Behavioural Effects of a Medical Delivery Drone on Feelings of Uncertainty: A Virtual Reality Experiment

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Abstract

Drones are being tested in healthcare settings to deliver medicines or equipment to humans during emergencies. Understanding how people perceive drone behaviour, specifically in terms of approach trajectories and delivery methods, and identifying factors that induce uncertainty is crucial for safety and trust. This VR experiment investigated the impact of approach trajectories and delivery methods on feelings of uncertainty. Forty-five participants observed drones following straight or curved paths, delivering packages by landing or using a cable while hovering above eye level. Participants felt uncertain and unsafe, especially when looking up at straight-line drone paths. Curved paths were perceived as less uncertain and by some commented as more natural, trustful, and safe. Uncertainty arose during landing attempts due to collision concerns and altitude changes. Using a cable for delivery reduced uncertainty and increased safety. The study recommends drones avoid hovering near humans, especially after landing attempts, to address uncertainty.

Keywords: Drones, Human-Drone Interaction, Proxemic, Uncertainty, Virtual Reality

Introduction

We are currently experiencing a period characterized by pervasive computing, where robots, including drones, are becoming increasingly integrated into our daily routines (Wojciechowski et al., 2019a). Herdel et al. (2022) conducted a review of past literature on Human-Drone Interaction (HDI), identifying over 100 use cases across 16 domains, ranging from leisure to professional activities, including entertainment, companionship, and emergency response. Among the 16 domains examined across 217 articles, emergency response emerged as the most frequently mentioned use case, accounting for 15.6% of the total, thereby emphasizing its societal significance in bolstering public safety. Medical delivery is an example of an emergency response scenario, where drones are used to deliver medicines, vaccines, and healthcare equipment to a recipient (i.e., humans who receive the package on the ground; Carrillo-Larco et al., 2018; Claesson et al., 2017; Javaid et al., 2022). A few advantages include accessibility to remote locations, shorter delivery times, and lower CO2 emissions than conventional road transport (Nyaaba et al., 2021). The medical delivery use case is becoming increasingly important, particularly in light of recent events such as the COVID-19 pandemic, where drones were instrumental in controlling the spread of the coronavirus (e.g., Koshta et al., 2021; Kumar et al., 2021; Mohsan et al., 2022). A person, who requests healthcare supplies, may need to interact with a drone as a recipient of a package (Zègre-Hemsey et al., 2020). For example, in a medical emergency scenario, a drone could deliver an external defibrillator to one or several individuals performing cardiopulmonary resuscitation on an unconscious person experiencing cardiac arrest, requiring immediate assistance with an external defibrillator (Sanfridsson et al., 2019).

There is a risk that the recipients do not have prior experience interacting with a drone or know what to expect or fear. According to a web article on US drone statistics (Leslie, 2022), only 15% of US residents have experience with flying a drone. Recipients, who rarely interact with drones in real life and lack knowledge of interaction protocols, may feel discomfort when a medical drone approaches. Lack of knowledge and information influences humans to feel uncertain when interacting with a robot, such as a drone (Meissner et al., 2020). The feeling of uncertainty in interactions characterises the boundaries of trust (Lee & See, 2004), which can have negative impacts on the effectiveness of automated systems, such as drones (Knodler et al., 2018). Despite the necessity of investigating uncertainty to facilitate a natural interaction between humans and robots (e.g., drones; Jane et al., 2017; Muthugala et al., 2016), there is a scarcity of literature on methods to investigate and address uncertainty in Human-Robot Interaction (HRI).

A possible solution to handle uncertainty is to use HRI cues to convey information that helps the recipient predict the intention of the drone and decide on an action. For instance, human factors researchers on automated vehicles explored different cues, such as vehicle behaviour (implicit cues) and external displays (explicit cues), to communicate the intent of the vehicle to pedestrians (Dey et al., 2019, 2021). Implicit cues, in terms of vehicle behaviour, are the primary form of communication used in traffic on roads (Moore et al., 2019; Sripada et al., 2021).

Along similar lines, a drone can use aerial paths to communicate its intention and there are several studies on comfort and proximity, and how such behaviour can be used to communicate intent with recipients has been previously studied (e.g., Bevins et al., 2021; Jensen et al., 2018; Szafir et al., 2014). For example, Bevins implemented a video-based study to test 16 aerial paths (e.g., hover, U-shape, descend) and categorized behaviour based on how participants perceived the intention of the drone. In a video-based study by Szafir et al. (2014), participants rated drone behaviours that have curve motions, anticipatory motions, and varied velocity profiles as natural and safer to interact with. Some HDI studies have explored the effect of flying altitudes of social drones on human responses in a closed-room environment. In a proxemics study by Yeh et al. (2017), participants maintained a larger lateral distance from a drone with a social shape and face flying at an altitude of 1.8m from the ground compared to flying at 1.2m. Bretin et al. (2022) provided a contrasting observation with a virtual reality experiment, participants maintained a closer distance with a drone flying at an altitude above the eye level (1.95m) of participants compared to below eye level (1m). These contrasting results raise questions about the implications of flying altitudes on human comfort beyond the social drone use case, especially for delivery drones operating at higher altitudes (> 40m; Wing, 2024), greater speeds (> 10m/s; Scott et al., 2017), and employing diverse delivery methods (e.g., parachutes, cable ropes, landing; Scott et al., 2017) from varying heights compared to drones tested indoors. Additionally, variations in drone purposes across use cases (e.g., social vs. medical) can significantly influence human expectations and attitudes towards the drone in the interaction (Herdel et al., 2021b).

