to present social cues and specifically for emotions. Robots' emotional states can be presented along diverse interaction modalities, such as by using the robot's movement, posture, sound, and color [23–25]. Further visual representations exist, such as Buddy an emotional companion robot [26] that expresses facial expressions of emotion on a screen. Other techniques exist, such as using haptics, where a furry robot conveys its emotional state Bucci et al [14, 27] as it breathes. In this work, participants are invited to "feel" the robots' breathing in addition to seeing the robot's behavior change. While these prior works can inform our design, drones present different affordances and form factors compared to ground robots and as such need to be studied in their own right. Indeed, a drone's innate ability to fly affects how people perceive them [19] so that their mental model when interacting with drones will most likely differ from the ones developed for ground robots. We then present BiRDe: a Bodily expressIons and Respiration Drone conveying Emotions as the first perched drone system.

## 3 BiRDe: Bodily ExpressIons and Respiration Drone Conveying Emotions

Our design goals are for BiRDe to convey its emotional states through its behaviors to people while perched, in a natural and compelling manner drawn from real-life flying creatures and from previous work on robotics. We arrived at the interaction, design choices, and metaphor for BiRDe after several rounds of design reflections. BiRDe was designed to resemble a flying creature with wings and a head, as well as a breathing ribcage, to convey emotions (Fig. 2). In this section, we introduce the design rationale as well as its final implementation.

### 3.1 Design Rationale

We here describe the main features considered when designing our perched drone.

#### 3.1.1 Example Scenario of a Perched Drone

We first envisioned a series of scenarios for perched drones. Writing these scenarios helped us define essential aspects of the design rationale for perched drones by establishing a better understanding of potential use cases, interaction needs, and mental models. While additional scenarios are further described in the example applications Sect. 6.3), we here present one exemplifying use case: Imagine Sarah cycling with her companion drone flying by her side (Fig. 3). Having a companion drone releases her from needing to carry it or pay attention to it while she is traveling (as opposed to a ground robot). Suddenly, her leg muscle cramps, and she experiences pain and decides to stop and rest. Her drone lands near her changing its state from flying to being perched. While perched, it supports Sarah by trying to distract her from the pain and comfort her. To do so, the perched drone needs to have the ability to express emotional states, which are traditionally based upon an emotional model.

#### 3.1.2 Emotional Model

We decided to use an emotional model that is universal, meaning that it is widely understood by people regardless of culture, and that enables to convey a large range of emotions. As such, we opted for Barrett and Russell's model [28], which answers our criteria and is widely used to convey, and to assess, emotions—successfully—in both HDI and HRI. In this model, emotions are positioned on a two-axis grid, composed of *Valence*: how positive or negative the emotion is, and *Arousal*: the level of stimulation the emotion is elicit-

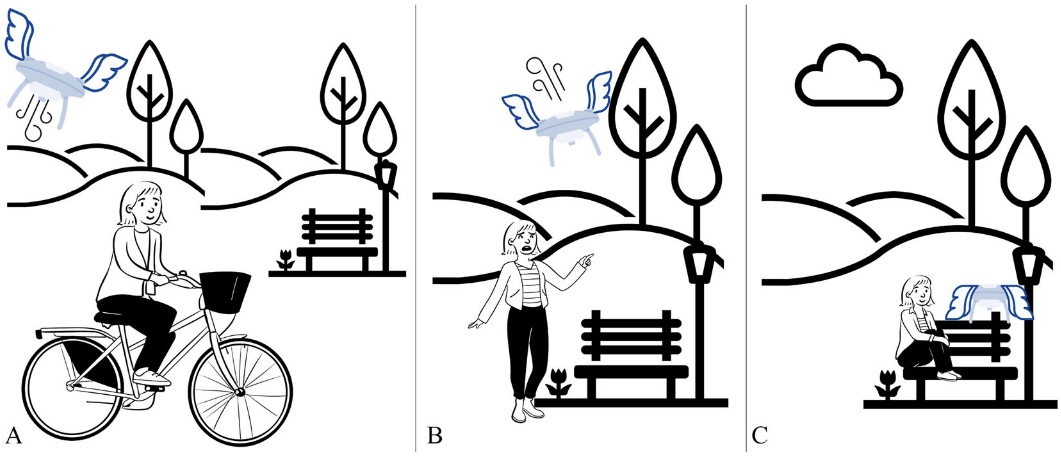


**Fig. 3** Example scenario of the use of a perched drone as a flying companion: (**A**) a woman cycles with her companion drone flying by her side. (**B**) she feels pain and stops cycling, so her drone switches from flying to being perched. (**C**) the drone is perched on the bench, trying to comfort her

ing [29]. This model also presents the advantage of not being directly linked to the drone's flying metaphor. Our next step was to identify how a perched drone could convey emotions through Valence and Arousal. To do so, we first identified potential design metaphors that would support the mental model of a perched drone [19].

#### 3.1.3 Flying Metaphors for Perched Drones

We wanted to create a perched drone that would convey the mental model of a drone, despite its non-flying state. In addition, this was an important process to separate perched drones from ground robotics designs, exploiting the design features and affordances that are inherent to aerial robots. As such, we decided to draw metaphors related to flight (e.g., aviation, flying objects, and creatures). Interaction techniques and metaphors are different for flying and perching states; for example, flying creatures cannot use their wings as a direct communication tool while flying, but only as a means of transport that can have indirect aspects of communication (e.g., distance, flight path, location). The same is true for aviation-related objects such as helicopters, and kites; once the object takes off its flying mechanism cannot be used for communication. However, it is important to acknowledge one theme which can be exempt from this limitation: abstract entities. These, such as ghosts, for example, do not necessarily have a well-defined aviation method and are thus free to communicate by any means.

In addition, we considered how emotions could be conveyed for each metaphor. This is crucial as there is no established best practice for a drone to convey emotional states in the literature, and since existing solutions cannot be directly applied to a perched drone. Given the novelty of this concept we did not want to exclude any naturally occurring means of communication within our designs and have therefore elected to only design for a perched state, i.e., the design of choice will not fly at all. We here present three distinct concepts to highlight our thought process. Note that these metaphors were discussed amongst the research team.

**Mechanical Drone Concept.**
We first described using an off-the-shelf drone and replacing its propellers with soft ones. However, when we introduced this design as an expressive perched drone, it was complex to envision how it would express itself in terms of emotional states. Indeed, this design was perceived as being more task-oriented or utilitarian, and prior work has shown that a more radical form drone could be perceived as having greater social skills [19]. This steered our design away from traditional drone designs.

**Cloud Concept.**
We then envisioned a cloud model that has a clear mental model for being airborne. However, when describing emotions the cloud could convey, the research team mostly associated negative valence emotions (e.g., sadness, grief) with the cloud. For instance, they described the cloud as being associated with rain and "feeling blue". We then had to further consider mental models that can be perceived as having a wide range of emotions.

**Flying Creature Concept.**
We considered the qualities of flying creatures, whether real (e.g., bird) or fictional (e.g., dragon) [19], and identified two main criteria for inclusion: 1. a well-defined physical body (as opposed to a spirit); and 2. the creature's liveliness (as opposed to a banshee) so that they can express a wider range of emotional states.

After several iterations, we opted for a creature inspired by both birds and bats which are familiar living creatures zoomorphic in nature, and therefore less likely to bias people's feelings and perceptions than a more anthropomorphized creature (e.g., a fairy or a genie). We note that, as for most flying creatures, people have most likely not interacted with them in the past [19], leaving the space needed for interpretation in our design.

#### 3.1.4 Conveying Emotions

Once the metaphor was selected, our next step was to define how emotions (valence and arousal) would be conveyed. We first decided that our perched drone would breathe. This functionality was chosen due to its relations with rhythms of the body, people's interactions with others, and its ability to convey emotions with affective robots [30]. Specifically, respiratory rate (RR) represents different arousal levels, so high arousal levels are correlated with fast RR, and low arousal levels with slow RR [31, 32]. While breathing can be represented through various body parts (e.g., nose, mouth, lungs), we opted for a rib-cage design that was successful in prior work [14] and can be applied to both ground and flying creatures (e.g., as opposed to a mouth and not a beak).

In addition to arousal, we aimed at conveying valence. We opted for the design of body language, which is a well-known technique in robotics to convey emotional states and valence, in particular, [23, 33, 34]. We chose two main design elements for body language: wings and a head, which we established as the basic design elements for the flying creature metaphor. We proposed several body postures based on their positioning. By opening its wings and protracting its head, our perched drone body posture is *Expanded* (i.e., "standing tall"), which is designed to represent positive valence. With folded wings and a retracted head, the body posture is *Contracted*, which is designed to represent negative valence emotional states. These assumptions are based on prior works showcasing the effects of the above body postures on the valence perception of robots [23, 33].

To summarize, our selected flying-creature metaphor presents three main components: a ribcage for respiratory rate, and wings and head for body posture. In the next section, we describe the implementation of our perched drone BiRDe.

### 3.2 BiRDe's Implementation

We here depict how each of BiRDe's components was implemented, animated, and assembled. The software implementation is described under the ***Motion*** paragraph of each component.

#### 3.2.1 Overall Structure and Frame

To connect BiRDe's main components (i.e., ribcage, wings, and head), we 3D modeled and printed: a square scaffold, two curved pins, one plate, and 5 gears (see Fig. 4). All 3D parts were modeled using Tinkercad[3] and printed with PLA. All of BiRDe's parts are described in Table 1 with material and dimensions.

To assemble BiRDe's frame, we connected the curved pins Fig. 4D) to the square frame (Fig. 4C), which was used to contain the ribcage (Fig. 4A). The pins were also connected to the head's motor bracket (Fig. 4E). To allow motion, four gears (Fig. 4H) were used for the wings (Fig. 4B) and screwed to the printed plate (Fig. 4G). The fifth gear was used for the head's motor bracket. This resulted in a complete frame that withheld the wings and head from vibrating with the breathing movement, as well as for BiRDe's main parts to be modified and replaced.

#### 3.2.2 Ribcage

We here describe the hardware design of the Ribcage.

***Mechanical Design.*** BiRDe's ribcage (Fig. 4A) is built off RibBit [14], a wooden ribcage with 34 ribs (17 on each side). Each rib is laser cut from a 4 mm plywood and assembled by wood-gluing, as well as by connecting skewers as pins. Its appearance is of wooden construction so it has a naturalistic aesthetic and its size (Table 1) allows it to easily fit in one's hand.

***Motion.*** The ribcage's motion is operated by a Tower Pro SG90 servo motor connected to its front and back by two springs. The servo motor's circular motion results in a rigid actuation, and its span is predetermined by the construction of this device. It can move (Fig. 4A) in a range of 15–35 degrees. BiRDe can be programmed to produce RRs by controlling the frequencies of the breathing cycle from not moving whatsoever, and up to 2 breathing cycles per second (2 Hz) given our servo motor's capacity. The power required for the breathing rate ranged from 0 Watts to 0.35 Watts for the high frequency.

#### 3.2.3 Wings

We here describe the hardware design of the wings.

***Mechanical Design.*** The wings were 3D modeled so that they would have five lines acting similar to a bat's fingers (phalanges). Three perpendicular lines were added for a more robust construct (Fig. 4B). After printing, they were dipped in warm water and placed on the inside of a bowl to create a curve that would envelop BiRDe. Each wing was glued to one out of a four-gear array, which was screwed into the plate.

***Motion.*** A Tower Pro SG90 servo motor was connected to one of the bottom gears (Fig. 5), and the other three gears were aligned with one another so that when the motor moved in one direction both wings responded symmetrically. The

[3] Tinkercad: https://www.tinkercad.com.

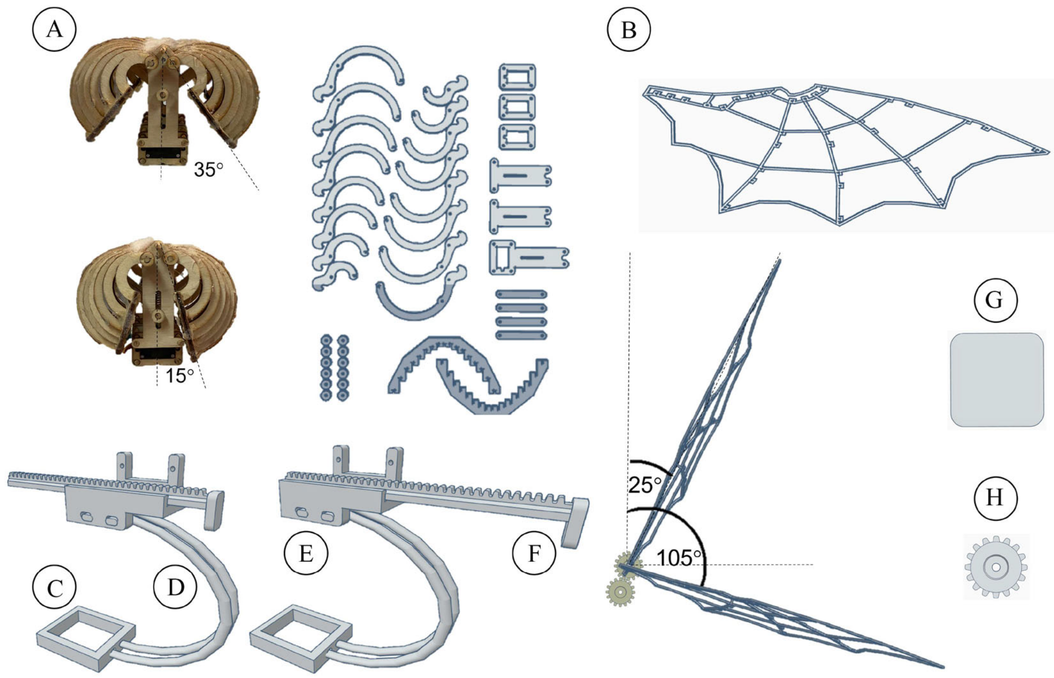


**Fig. 4** BiRDe's components: (**A**) the ribcage parts [14] comprised of 34 ribs, and angles of motion moving from 15 degrees to 35 degrees, (**B**) wings layout, which in our experiment were positioned in either 25 degrees, or 105 degrees, (**C**) square scaffold, (**D**) curved pins, (**E**) motor bracket, (**F**) pusher (head), (**G**) plate, and (**H**) gear. Parts B to G were 3D modeled and printed in PLA

**Table 1** BiRDe's parts (as presented on Fig. 4) name, material and dimensions

| Name | Number | Part | Material | Dimensions in cm (length, width, height) |
|---|---|---|---|---|
| Ribcage | A | Ribs | Plywood | 11 × 11.5–13.5 × 7.5 |
| | B | Wings | PLA | 21 × 7 × 0.1 |
| Frame | C | Square scaffold | PLA | 4.3 × 5 × 0.9 |
| | D | Curved pins | PLA | 9.5 × 7.7 × 1.7 |
| Head | E | Motor bracket | PLA | 5.5 × 3 × 3.4 |
| | F | Pusher | PLA | 12.5 × 1 × 1 |
| Connectors | H | 5 Gears | PLA | Each 1.8 × 1.8 × 0.6 |
| | G | Plate | PLA | 4.5 × 4.5 × 0.1 |

wings can change their position in real-time between being fully opened (0 degree) to being folded (max 146 degree for each wing), its upper limit given by the ribcage, and can hold any position in this range. The power required for changing the wings' position is 0.1 Watts.

#### 3.2.4 Head

We here describe the hardware design of the head.

***Mechanical Design.*** A motor bracket, gear, and a 12.5 cm pusher accounted for BiRDe's head. The bracket was designed with a rail for the pusher, and with holes at its bottom so it could connect to the frame (Fig. 4E, F).

***Motion.*** A Tower Pro SG90 servo motor was connected to the fifth gear and screwed to the bracket (Fig. 5). This allowed converting the motor's circular motion to linear motion which represented BiRDe's head movement from retracting (in-line with the bracket) to protracting (full length of the pusher) and can hold any position in this range. The power required for changing the heads' position is 0.1 Watts.

## 4 Validation Study

To answer our research questions related to the effects of each individual component of BiRDe (RQ 1.a), and their ability to recognize a perched drone's emotional state (RQ 1.b), as well as their understanding of which emotional states increase users' willingness to interact (RQ2) (see Sect. 1), we ran a validation study using BiRDe.

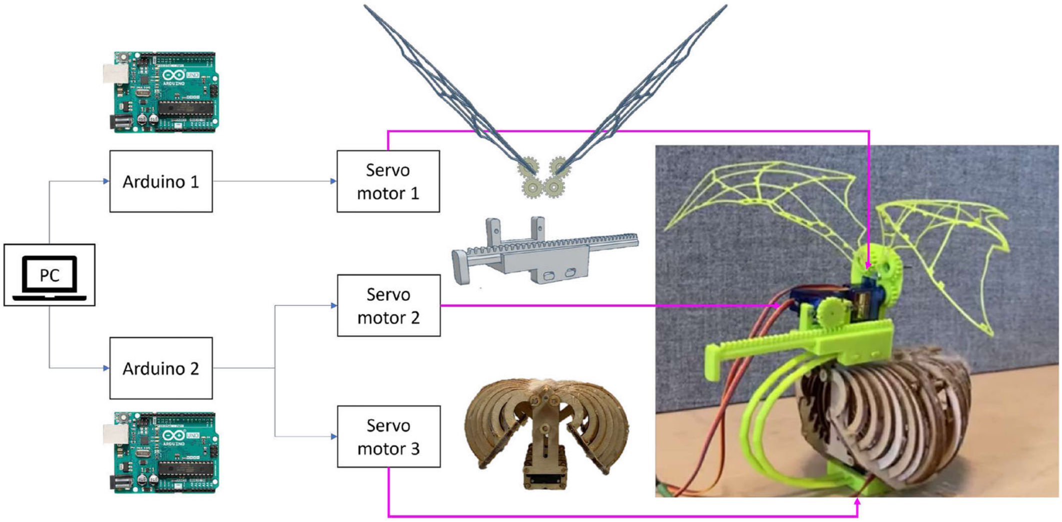


**Fig. 5** BiRDe's assembling process: Two Arduino Duemilanove boards connected to a computer were used to actuate three Tower Pro SG90 servo motors that controlled the ribcage for RR, and the wings and head for the body position

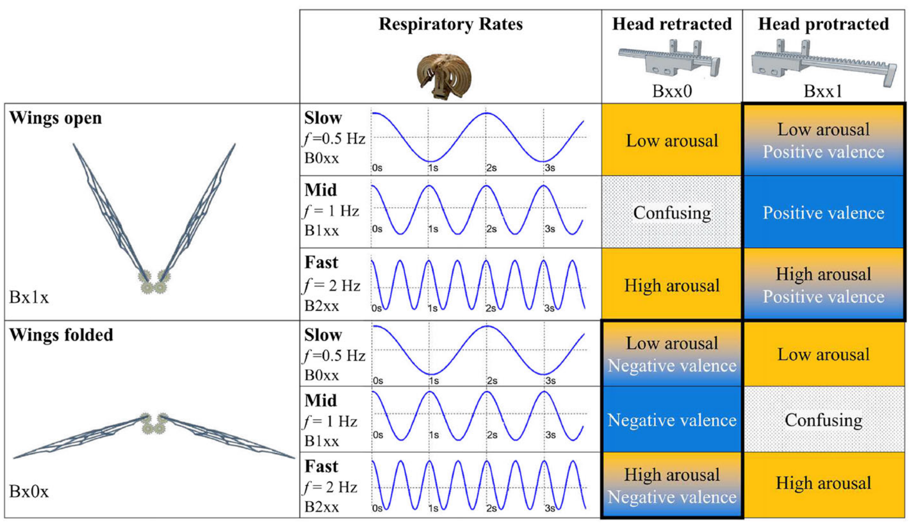


**Fig. 6** BiRDe's twelve behaviors presented by RR: slow, mid, and fast (B0/1/2,xx); wings positions: folded and open (Bx0/1x); and head positions: retracted and protracted (Bxx0/1), marked as B000-B211. The colored backgrounds represent expected arousal levels (yellow) and expected valence levels (blue). The black frames highlight matching wings and head positions as Expanded (black frame—right), or Contracted (black frame—left). (Colour figure online)