The current delivery drones use different methods to deliver healthcare supplies (Scott et al., 2017). For instance, drone companies such as Zipline and Wing employed drones to use parachutes (Khazan, 2016) and cable rope (Wing, 2024) to deliver packages on the ground while hovering, respectively. An ambulance drone prototype, developed by TU Delft (2024), delivers an Automated External Defibrillator (AED) by landing on the ground. These methods may influence the recipient's sense of safety and predictability, seldom explored in the literature. For instance, the parachute method presents challenges due to wind conditions, making it difficult for the recipient to anticipate the precise delivery location on the ground. Additionally, recipients may feel discomfort and unsafe when the drone descends (Bretin et al., 2022), such as during landing attempts. Given the novelty of these delivery methods and the scope for a lack of predictability and perceived safety, there may be an increase in uncertainty during interaction. There is a research need to investigate the impact of delivery methods on perceived uncertainty and to propose strategies for managing it, as positive perceptions can enhance social acceptance of delivery drones (Khan et al., 2019).

Literature is scarce on how drone behaviour affects people's feelings of uncertainty near drones, and even more so in scenarios of delivery drones in the field of HDI. Our study attempts to fill these gaps and contribute to the future development of natural interaction between recipients and drones, specifically for the medical delivery use case.

Aim and scope

Our research aims to study experiences of uncertainty connected to drone behaviour. This concerns uncertainty related to the approach trajectory (straight line or curved line) and delivery method (package delivered when hovering with a cable or by landing with a package), focusing on a scenario with a medical delivery drone. In this study, the approach trajectory means the drone’s aerial paths when flying towards a recipient. The delivery method reflects the techniques through which a drone delivers the medical package to a recipient. The parachute method was not studied due to challenges with simulating realistic wind effects. The created Virtual Reality (VR) environment is made as an urban open space, where there is no dedicated infrastructure for drones. This scenario was inspired after consulting a few experts in the field, who reflected on the potential use cases. The drone, in this study, is considered autonomous and has a hybrid vertical take-off and landing design (VTOL), combining the advantages of multirotor and fixed-wing design. Hybrid VTOL drones have been deployed for commercial delivery by Google Wing (Straight, 2022) and Zipline (Shankland, 2023).

Given the scarcity of literature on measuring feelings of uncertainty in HRI, a mixed-method analysis was employed, incorporating continuous measures from a physical slider, questionnaires, sketches, and interviews to gain comprehensive insights into uncertainty. In addition, trust and predictability were studied with questionnaires to further understand human perception (Reinhardt et al., 2017) and uncertainty (Lee & See, 2004; Windschitl & Wells, 1996).

Questions

Research question (RQ): How do the behavioural characteristics of a medical delivery drone affect the recipient’s feeling of uncertainty?

Sub-questions:

- RQa: How does the approach trajectory (straight line and curved line) of the drone affect the recipient's feeling of uncertainty?
- RQb: How does the delivery method (cable or landing) affect the recipient's feeling of uncertainty?
- RQc: Are there other elements related to medical delivery drones that affect the recipient's feeling of uncertainty?

Method

Participants were recruited for a VR experiment with a head-mounted display (i.e., Meta Quest 2; see Figure 1)). Recruitment advertisements were shared on social media, student groups, and employee groups at the Netherlands Aerospace Centre and the Eindhoven University of Technology. The recruitment criteria were age over 18 years and not being prone to motion sickness and VR sickness. The study design was reviewed by the ethical committee of the Eindhoven University of Technology.

Figure 1: Participant with a head-mounted display in the VR experiment to assess feelings of uncertainty as a drone is flying towards her (in a straight line, curved line and either landing or doing a cable drop). In her hands, the participant holds a physical slider to express her uncertainty on a scale between 0 (no uncertainty) to 100 (absolute uncertainty).

Independent variables

This 2x2 within-participant study design comprised two independent variables:

(1) The approach trajectory consists of two levels: *Straight* and *Curve*. *Straight* approach involved an approach with two straight lines with a 90-degree angle. *Curve* approach is symmetric and exists as a spherical chord between two points rather than as a straight line (Szafir et al., 2014). The two approaches are shown in Figure 2. The drone flew at a height of 45 m, parallel with Wing (2023), before lowering its height.