### 4.1 Design of Independent Variables: Studied Behaviors and Apparatus

To conduct the study, we programmed BiRDe to produce three RRs, two wings positions, and two head positions, resulting in 12 behaviors (3 RR × 2 wings × 2 head; Fig. 6). BiRDe's twelve behaviors were presented to participants so that they could label them, and rate their willingness to interact with BiRDe for each behavior. We used a slow, mid, and fast RR (Fig. 6 middle), the slow RR (0.5 cycles per second; 0.5 Hz) and fast RR (2 cycles per second; 2 Hz) were used to represent low and high levels of arousal accordingly [31, 32]. A mid-RR (1 cycle per second; 1 Hz) was created to explore how a moderate RR would affect the interpretation and labeling of BiRDe's behaviors. The wings and head positions were chosen so that BiRDe's open wings (Fig. 4, 25 degrees), and protracted head (Fig. 4F), would represent positive valence emotional states (Fig. 6, black frame—right). Whereas folded wings (Fig. 4, 105 degree), and retracted head, would represent negative valence emotional states (Fig. 6, black frame—left) [33].

In terms of our apparatus, we acknowledge that the current instantiation of the BiRDe system presents flying features (i.e., wings) but does not have the actual ability to fly. This design choice to focus on fully working behaviors over flying capability is coherent with our hypotheses (see below) where our research focuses on BiRDe's behaviors while perched. In addition, this is on par with prior research exploring future drone designs using low- and mid-fidelity prototypes that do not fly [9, 13, 14, 19, 35, 36].

### 4.2 Hypotheses

Based on BiRDe's design and to answer RQ 1.a and RQ 1.b, we articulate our hypotheses related to BiRDe's behaviors, that is represented by its ribcage's RR, its wings positions, and its head's position. Figure 6 presents a summary of the 12 behaviors and of the associated emotional states related to the hypotheses presented below.

H1 A matching body posture corresponds to valence-related labeling with:

- *H1a*: Expanded body posture represents positive valence.
- *H1b*: Contracted body posture represents negative valence.

Indeed, BiRDe was designed so that its body language could convey valence. Specifically, in terms of body postures: when it is Expanded (i.e., wings open and head protracted), we expect participants to assess its valence as positive; when it is Contracted (i.e., wings folded and head retracted) we expect participants to assess its valence as negative. Additionally, we expect that a mismatching body posture will lead to participants focusing on the RR (see H2).

H2 Respiratory rates correspond to arousal-related labeling with:

- *H2a*: Slow RR represents low arousal.
- *H2b*: Fast RR represents high arousal.

Based on prior work, we posit that a slow – respectively fast – RR would be assessed by participants as a low – resp. high – arousal accordingly.

H3 Combined RR and matching body postures correspond to respective valence and arousal labeling with:

- *H3a*: Slow RR + Expanded body posture represents low arousal + positive valence.
- *H3b*: Slow RR + Contracted body posture represents low arousal + negative valence.
- *H3c*: Fast RR + with an Expanded body posture represents high arousal + positive valence.
- *H3d*: Fast RR + with an Contracted body posture represents high arousal + negative valence.

We hypothesize that when BiRDe displays a matching body posture (as in H1) combined with either slow or fast RR (as in H2), participants should assess these behaviors as a combination of the respective valence and arousal.

H4: mid-RR leads participants to focus on body posture.

- *H4a*: mid-RR + matching body postures lead to the matching body postures' valence (as in H1).
- *H4b*: mid-RR + mismatching body postures lead to confusion.

Since the mid-RR was not designed to convey either low or high arousal, we expect participants to primarily rely on body posture. In case the posture is matching, we are in the same condition as H1. When it is mismatching, we suggest that the behavior will not provide any reliable information for participants to assess it and would create confusion.

### 4.3 Variables

To answer RQ 1.a, RQ 1.b, and verify our hypotheses, we used emotional labels and measured their valence and arousal. We chose these strategies as they were successful to let people assess a drone's emotional states in prior work [11, 21]. We chose our study's emotional labels database, following the footsteps of Bucci et al [14] and used a subset of words from the Positive and Negative Affect Schedule (PANAS) [15], which consists in descriptive emotional labels that rely on the word's valence and arousal levels, as follows: Words representing only negative valence: *miserable, troubled*; positive valence: *happy, pleased*. Words representing only low arousal: *sleepy, still*; high arousal: *alert, hyperactivated*. We also selected combinations of both: Positive valence and low arousal: *calm*; Positive valence and high arousal: *excited*; Negative valence and low arousal: *bored*; Negative valence and high arousal: *scared* [15]. To answer RQ 2, we used a 7-point Likert scale rating of participants' willingness to interact.

### 4.4 Participants

We recruited 30 volunteers (13f, 17 m) from 20 to 30 y.o. consisting of a convenience sample ($\mu = 24.67$ y.o., SD = 2.12). Participants' culture was diverse and included people from Canada, China, India, Iran, Israel, Russia, and the USA. Participants' occupations varied, such as students, social workers, engineers, and even nurses. All participants had seen a drone prior to the study, and no one had piloted or owned a drone. Participants were recruited from two institutions' databases and via word of mouth. They were compensated the equivalent of US$30 in local currency for their participation.

## 4.5 Protocol

We here describe each step in our study's protocol.

**Step 1: General Information.** Participants ($N = 30$) were asked to take part in a two-hour study. They were compensated the equivalent of US$30 for their time. The experiment took place in a research lab where participants were welcomed, invited to sit in front of BiRDe, given a description of the study, and asked to fill out the experiment's consent form. Following, participants' personal information such as their age, gender, occupation, and previous encounter with drones was administered. The next step was to ask them to fill out the Negative Attitude Towards Robots Scale (NARS): a 14-item self-report inventory measuring attitude towards robots. We opted to use the original process, as in [37], and participants rated each item on a 5-point Likert scale. Throughout the entire time participants filled an answered questionnaires, BiRDe did not move at all, and participants had that time to observe our system's design.

**Step 2: Emotional States Baseline.** Participants received a sheet of paper with the subset of PANAS words (see Sect. 4.3) in a randomized order. For each word, participants were asked to assign a value for the word's valence and arousal. To do so we used the same process as Bucci et al [14] and presented beneath each of the PANAS words two 9-point Likert scales, one for valence and one for arousal. This process helped establish a baseline for each emotional state label per person, which will be used in the analysis process.

**Step 3: Emotional Behaviors Labelling and Willingness to Interact.** Participants were introduced to BiRDe, which was presented as a prototype for a perched drone. We specified that a final product may differ in its engineered design, but not conceptually in terms of its role and form factor. We used a within-subject design so that all participants observed all 12 of BiRDe's behaviors in a randomized order. After each behavior, participants were asked to select up to 3 words from the PANAS subset that best defines what the drone is feeling. As opposed to Bucci et al [14], we did not force participants to select 3 words but allowed a lower number of words to be selected (a minimum of 1). This was done to eliminate "noise" in our data in the case participants were relating to fewer words to label BiRDe's behavior. Following their word selection, they then indicated how confident they were with their choice on a 7-point Likert scale. Finally, they answered how willing they are to interact with the drone during the current behavior they are observing on a 7-point Likert scale.

**Step 4: Structured Interview.** Finally, in a structured individual interview, participants were asked three open-ended questions to further investigate their perception of our prototype: 1. "Did the drone behaviors remind you of anything?", "2. Were the drone behaviors familiar to you in any way?", and 3. "Do you have any concerns regarding the drone?".

## 4.6 Data Analysis

We here describe the methods used to analyze our independent variables.

### 4.6.1 NARS

We analyzed the results of the NARS questionnaire by calculating the result of each subscale (S1, S2, and S3) individually as recommended for the regular NARS questionnaire [37].

### 4.6.2 Effects of RR, Wings, and Head on Valence and Arousal

To statistically analyze the effects of each independent variable on valence and arousal (RQ 1.a), a multinomial regression model was utilized within the framework of General Linear Model (GLM). Three independent variables and their full factorial interactions were included in the initial model as fixed effects: RR, which had three levels: slow, mid, and fast. It was coded in the analysis as 0/1/2 accordingly. Wings, which had two levels: folded, and open. It was coded in the analysis as 0/1 accordingly. And head, which had two levels: retracted, and protracted. It was coded in the analysis as 0/1 accordingly. Participants were included as random effects to account for variations among them. We applied a backward elimination procedure to yield the final model.

### 4.6.3 Interpretation of BiRDe's Behaviors as Emotional States

Aiming to analyze whether BiRDe's 12 behaviors were perceived distinctly from one another (RQ 1.b), we conducted a discriminant analysis on the behaviors ($3\times2\times2$) using the participant's assigned valence and arousal values as the independent variables.

### 4.6.4 Confidence and Willingness to Interact

To statistically analyze the effects of Confidence and Willingness to Interact, a multinomial regression model was utilized within the framework of General Linear Mixed Model (GLMM) for each dependent variables. One independent variable was included in the model as a fixed effect: BiRDe's Behaviors and one variable was included in the model as a random effect: Participants.

**Table 2** NARS Results: Means and Standard Deviations (SD) for S1 (ranging from 6–30), S2 (5–25), and S3 (3–15)

| S1—Interaction | | S2—Social | | S3—Emotion | |
|---|---|---|---|---|---|
| Mean | SD | Mean | SD | Mean | SD |
| 11.3 | 3.23 | 14.8 | 3.25 | 9.3 | 2.77 |

# 5 Results

The results of our statistical analysis are described below. We first present the results of the NARS questionnaire to evaluate people's negative attitudes toward robots before the study. We then present the effect of each independent variable (RR, Wings, Head) on the main dependent variables: valence and arousal, answering *RQ 1.a*. Once the effects are identified, we describe the results of the participant's recognition of BiRDe's behaviors as emotional states, answering *RQ 1.b*. Finally, we present which emotional states yielded a higher willingness to interact with BiRDe, answering *RQ 2*.

## 5.1 Negative Attitude Towards Robots

Table 2 presents the detailed means and standard deviations of the NARS data collected prior to the study. Note that a high score in S1 (Situations of Interaction with Robots) and S2 (Social Influence of Robots) means a negative attitude. On the contrary, a high score in S3 (Emotions in Interaction with Robots) means a positive attitude. Our results show that overall, participants had a positive attitude toward interacting with robots (S1) and a neutral attitude toward their social influence (S2) and emotions in interaction (S3).

## 5.2 Effect of Independent Variables on Valence and Arousal

The multinomial regression results on valence and arousal are reported in Table 3 (a) and (b), respectively. The analysis shows that each attribute has its own effect on valence and arousal (no interactions were significant).

### 5.2.1 Valence

Valence was affected by RR, wings, and head. As Table 4 shows, overall, participants differentiated between the different levels of valence, which ranged from -4 (most negative) to 4 (most positive) with the exception of 0 which was not perceived as different. Wings and head have two levels each, which were significantly different. RR had three levels, which were significantly different.

### 5.2.2 Arousal

Arousal was affected by RR and head. As Table 5 shows, overall, participants differentiated between the different levels of arousal, which ranged from −4 (least arousing) to 4 (most arousing) with the exception of 2, which was not perceived as different. RR's three levels were all significantly different from one another. Head has two levels, which were significantly different.

## 5.3 Interpretation of BiRDe's Behaviors as Emotional States

The discriminant analysis revealed two discriminating factors (Table 6). The first explained 75.3% of the variance, canonical $R^2 = .24$, whereas the second explained 24.7%, canonical $R^2 = .09$.

The first, $\Lambda = .68$, Wald $\chi^2(22) = 266.911$, $p < .000$, and second, $\Lambda = .90$, Wald $\chi^2(10) = 70.516$, $p < .000$, functions significantly differentiated the behaviors (Table 7).

The correlation between the outcomes and the discriminant function revealed that arousal was loaded more highly on the first function (Table 8; r = .863) than the second function (r = .516), whereas valence loaded more highly on the second function (r = .912) than the first function (r = -.423).

The discriminant analysis in Table 9 reports each behavior's centering around valence and arousal. A 0.5 threshold was chosen to determine each behavior's main factor. The overall centroids scatter plot can be found in "Appendix A"—Fig. 10.

### 5.3.1 Slow RR (B0xx)

The analysis in Table 9 shows that slow RR is generating behavior interpretation that centers around valence, and arousal. One behavior is centered around valence, which is when a Contracted body posture is presented, i.e., the wings are folded and the head is retracted (B000). An expanded

**Table 3** Wald Chi-Square test for effects of RR, Wings, and Head on valence (a) and arousal (b)

| (a) Valence: Source | Wald Chi-Square | df | Sig. | (b) Arousal: Source | Wald Chi-Square | df | Sig. |
|---|---|---|---|---|---|---|---|
| RR | 13.981 | 2 | **<.001**** | RR | 50.734 | 2 | **<.001**** |
| Wings | 27.147 | 1 | **<.001**** | Wings | .321 | 1 | .57 |
| Head | 9.167 | 1 | **<.005*** | Head | 4.216 | 1 | **<.05*** |

$^{**}p < .001$, $^{*}p < .01$, $p < .05$

**Table 4** Wald Chi-Square test for effects of each level of RR (slow = 0, mid = 1, fast = 2), Wings (folded = 0, open = 1), and Head (retracted = 0, protracted = 1) on valence

| Parameter | B | Std. Error | Lower | Upper | Wald Chi-Square | df | Sig. |
|---|---|---|---|---|---|---|---|
| Valence = −4 | −2.714 | .2148 | −3.141 | −2.286 | 12.6368 | 1 | **.000**** |
| Valence = −3 | −1.777 | .2884 | 2.342 | −1.212 | 37.964 | 1 | **<.001**** |
| Valence = −2 | −.88 | .2721 | −1.414 | −.347 | 10.463 | 1 | **.001**** |
| Valence = −1 | −.438 | .2676 | −.963 | .086 | 2.681 | 1 | **.01*** |
| Valence = 0 | .151 | .2659 | −.37 | .672 | .322 | 1 | .295 |
| Valence = 1 | .303 | .2662 | −.218 | .825 | 1.298 | 1 | **.038** |
| Valence = 2 | .998 | .2721 | .465 | 1.531 | 13.453 | 1 | **<.001**** |
| Valence = 3 | 1.751 | .2918 | 1.18 | 2.323 | 36.032 | 1 | **<.001**** |
| RR = 0 | 1.01 | .2737 | .473 | 1.546 | 13.61 | 1 | **<.001**** |
| RR = 1 | .53 | .2876 | −.034 | 1.094 | 3.397 | 1 | **.001**** |
| RR = 2 | 0 | . | . | . | . | . | . |
| Wings = 0 | −1.053 | .2291 | −1.502 | −.604 | 21.106 | 1 | **<.001**** |
| Wings = 1 | 0 | . | . | . | . | . | . |
| Head = 0 | −.563 | .2245 | −1.003 | −.123 | 6.282 | 1 | **.012** |
| Head = 1 | 0 | . | . | . | . | . | . |

[1] Model $\chi^2(84) = 70.4$, ***p* <.001,**p* <.01, *p* <.05

**Table 5** Wald Chi-Square test for effects of each level of RR (slow = 0, mid = 1, fast = 2), Wings (folded = 0, open = 1), and Head (retracted = 0, protracted = 1) on arousal

| Parameter | B | Std. Error | Lower | Upper | Wald Chi-Square | df | Sig. |
|---|---|---|---|---|---|---|---|
| Arousal = −4 | −3.16 | .3261 | −3.799 | −2.521 | 93.894 | 1 | **.000**** |
| Arousal = −3 | −2.688 | .308 | −3.291 | −2.084 | 76.15 | 1 | **.000**** |
| Arousal = −2 | −2.055 | .2887 | −2.621 | −1.489 | 50.632 | 1 | **<.001**** |
| Arousal = −1 | −1.874 | .2842 | −2.431 | −1.317 | 43.481 | 1 | **<.001**** |
| Arousal = 0 | −1.109 | .269 | −1.636 | −.582 | 16.988 | 1 | **<.001**** |
| Arousal = 1 | −.392 | .2619 | −.905 | .121 | 2.24 | 1 | **.003*** |
| Arousal = 2 | .482 | .2651 | −.0375 | 1.002 | 3.307 | 1 | .11 |
| Arousal = 3 | 1.787 | .3141 | 1.171 | 2.402 | 32.366 | 1 | **<.001**** |
| RR = 0 | −2.064 | .2909 | −2.634 | −1.494 | 50.341 | 1 | **<.001**** |
| RR = 1 | −.891 | .2858 | −1.451 | −.331 | 9.722 | 1 | **.002*** |
| RR = 2 | 0 | . | . | . | . | . | . |
| Wings = 0 | −.111 | .2239 | −.55 | .328 | .246 | 1 | .572 |
| Wings = 1 | 0 | . | . | . | . | . | . |
| Head = 0 | .178 | .2236 | −.261 | .616 | .632 | 1 | **.043** |
| Head = 1 | 0 | . | . | . | . | . | . |

[1] Model $\chi^2(84) = 95.74$, ***p* <.001,**p* <.01, *p* <.05

body posture, i.e., the wings are open and the head is protracted (B011), and the remaining behaviors are centered around arousal.

#### 5.3.2 mid-RR (B1xx)

The analysis shows that a mid-RR is generating behaviors centered either around arousal or on neither valence nor arousal around, dependent on BiRDe's body posture. When it presents a Contracted body posture, i.e., the wings are folded and the head is retracted (B100), the behavior is centered around arousal. The other body postures are not centered around valence or arousal.