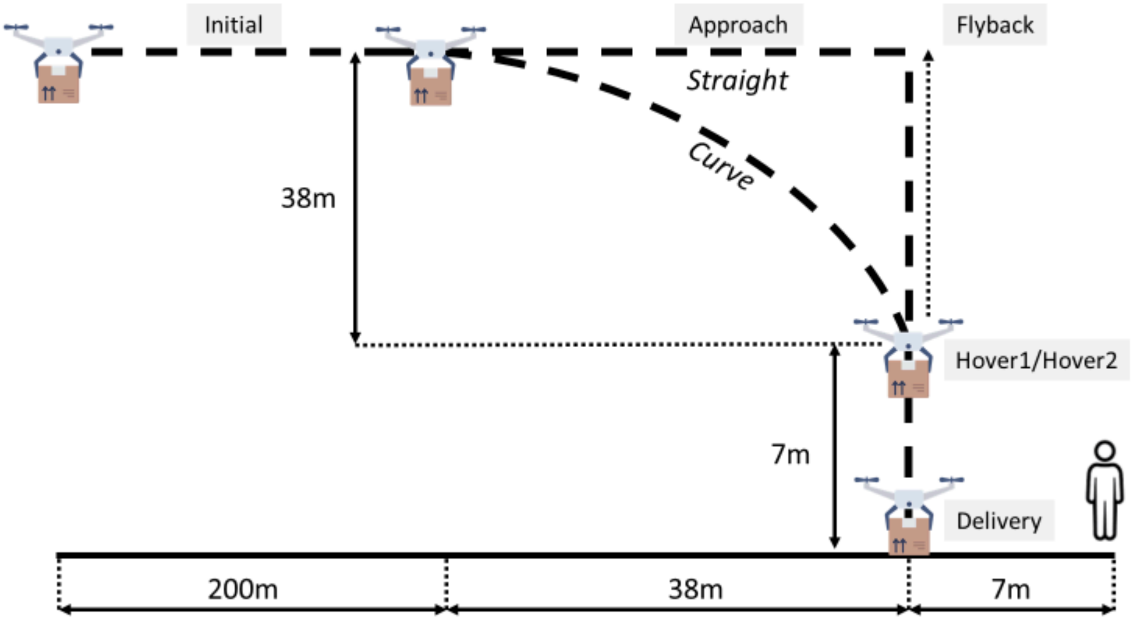

Figure 2: Experimental layout showing the two approach trajectories, namely *Straight* and *Curve*, and the six phases of flying behaviour, occurring sequentially: Initial, Approach, Hover1, Delivery, Hover2, and Flyback. Figure not to scale.

(2) Delivery method, with two levels: drone landing (*Land*) and cable drop (*Cable*). *Land* method involves a drone that descends to the ground from a height of 7m and drops the package. *Cable drop* includes a drone that suspends a cable rope to drop the package on the ground when hovering at 7m height. These delivery methods are adopted by drone companies as mentioned in Scott et al. (2017) and are shown in Figure 3.

Figure 3: The two delivery methods, namely *Land* (left) and *Cable* (right).

To manage the repeatability of the interaction, a filler scenario was added to the study design.

Experimental design

The dimensions (1.3m x 1.0m x 0.4m) of the drone model were inspired by the real drone model of Wing Corporation (Wing, 2024).

The experiment was devised in Unity 3D (version 2022.3.5f1), employing a non-populated urban setting resembling a public park to have as few distractors and visual clutter in the scenarios. A medical delivery drone approaches the recipient based on predetermined routes and over 6 different phases of flying behaviour, namely Initial, Approach, Hover1, Delivery, Hover2, and Flyback (see Figure 4). The drone flew at a maximum speed of 11.11m/s[1], from a lateral distance of 245m, and it maintained a height of 45m from the participant (referred to as Initial). Following the approach trajectory (see Figure 2; referred to as Approach), the drone hovered (referred to as Hover1) at a height of 7 m (Wing, 2024) and positioned 7m laterally—which is considered within the realm of public space for human-human interaction as per Hall (1966)—for 5s. The drone delivered the package using the designated delivery method within 6s and retracted to its initial position (referred to as Delivery). After the package delivery, the drone hovered for 5s (referred to as Hover2) before ascending to a height of 45m (referred to as Flyback). Each trial took 59s for the drone to complete 6 different phases. Figure 4 shows the speed of the drone in the 4 scenarios. The drone speeds were adjusted for the 4 scenarios so that the phases consisted of similar duration in all 4 scenarios.