#### 5.3.3 Fast RR (B2xx)

The analysis shows that a fast RR is generating behaviors' interpretations that are centered either around arousal or on neither valence nor arousal, depending on BiRDe's wings position. When the wings are in folded positions (B20x),

**Table 6** Eigenvalues resulting from the discriminant analysis for the twelve behaviors

| Function | Eigenvalue | % of Variance | Cumulative% | Canonical Correlation |
|---|---|---|---|---|
| 1 | .318 | 75.3 | 75.3 | .491 |
| 2 | .104 | 24.7 | 100.0 | .307 |

Results show that Arousal and Valence account for 100% of the results

**Table 7** Wilk's Lambda resulting from the discriminant analysis for the twelve drone's behaviors

| Test of Functions(s) | Wilks' Lambda | Chi-square | df | Sig. |
|---|---|---|---|---|
| 1 through 2 | .687 | 266.911 | 22 | .000 |
| 2 | .906 | 70.516 | 10 | .000 |

**Table 8** Structure Matrix: Pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions

| Function | 1 | 2 |
|---|---|---|
| Arousal | .863* | .516 |
| Valence | −423 | .912* |

Variables are ordered by the absolute size of correlation within the function

**Table 9** Functions at Group Centroids from the discriminant analysis for the twelve behaviors

| Behavior (RR,Wings,Head) | Arousal | Valence |
|---|---|---|
| B000 | −.629 | **−.674** |
| B001 | **−.708** | .136 |
| B010 | −.415 | .167 |
| B011 | **−.520** | −.021 |
| B100 | **.549** | .033 |
| B101 | −.304 | −.183 |
| B110 | −.013 | .056 |
| B111 | −.333 | .364 |
| B200 | **.885** | −.338 |
| B201 | **.796** | −.363 |
| B210 | **.503** | .344 |
| B211 | .410 | .443 |

The first digit is for RR (0 = low, 1 = mid, 1 = fast), the second is for wings (0 = folded, 1 = open), and the third is for the head (0 = contracted, 1 = extracted). A 0.5 threshold is administered and presented as bolded

the behaviors interpretations are centered around arousal. Whereas when the wings are in an open position (B21x), interpretations either rely on arousal or not on either one. These results show that for fast RR, the wings' position, and not the heads, is the determining factor.

### 5.3.4 Hypotheses Validation

To determine the final valence and arousal values for each behavior, we considered the behaviors' Centroid (see Section A–Fig. 10), as well as each behavior's valence and arousal's average and dispersion throughout the grid (see Section "Appendix A"—Figs. 11, 12, 13).

We here describe how our hypotheses from Sect. 4.1 were verified (see Fig. 7).

***H1 was partially supported***

- *H1a*: The three behaviors with expanded body posture (B011,B111,B211) were labeled with positive valence.
- *H1b*: Two of the three behaviors with contracted body posture (B000,B200) were labeled with negative valence. However, B100 was not assigned a consistent valence level.

***H2 was fully supported***

- *H2a*: The four behaviors with slow RR (B000,B001, B010,B011) were labeled with low arousal. Further to our assumption, we found that the two behaviors with slow RR and mismatching body postures (B010, B001) were in addition to low arousal labeled with positive valence.
- *H2b*: The four behaviors with fast RR (B200,B201, B210,B211) were labeled with high arousal. Further to our assumption, we found that three behaviors in addition to high arousal were also labeled with valence such that behaviors with folded wings (B200, B201) were labeled with negative valence and Behavior B211 with positive valence.

***H3 was fully supported***

- *H3a*: Slow RR and Expanded body posture (B011) was labeled with low arousal and positive valence.
- *H3b*: Slow RR and Contracted body posture (B000) was labeled with low arousal and negative valence.
- *H3c*: Fast RR and Expanded body posture (B211) was labeled with high arousal and positive valence.
- *H3d*: Fast RR and Contracted body posture (B200) was labeled with high arousal and negative valence.

***H4 was partially supported***

- *H4a*: For mid-RR and matching expanded body posture (B111), the behavior was labeled with positive valence,

| | Respiratory Rates | Head retracted Bxx0 | Head protracted Bxx1 |
|---|---|---|---|
| **Wings open** Bx1x | **Slow** B0xx | B010 Low arousal ***Positive valence*** | B011 Low arousal Positive valence |
| | **Mid** B1xx | B110 Confusing | B111 ***Low arousal*** Positive valence |
| | **Fast** B2xx | B210 High arousal | B211 High arousal Positive valence |
| **Wings folded** Bx0x | **Slow** B0xx | B000 Low arousal Negative valence | B001 Low arousal ***Positive valence*** |
| | **Mid** B1xx | B100 **High arousal** | B101 Confusing |
| | **Fast** B2xx | B200 High arousal Negative valence | B201 High arousal ***Negative valence*** |

**Fig. 7** Participants' interpretations of BiRDe's 12 behaviors. Cells containing yellow backgrounds represent arousal-labeled behaviors, and blue backgrounds represent valence-labeled behaviors. Bold and Italic writing represents behaviors that were labeled with an added dimension. Behavior B100 is written in red which represents a missing dimension from our prediction: valence

and further to our assumption, we found that it was also labeled with low arousal. For mid-RR and matching contracted body posture (B100), the behavior was not labeled with consistent valence values, which was against our assumption. Further to our assumption, it was labeled with high arousal. Overall, a mid-RR with a matching body position yields a high arousal labeling for contracted body posture, and low arousal labeling for expanded body posture.

- *H4b*: None of the two mid-RR and mismatching body postures (B101, B110) were labeled with consistent valence or arousal.

Overall, 11 out of the 12 behaviors were labeled as expected or with an added dimension that enriched our initial assumptions. The outlier was B100 which was speculated to result in valence labeling but resulted in only arousal labeling.

### 5.4 Confidence

The analysis of the multinomial regression on BiRDe's behaviors shows that there were no significant differences between the different behaviors on participants' Confidence ($F_{(11,55)} = 1.39$, $p = .203$).

Confidence levels are presented in Table 10, and ranged from 3.8 to 5.3. Slow RR resulted in the highest confidence levels (4.5−5.3), behaviors B211 and B201 as well. Behaviors B110 and B101 yielded the lowest confidence levels (3.8–4).

We also present confidence levels in Fig. 8, where each behavior (Bxxx) displays its confidence rating grouped into low confidence levels (1–3 out of 7) in red, mid-levels (4–5) in yellow, and high levels (6–7) in green. Additionally, percentages for each confidence group are presented.

Fast RR behaviors (B2xx; top part) resulted in mostly confident ratings. Behavior B210 is the exception since it has more mid-confidence levels than low or high. For mid-RR (B1xx), participants' confidence rantings were mid- to low-confident levels. Behaviors B110 and B101 have the highest levels of low confidence ranting out of all the twelve behaviors, as expected. For slow RR behaviors (B0xx), participants were most confident in their emotion labeling.

### 5.5 Willingness to Interact

The analysis of the multinomial regression on BiRDe's behaviors shows that there were no significant differences between the different behaviors on participants' Willingnes to interact ($F_{(11,55)} = .561$, $p = .851$).

Willingness to interact levels are presented in Table 11, and ranged from 2.3 to 3.8. Fast RR resulted in the lowest levels (2.3−3.3), and slow RR resulted in the highest levels (3.1−3.8), the same goes for behaviors B111 (M = 3.5), and B211 (M = 3.3).

### 5.6 Interview Results and Observations

Participants were asked in the interview both about the drone's behavior and about their potential concerns. In terms of behavior, participants mentioned that the drone reminded them of a variety of flying animals, such as a bird, a bat, and an owl. P9 further mentioned that BiRDe reminded them of a dragon. In particular, participants mentioned that BiRDe's movement looked familiar, like the one of a (living) animal, such as P3 "it looks like an animal when breathing". Regarding their concerns, participants' responses can be classified in terms of: Safety, Surveillance, Privacy, and Noise. *Safety* was only addressed when referring to the drone flying, such as *"the drone could hit me while flying, or break something" (P3)*. Interestingly, other participants brought a positive outlook on safety: *"it can fly around me and be my guardian" (P10)*. Regarding *Surveillance*, participants expressed concerns about the potential embedded sensors: *"if it will fly*

**Table 10** Confidence mean and SD for BiRDe's 12 behaviors on a 7-point Likert scale

| | Respiratory rates | Head retracted Bxx0 | Head retracted Bxx1 |
|---|---|---|---|
| Wings open Bx1x | Slow B0xx | M = 4.5 SD = 1.83 | M = 5 SD = 1.58 |
| | Mid B1xx | M = 3.8 SD = 1.59 | M = 4.6 SD = 1.6 |
| | Fast B2xx | M = 4.5 SD = 1.67 | M = 5.4 SD = 1.56 |
| Wings folded Bx0x | Slow B0xx | M = 5.3 SD = 1.32 | M = 5.2 SD = 1.31 |
| | Mid B1xx | M = 4.4 SD = 1.45 | M = 4.0 SD = 1.87 |
| | Fast B2xx | M = 4.6 SD = 1.74 | M = 4.9 SD = 1.71 |

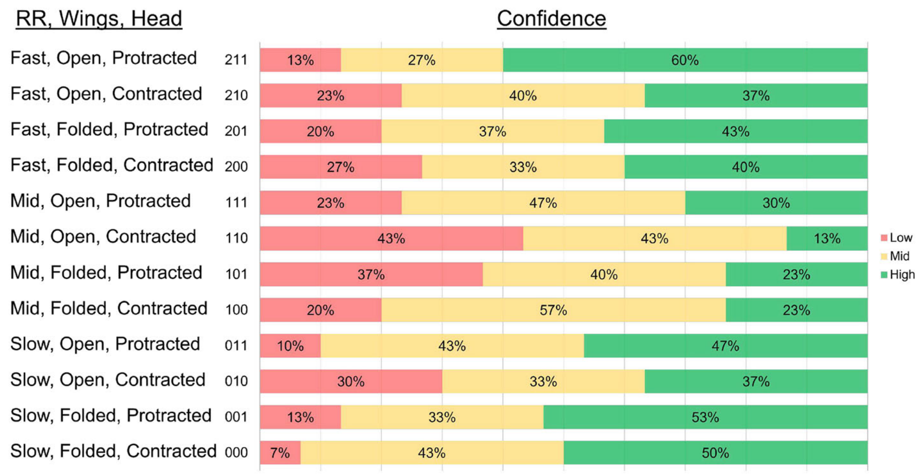


**Fig. 8** All behavior's confidence levels ratings grouped into low confidence level (represented by a rating of 1–3) in red, mediocre level (4–5) in yellow, and high level (6–7) in green. All behaviors also show confidence levels by their percentages. The figure's bottom part represents slow RR, the mid part mid-RR, and the top part fast RR. (Colour figure online)

**Table 11** Willingness mean and SD for BiRDe's 12 behaviors on a 7-point Likert scale

| | Respiratory rates | Head retracted Bxx0 | Head retracted Bxx1 |
|---|---|---|---|
| Wings open Bx1x | Slow B0xx | M = 3.1 SD = 1.96 | M = 3.8 SD = 2.12 |
| | Mid B1xx | M = 2.7 SD = 1.64 | M = 3.5 SD = 2.02 |
| | Fast B2xx | M = 2.6 SD = 2.01 | M = 3.3 SD = 1.95 |
| Wings folded Bx0x | Slow B0xx | M = 3.8 SD = 2.13 | M = 3.8 SD = 2.02 |
| | Mid B1xx | M = 3 SD = 1.83 | M = 2.8 SD = 1.93 |
| | Fast B2xx | M = 2.3 SD = 1.73 | M = 2.8 SD = 1.95 |

*around me and record me with a camera, I will have some concerns" (P4)*; the resulting data access: *"Could someone hack it and have all the data inside?" (P26)*; and ownership *"it depends which company creates it. Some I trust more than others and it will affect if I will buy it" (P12)*. Regarding *Privacy*, participants expressed concerns for themselves: *"if the drone's responses are generalized, then others might be able to know what I am feeling without my consent" (P20)*; as well as concerns for bystanders: *"It could be violating other's privacy by flying around them" (P1)*. Lastly, participants expressed concerns regarding *Noise*, mentioning that the operating noise the drone creates could be distracting. Interestingly, all the concerns that were mentioned related to BiRDe being in a flying state and not in a perched state. This is in addition to participants asking about BiRDe flying during the study. This is a particularly interesting result, which we further discuss in Sect. 6.2.1.

# 6 Discussion

In this section, based on the validation study's results, we reflect on our concept of a perched drone, present design implications, and examples of applications for perched drones.

## 6.1 Perched Drone Conveying Emotions

We designed BiRDe as the first physically expressive perched drone meant to convey emotions. Our first research question was: *RQ 1.a: How do BiRDe's components (i.e., RR, Wings, Head) affect peoples' interpretations of its Arousal and Valence?* Overall, our results show BiRDe's RR and head position affected participants' interpretation of BiRDe's arousal levels. Additionally, both components, as well as BiRDe's wing position, affected participants' interpretation of BiRDe's valence levels (see Table 3).

The combinations of those components, investigated through *RQ 1.b: Can people recognize a perched drone's behaviors (i.e., the combinations of RR, Wings, and Head) into emotional states?* have led participants to interpret BiRDe's 11 out of its 12 states, at least as hypothesized, or presented an added dimension that enriched our initial assumption (see Fig. 7). The remaining behavior (B100) was hypothesized to yield negative valence but only resulted in high arousal, without consistent valence labeling. This demonstrates that BiRDe's RR, wings, and head positions contribute to peoples' understanding and interpretation of its behaviors as emotional states as designed, and provides positive answers to RQ 1.a, and RQ 1.b.

When comparing with prior work in ground robotics where a similar breathing mechanism was only able to convey arousal [14], BiRDe's RR could influence both valence and arousal (see Table 3). However, RR on its own could not convey the same emotional repertoire as BiRDe's full design. Indeed, we found that BiRDe's combined RR and body postures successfully conveyed both arousal and valence. Five out of six behaviors confirm that when the wings and head positions matched so that the body posture is Expanded or Contracted, then the perceived valence is respectively positive or negative. The outlier is B100 which was assumed to result in negative valence but resulted in high arousal.

Lastly, we introduced a mid-RR level, which when combined with a mismatched body posture resulted in inconsistent labeling as predicted. However, a mid-RR with a matching body posture resulted in arousal labeling such that an expanded body posture was labeled as low arousal and vice versa.

Our second research question *RQ 2: Which of BiRDe's emotional states increases users' willingness to interact with it?* related to the effect of BiRDe's behavior on interaction. Overall, participants were neutral about interacting with BiRDe ($\mu$=3.15/7). Our results demonstrated that participants were more willing to interact with BiRDe and were more confident in their labeling when it presented a slow RR (Table 11, and Table 10; respectively). Their willingness decreased as the RR arose, which could reflect peoples' internal safety concerns from the drone [36], even in a perched state or could also be ascribed to the level of prototyping of BiRDe, that included visible wiring. To improve this result and increase willingness to interact, we believe future drone designs should consider a more zoomorphized appearance that, according to prior work, also contribute to an increased willingness to interact and to perceived friendliness in drones [4]. We also believe that this could induce the perception of the drone as having greater social skills [19].

## 6.2 Design Implications

The design implications for future research with perched drones are divided into three aspects, Perched drones' Mental model, BiRDe as a Modular System, and Designing Input for BiRDe.

### 6.2.1 Perched Drones' Mental Model

Despite the level of fidelity of the prototype, which included a wooden ribcage and skeleton-like wings, so that the prototype could not fly and was kept in its perched state, participants clearly expressed their understanding of it as a flying entity. Indeed, participants' interpretation of BiRDe's physical appearance was of a bird, a bat, and even a dragon. All these drew from mental models corresponding to a flying creature concept, whether real or fictional as described in the use of radical form for drones [19]. Interestingly, this could potentially expand to other radical forms, such as numerous flying objects that do not have distinguishable flying components (e.g., kites, hot-air balloons, clouds). Moreover, when participants expressed concerns around safety and privacy when using BiRDe (see Sect. 5.6), it was when envisioning it in a flying state beyond the experimental setting in a perched state. These results support our initial premise that drones, in their perched or flying states, present different form factors and affordances compared to ground robots and need to be studied in their own right.

### 6.2.2 BiRDe as a Modular System

BiRDe's initial prototype consists of three main components, namely a ribcage, perforated and skeleton-like wings, and a head. Despite its mid-level fidelity prototyping, participants understood and recognized its flying creature design. However, the current design did not lead to a high willingness to interact with it. We suggest future work to build upon the existing system and consider BiRDe as a modular configuration where new features can be added (e.g., a bird's tail) and where the level of realism can be improved.

### 6.2.3 Designing Input for BiRDe

Our work focused on a perched drone conveying information to people, yet, our results open the door to bi-directional communication with perched drones. While the current state of the art in collocated HDI proposes interaction techniques essentially designed for drones in a flying state, we propose that future work should consider input techniques for perched drones. Previous work showed that people are comfortable with drones close to their body [5], to the extent that a drone could land on them [17]. We then suggest that input techniques for perched drones could widely vary depending on

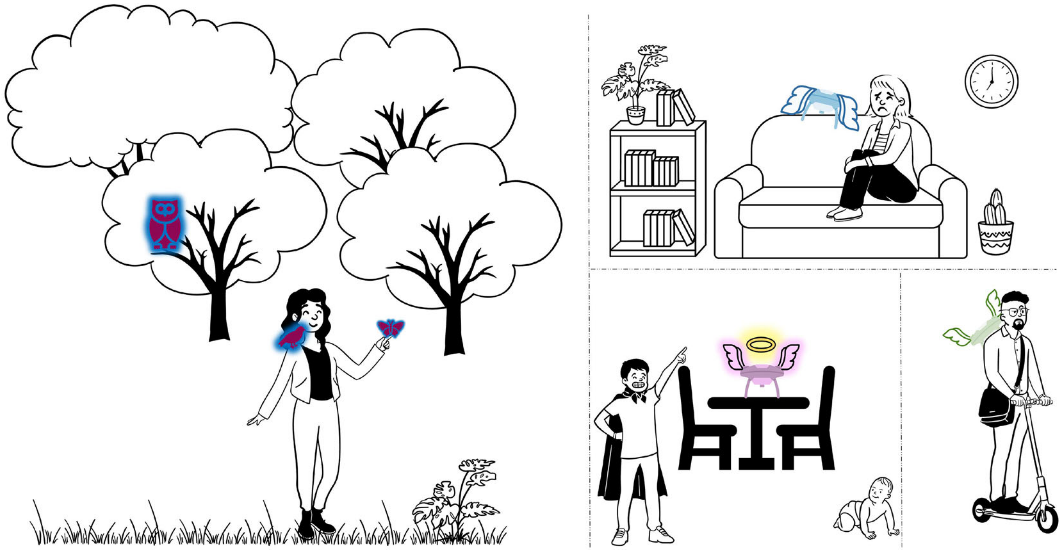

**Fig. 9** This image presents example applications for a perched drone: A Pet Drone (Left—purple); a Companion Drone (Right Bottom—green); an Emotional Support Drone (Right Top—blue); and a Guardian Angel Drone (Middle—pink). (Colour figure online)

whether the drone is on the body, perched within hand's reach or further away, opening a whole new plethora of applications and interactive situations.

### 6.3 Example Applications for Perched Drones

While a plethora of applications has been investigated for human–drone interaction [1] inside and outside the private context, to the best of our knowledge, this work is the first to introduce the notion of a perched drone. We present below example applications and use cases for perched drones (Fig. 9).

*Companion & Pet*

Companion drones have been investigated and suggested for the home environment [2] as utilitarian-oriented devices that can support people in their daily life. We further suggest that a companion perched drone could even resemble a pet drone, since drones were already envisioned as living creatures [38], such as pets [11] and accompany people throughout their day. Such drone companions or pets, could not only keep the person company, but they could also act as a confidant, listen to their stories, and be with them when needed (Fig. 9 green, and purple). Perched drones would have the ability to sit next to people on the sofa or on their bed, have long conversations, taking a more social stance, beyond supporting people in specific tasks.