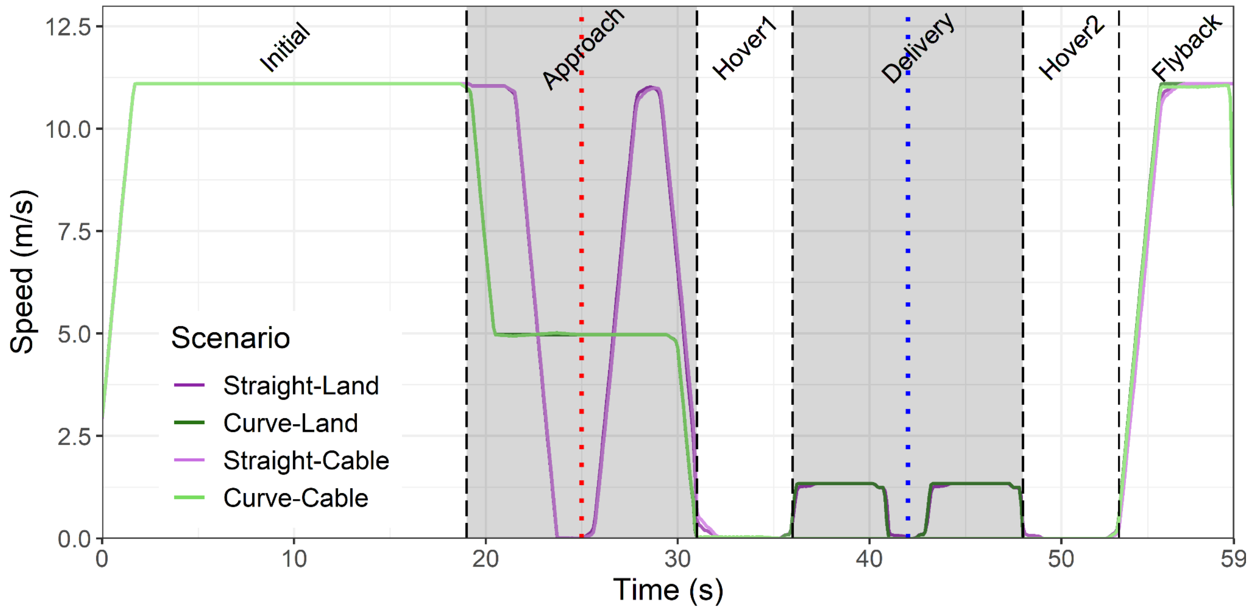

Figure 4: Speed profile of drone in different phases of flying behaviour for the 4 scenarios. The approach and delivery methods are varied in the Approach and Delivery phases, respectively. A vertically red dotted line at 25s and a vertically blue dotted line at 42s represent the moment when the drone starts to descend from a height of 45m towards the ground in the *Straight* approach and when the package is delivered on the ground, respectively. The shaded grey areas indicate the phases of flight behavior where the manipulations were performed in the four scenarios.

In the filler scenario, the drone flew at a speed of 11.1m/s and 45m altitude over the public space. The drone started from a lateral distance of 245m and flew 45m past the participant. The drone had no intent to deliver the package to the recipient and thus, flew over. The filler

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[1] Within the speed range of 11.1 m/s to 25 m/s, as observed in healthcare drone models by Scott et al. (2017), the lower speed threshold was selected to ensure participants had sufficient time to interpret the approach method and respond.

scenario took 26.1s to complete and was omitted from the data analysis as the drone did not deliver the package and the interaction time was not comparable.

Dependent variables

The dependent variables consisted of subjective responses from slider measures, questionnaires, interviews, and sketches (see below).

Slider measures

A physical slider (adapted from Walker et al., 2019), integrated with Unity 3D using Arduino[2], was used to measure the participant level of uncertainty throughout the interaction with the drone. Participants were asked to indicate their uncertainty level using the slider, assessed on a continuous scale ranging from 0 (absolutely certain) to 100 (absolutely uncertain), in the VR environment. The data was recorded at 10Hz.

Mean uncertainty and phase range were computed from the slider measure data for each scenario and each phase. Phase range was calculated as the difference between the maximum and minimum slider values observed within a phase.

From the slider measure data in the Delivery phase, 'Time to Minimum Uncertainty' (TMU) was determined as the duration from the start of the phase to the moment the slider value reached its minimum.

Questionnaires

Questions (see Table 1) were asked in the VR environment after each trial on predictability, trust, uncertainty, and certainty towards the behaviour of the drone using a five-point Likert scale (1: strongly disagree; 5: strongly agree). Questions on predictability and trust were adapted from the “Trust in Automation” questionnaire (Körber, 2019).

Table 1: Questions on uncertainty, predictability, certainty, and trust towards the behaviour of drones.

Scale	Item
Uncertainty	The behaviour of the drone made me feel uncertain.
Predictability	The drone behaviour was always clear to me.
	I was able to understand why things happened.
	The drone behaves unpredictably.*
	It’s difficult to identify what the drone will do next.*
Certainty	I felt certain about the behaviour of the drone.
Trust	I trust the drone.
	I can rely on the drone.

* inverse statement

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[2] Access the Arduino code here: https://github.com/bazilinskyy/crossbox

After the experiment, participants were asked to express their preferred choices using an online questionnaire for both the approach trajectory and the delivery method.

Interviews and sketches

Participants were requested to sketch the two approach trajectories as perceived using pen and paper. After which, semi-structured interviews were conducted to understand participant experiences from experimental conditions. Participants were asked to reflect on their expectations of flying behaviour, their motivations behind their selected preferences, factors affecting their feelings of uncertainty (if any), any information required about the drone, and their overall experience with the experiment.

Procedure

Before the start of the experiment, participants were asked to fill in the demographics questionnaire and their affinity towards technology interaction (Franke et al., 2019). Participants were briefed with information on the purpose and arrival direction of the autonomous medical delivery drone. Participants were informed that a medical drone would arrive at their location in a public park to deliver a package containing an AED, used to treat a patient who was seated on a bench within visible distance. After filling out the consent form, participants experienced a test scenario to familiarise themselves with the environment and slider measure. The test scenario was one of the 4 scenarios. After familiarizing with a test scenario, participants experienced all the experimental scenarios, including the filler, and each scenario is repeated three times (i.e., (4 scenarios + 1 filler) * 3 runs = 15 trials, in total). The selection of test scenarios and the order of trials were randomized based on the Latin square method to reduce learning effects.

During each trial, participants rated their feelings of uncertainty with a slider measure. Participants were asked to continuously indicate their feelings of uncertainty based on the question: "*How much do you rate your feeling of uncertainty on a scale from 0 (absolutely certain), to 100 (absolutely uncertain) about the behaviour of drone? The higher you rate, the more uncertain you feel.*" Participants were instructed to focus only on the drone and its behaviour and not on the use of AED to treat the patient.

Participants were not allowed to perform any secondary tasks and were asked to quit the experiment if they felt unwell. At the end of each trial, the experimentator reset the slider to 50 and the participants rated their subjective feelings on predictability, trust, uncertainty, and certainty using a joystick (i.e., Quest 2 controller) in the virtual environment. After every 5 trials, a short break was scheduled. After performing all 15 trials, participants completed an online questionnaire on their preferences for the approach and delivery methods, sketched the perceived approach trajectories, and then answered interview questions. The total experimental duration was approximately 70 minutes. Finally, participants were debriefed, thanked, and compensated for their time with a 15 Eur bol.com voucher.

Participants

A total of 45 individuals (24 females, 21 males[3]) with ages between 23 years and 59 years (M = 32.3; SD = 11.3) participated. Eighteen participants were Dutch, 9 Indian, 6 Chinese, and the remaining were from 12 other nationalities including America, Belgium, Canada, France, Germany, Italy, Japan, Portugal, Romania, Spain, Taiwan, and Turkey. With regards to the level of education, 4 participants completed doctoral education, 28 Master's or equivalent education,

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[3] None of the participants expressed their gender as non-binary or 'prefer not to say'.

10 Bachelor’s or equivalent education, and 3 Secondary education. Thirty-nine participants were employed and the remaining 6 were students.

All the participants reported having seen a drone in media or reality and 5 said to own a drone. Forty participants had seen a drone from a distance or in close proximity, 14 had experience piloting a drone and 5 had never seen a drone in reality. Overall, participants claimed to have a positive attitude towards technology interaction (M = 3.8; SD = 1.0), and none experienced simulator sickness symptoms during the study.

Analyses

A total of 540 trials (45 participants x 4 scenarios x 3 repetitions) were available for the analysis of slider measures and subjective measures. The TMU measure was available for 469 out of 540 trials; in the remaining 81 trials, the participant did not express a lower uncertainty score with the slider compared to when the delivery phase was initiated.

The slider measure and Likert scale data were averaged over three repetitions and analyzed using parametric tests to maintain statistical efficiency and result homogeneity. Past research suggests that data from a Likert scale with 5 points or more and with a larger participant sample size (> 30) leads to negligible Type I and Type II errors (Dey et al., 2020; De Winter & Dodou, 2010; Mircioiu & Atkinson, 2017; Murray, 2013). A two-way ANOVA with repeated measures (henceforth, referred to as ANOVA) was performed and post-hoc pairwise comparisons with Bonferroni correction (henceforth, referred to as post-hoc test) were followed for significant effects. In addition to the main effects, paired t-test comparisons (henceforth, referred to as t-test) were performed at every 1s interval for the slider measure data to obtain insights on the effect of drone behaviour at specific time instances. Only statistically significant effects with Bonferroni correction ($p < 0.005$) were reported to attain brevity.

A Pearson correlation analysis was performed on questionnaire scores to examine the relationship between uncertainty and other measures, such as certainty, predictability, and trust.

Each participant generated sketches for the two approach trajectories, yielding a total of 90 sketches. The sketches were categorized based on participants' perceptions of distance from the drone and the form of the two approach trajectories. The first author categorized the sketches and analysed the interviews. The interviews were transcribed using automatic transcription software (Otter.ai), and the transcribed text was reviewed and corrected based on the recordings. A thematic analysis (Braun & Clarke, 2006) was conducted on the transcribed interview data, with themes and codes emerging from the data. The codes were developed to understand the reasoning behind participants' preferences for approach trajectories and delivery methods and to identify factors influencing feelings of uncertainty. Codes were then assigned to potential themes, based on similarities, differences, and repetitions. Additionally, sketches were used to support a few interview results, aiding in understanding participants' perceptions of the approach trajectories.

Results

Slider measures

Figure 5 exhibits the mean uncertainty score for the four scenarios over the different phases of drone behaviour for every 1s interval.