*Emotional Support*

Previous work has imagined drones as emotional support systems [21]. Such drones could share complex experiences with people using their expressive emotional states. These systems are not limited to any specific size or shape and we envision that they could be both of small size (several centimeter scales), hiding from the person's surroundings and enabling a hidden interaction, or of large size, acting in a similar way to an emotional support animal. Such drones could be perched on the person's body, which is supported by prior work showing acceptable body parts for a drone landing [17]. We envision these emotional support drones to have the ability to connect with a person, in a similar way to a flying companion such as Disney's Tinkerbell or Jiminy Cricket who in addition to their ability to fly, provide close interaction and support while being perched (Fig. 9 blue).

*Guardian Angel Drone*

Drones have been speculated to portray a guardian angel metaphor, such as in the work of Deng et al [39], where drones were described as escorting people home at night. We suggest expanding this notion to even a guardian angel drone that can watch over people. We imagine such a drone with specific features that would accommodate such a metaphor (e.g., a halo above the body) (see Fig. 9 pink). While the drone could watch over people in a potentially dangerous situation, it would also interact with them while not flying, recommending safety behaviors for example.

*Personal Digital Assistant*

Many people now have personal digital assistants in their homes (e.g., Siri, Alexa) [40]. Using a perched drone as a personal digital assistant can eliminate the need of having several devices spread around the home by having it execute different tasks and move locations based on the user's needs. Moreover, the drone presents additional sensors to current devices, such as cameras that can enable it to gather additional contextual information that other devices cannot. For instance, the drone could go and check by the window whether the children are on their way back from school, who is knocking on the door or even check on an elderly neighbor while their family is away.

## 7 Limitations and Future Work

Our work presents several limitations, as well as new opportunities for future research, that we describe below.

One limitation of our prototype is that, in its current instantiation, BiRDe was designed and developed as a perched drone with flying features but without the ability to actually fly. Our design process focused on the flying creature metaphor at rest and the implementation of its emotional states, presenting an initial concept and exploration for our system. Although prior research successfully used various levels of prototyping for designing drones, from low-fidelity (e.g., paper prototype) to mid-fidelity (e.g., 3D printing of non-flying drones) [9, 13], this exploration into perched drones could have led to participants understanding BiRDe more as a ground than as a flying robot. Yet, our results show that our design was successful since participants described BiRDe as a flying creature and referred to its flying state (see Sect. 6.2.1). In the future, a more realistic design (e.g., shape, material, flying capability) might present a more realistic bodily expression and open new opportunities for exploration. In addition, we suggest future works should further investigate the perception of perched drones along the aerial—ground robots continuum.

Other than BiRDe's design, we enquired about participants' concerns, which were expressed along four dimensions: safety, surveillance, privacy, and noise. Within this, participants expressed ethical concerns about a robotic system being close to them, both physically and emotionally. They described that not only could BiRDe record pictures and videos of them and their surroundings, but BiRDe's expression of emotional behavior could be revealed when others are around. These ethical questions are indeed significant and future research should investigate, for instance, whether BiRDe's behaviors need to be modified for one-on-one interactions as opposed to public interactions. Such actions could mitigate peoples' concerns about privacy and surveillance and help ensure that personal information will not be exposed.

Our methodology and experiment structure has speculated that respiratory rate (RR) would only have an effect on the arousal levels of BiRDe. The results demonstrated that it affected valence as well, particularly in the mid-RR behaviors. We found that participants drew more from the RR than initially expected, a notion that needs to be further explored, such as with more defined body parts.

## 8 Conclusion

This paper proposed BiRDe, a novel approach for human–drone interaction, that takes into account perched drones (i.e., drones that are not currently flying). We presented the interaction design of BiRDe via expressions of emotions through its ability to modulate its respiratory rate and change its body posture using reconfigurable wings and head positions. We performed a validation study ($N = 30$) to explore people's interpretations and labeling of BiRDe's bodily expressions and respiration rate as emotional states. Our approach enabled people to recognize 11 out of 12 of BiRDe's emotional behaviors as emotional states in terms of valence and arousal, while BiRDe was perched. We contribute a novel approach for perched HDI, as well as design implications and examples of future applications for perched drones.

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**Data Availability** The data that support the findings of this study are available upon reasonable request from the corresponding author [OF]. The data are not publicly available due to ethical restrictions.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

**Ethics Approval** The questionnaires and methodology for this study were approved by the Human Research Ethics Committee of Ben-Gurion University of the Negev.

**Consent to Participate** Informed consent was obtained from all individual participants included in the study.

**Consent for Publication** Patients signed informed consent regarding publishing their data.

## Appendix A: BiRDe's 12 Behaviors

See Figs. 10, 11, 12, 13.

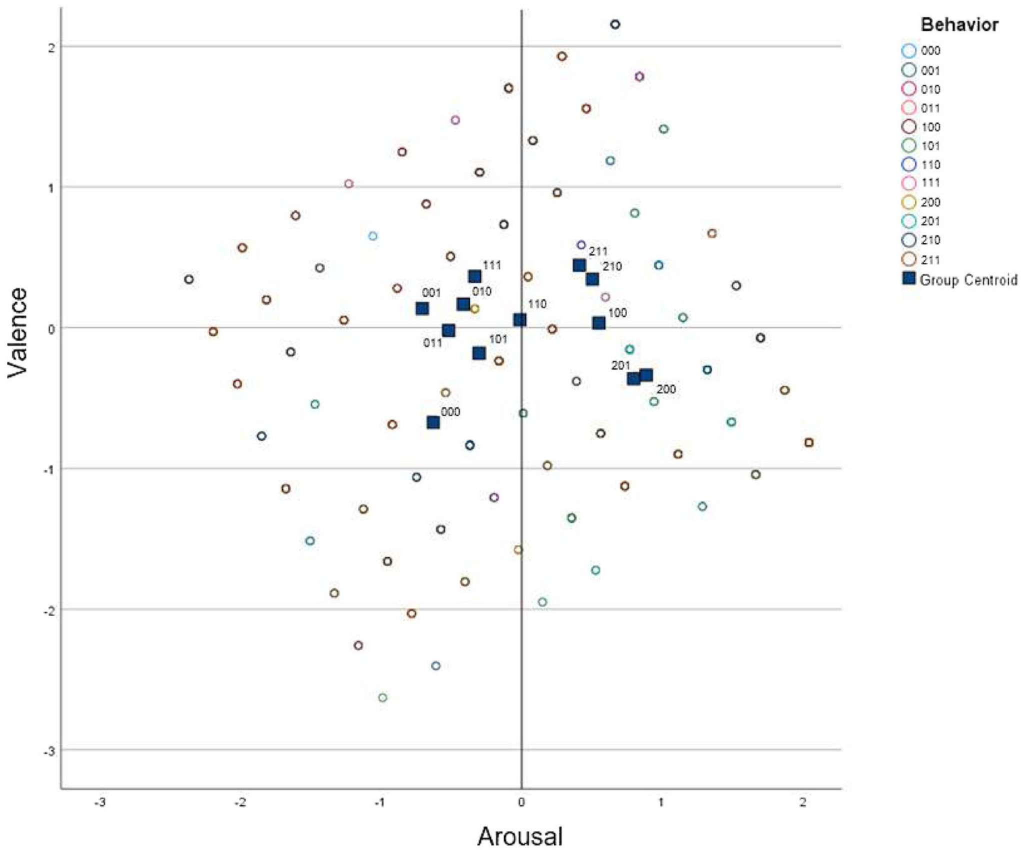


**Fig. 10** This scatter-plot shows all of BiRDe's 12 behaviors centroids resulting from the discriminant analysis. The X axis is Arousal, Y axis is Valence