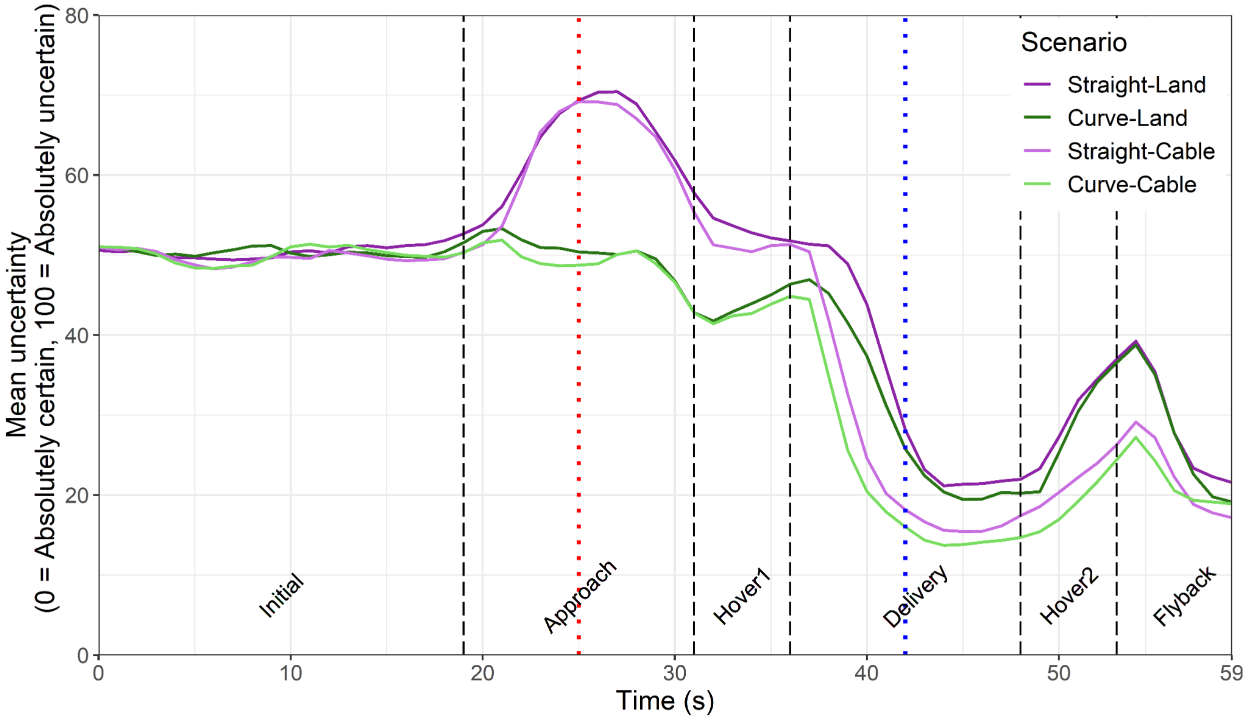

Figure 5: Mean uncertainty score as expressed in the 4 scenarios over the 5 different phases of drone behaviour. A vertically red dotted line at 25s and a vertically blue dotted line at 42s represent the moment when the drone is about to descend from a height of 45m towards the ground in the *Straight* approach (referred to as *above-head*) and when the package is delivered on the ground, respectively.

ANOVA was performed to evaluate the effects of approach and delivery methods on the mean uncertainty over the different phases. The ANOVA results showed significant main effects and larger effect sizes of the approach trajectory during the Approach (F(1, 44) = 49.54, $p < 0.001$, ηp2 = 0.53), Hover1 (F(1, 44) = 15.35, $p < 0.001$, ηp2 = 0.26), and Delivery phases F(1, 44) = 7.79, $p = 0.008$, ηp2 = 0.15); and significant main effects and larger effect sizes of the delivery method during the Delivery (F(1, 44) = 20.42, $p < 0.001$, ηp2 = 0.32)), Hover2 (F(1, 44) = 16.7, $p < 0.001$, ηp2 = 0.28)), and Flyback (F(1, 44) = 7.7, $p = 0.008$, ηp2 = 0.15) phases.

In Figure 6, mean uncertainty and error bars show variations across phases for the four scenarios. Post-hoc tests revealed significant differences in mean uncertainty between *Straight* and *Curve* during Approach, Hover1, and Delivery phases. Notably, mean uncertainty was significantly higher for *Land* than *Cable* in Delivery, Hover2, and Flyback phases.

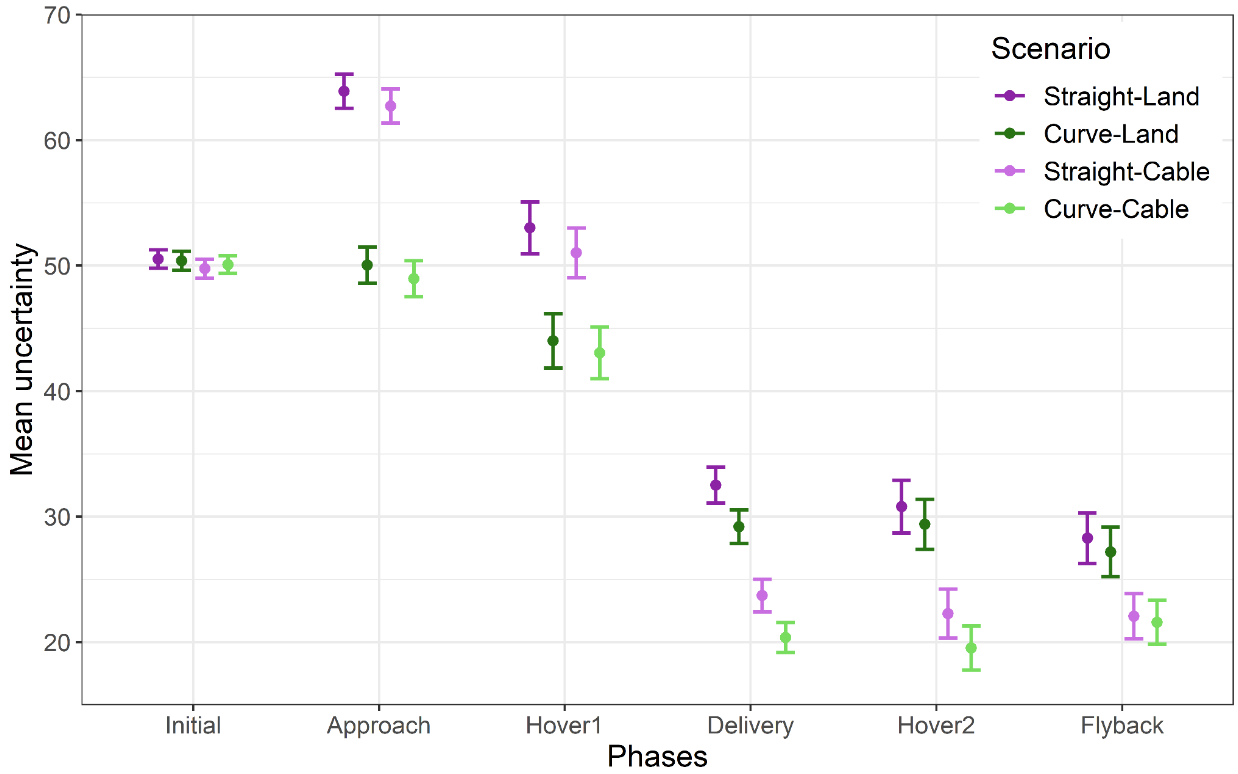

Figure 6: Mean and error bars (CI ~ 95%) of the uncertainty for the 4 scenarios in 6 different phases of flying behaviour.

The ANOVA results for the phase range measure indicated significant main effects and medium effect sizes of the approach trajectory during the Approach (F(1, 44) = 24.75, *p* < 0.001, ηp2 = 0.16), Hover1 (F(1, 44) = 9.57, *p* = 0.002, ηp2 = 0.07), and Delivery(F(1, 44) = 9.23, *p* = 0.003, ηp2 = 0.07) phases; and significant main effects and medium effect sizes of the delivery method during the Delivery (F(1, 44) = 6.68, *p* = 0.011, ηp2 = 0.05), Hover2 (F(1, 44) = 27.63, *p* < 0.001, ηp2 = 0.17) and Flyback (F(1, 44) = 30.7, *p* < 0.001, ηp2 = 0.19) phases.