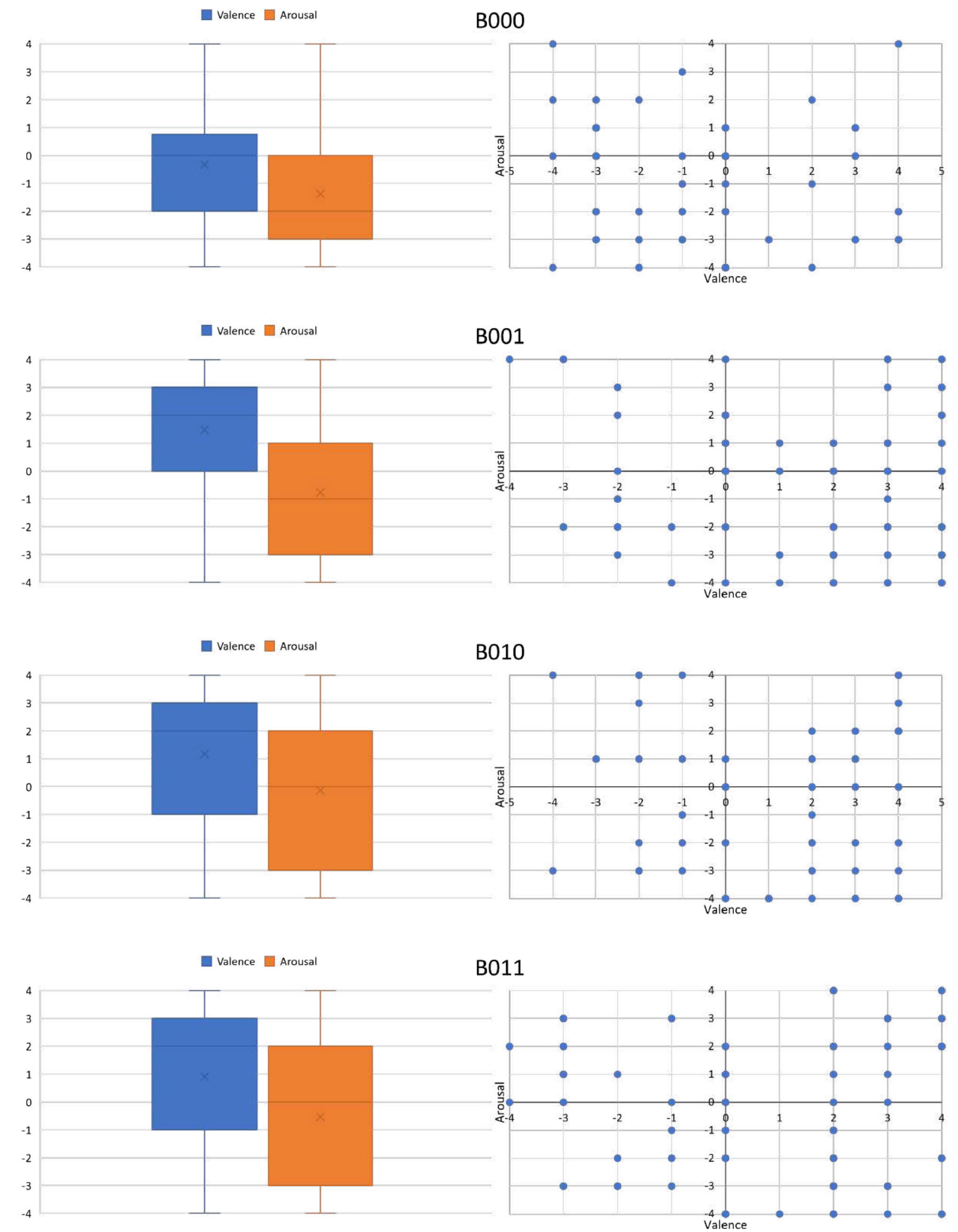


**Fig. 11** These graphs show each behavior's valence and arousal's average, as well as their dispersion throughout the grid. This graph presents the valence and arousal values for behaviors B000, B001, B010, and B011

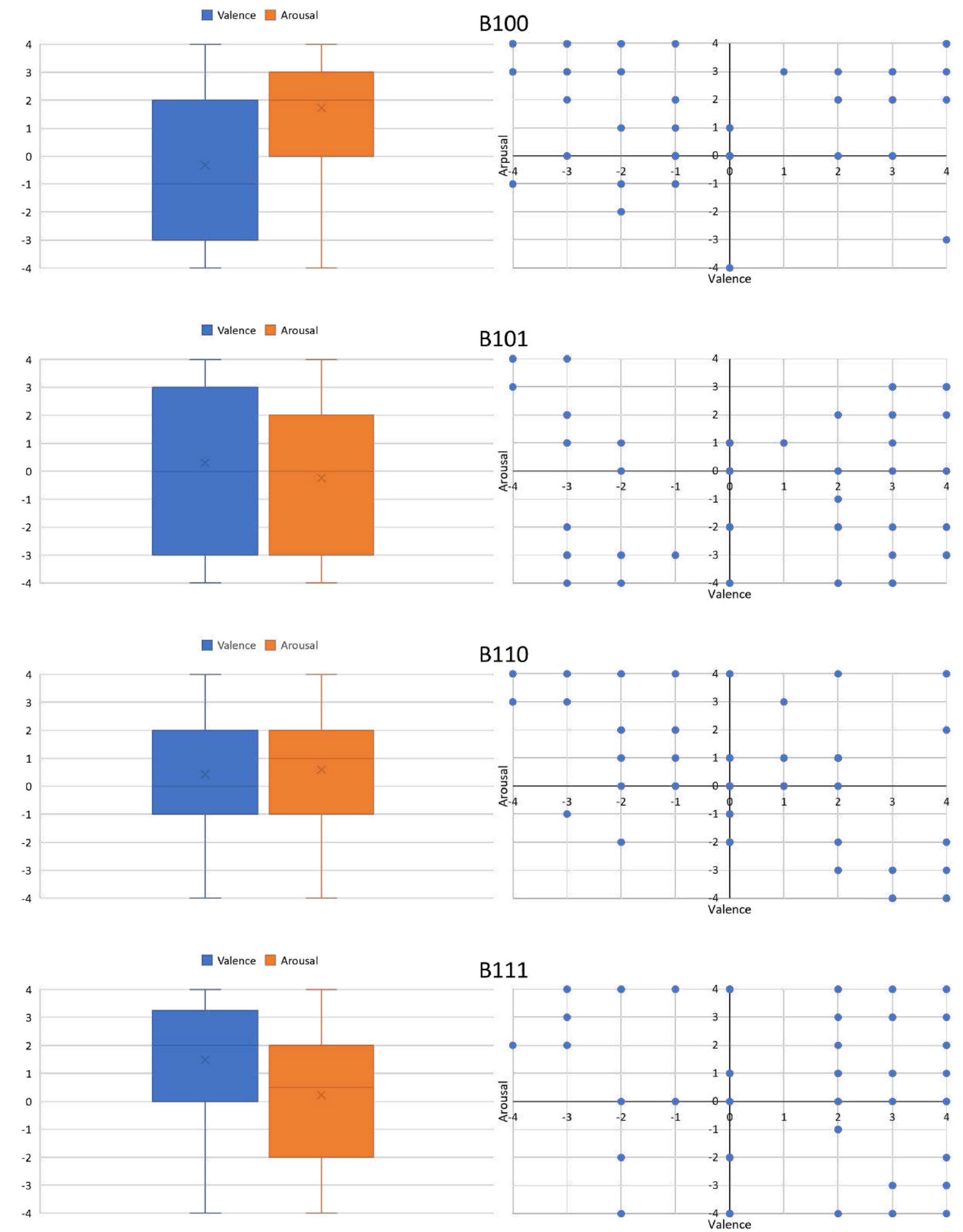


**Fig. 12** These graphs show each behavior's valence and arousal's average, as well as their dispersion throughout the grid. This graph presents the valence and arousal values for behaviors B100, B101, B110, and B111

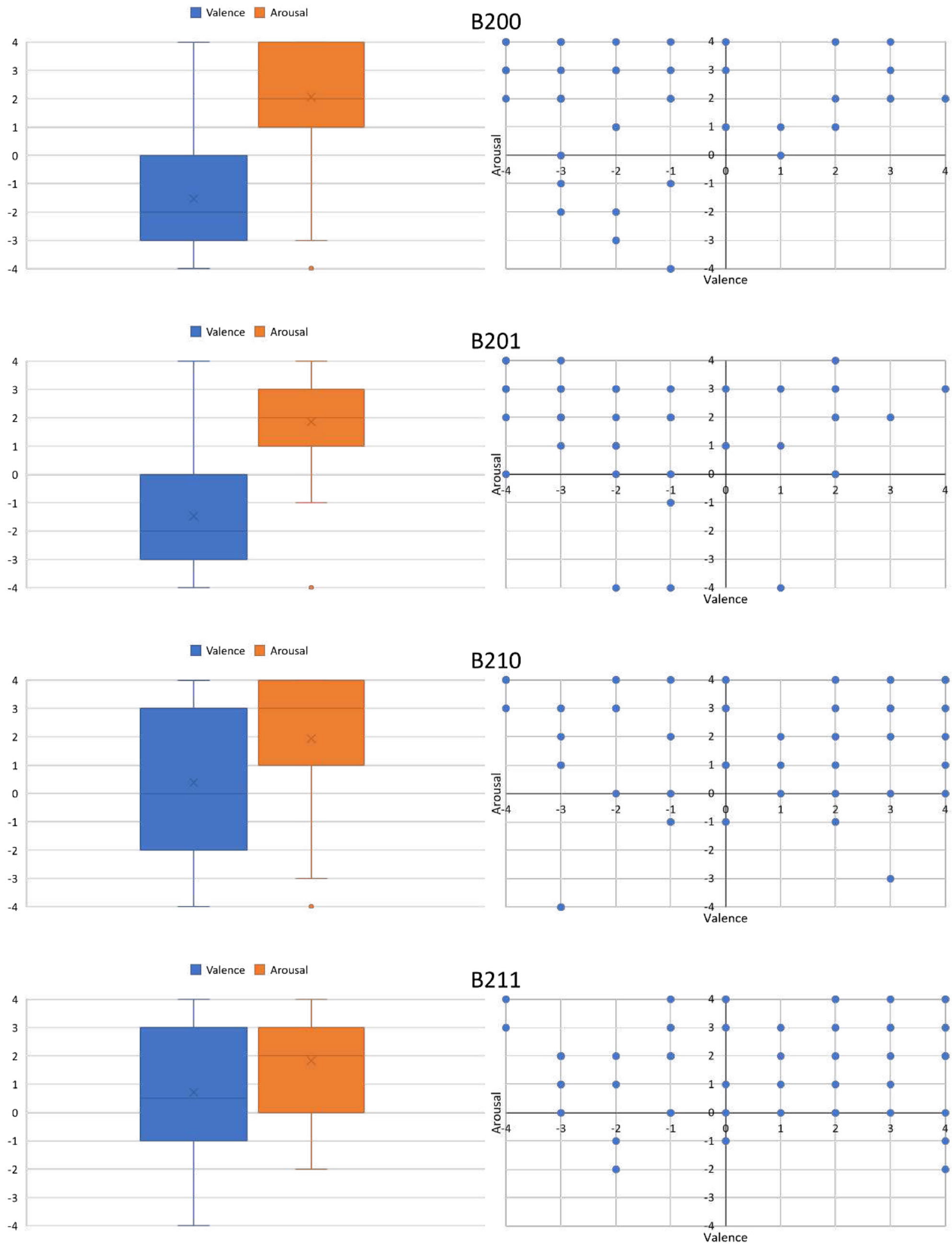


**Fig. 13** These graphs show each behavior's valence and arousal's average, as well as their dispersion throughout the grid. This graph presents the valence and arousal values for behaviors B200, B201, B210, and B211

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