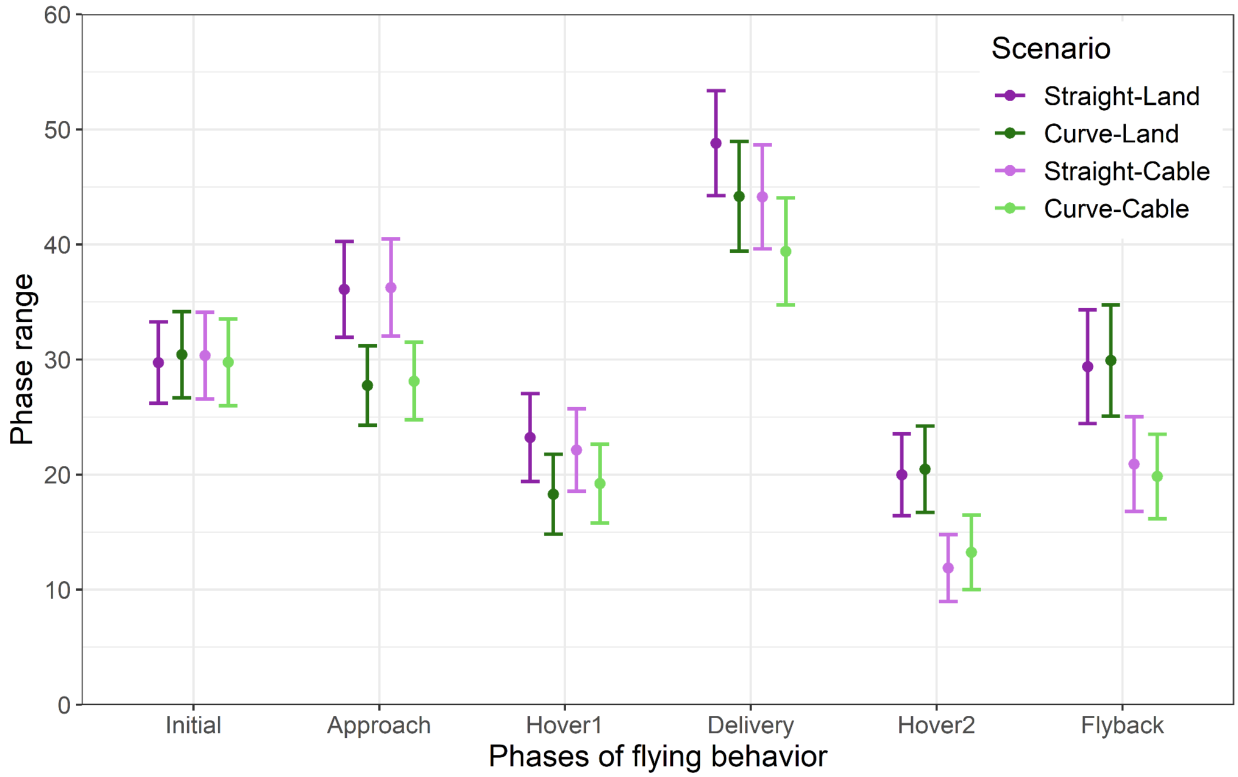

Figure 7: Mean and error bars (CI ~ 95%) of the phase range for the 4 scenarios in 6 different phases of flying behaviour.

Phase range and error bars in Figure 7 illustrate the mean and variations across phases for the four scenarios. Post-hoc tests revealed significant differences in phase range between *Straight* and *Curve* during Approach, Hover1, and Delivery phases. Phase range was significantly higher for *Land* than *Cable* in Delivery, Hover2, and Flyback phases.

Figure 8 (left) indicates significantly higher mean uncertainty in the *Straight* compared to the *Curve* between 22s and 33s for the *Land* method (p < 0.005). Participants felt more uncertain two seconds into the approach phase until two seconds before the Hover1 concluded, for the Straight approach compared to the Curve approach. Figure 8 (right) shows significantly higher mean uncertainty in the *Straight* compared to the *Curve* approach between 22s and 35s and at 38s and 39s for the *Cable* method (p < 0.005). Participants started feeling uncertain a second into the Approach phase, persisting until one second before Hover1 ended and for two seconds at the beginning of the Delivery phase.

Figure 9 (left) shows significantly higher mean uncertainty in the *Land* delivery compared to *Cable* from 39s to 42s and 51s to 54s for the *Straight* approach (p < 0.005). Participants felt uncertain two seconds into the Delivery phase and until the package dropped on the ground and at the end of Hover2 and the beginning of the Flyback phases. Figure 9 (right) exhibits significantly higher mean uncertainty in the *Land* delivery compared to *Cable* from 38s to 42s and 50s to 55s for the *Curve* approach (p < 0.005). Participants experienced uncertainty a second into the Delivery phase, until the package drop, and at the end of Hover2 and the beginning of the Flyback phases.

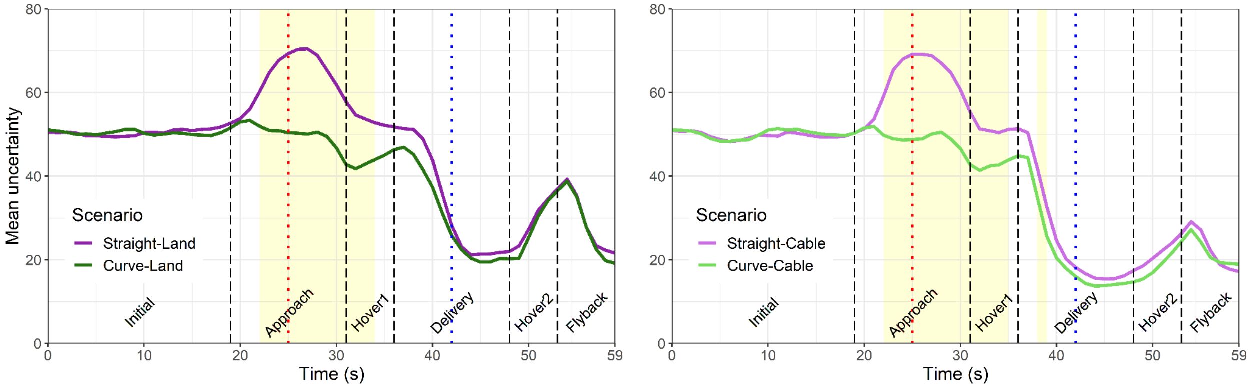

Figure 8: Mean uncertainty for the *Straight* versus *Curve* approach for the Land (left) and the Cable (right) delivery. The yellow region indicates a significant difference between the two scenarios for the respective 1s interval from the t-test, $p < 0.005$. A vertically red dotted line at 26s and a vertically blue dotted line at 42s represent the *above-head* moment and when the package is delivered on the ground, respectively.

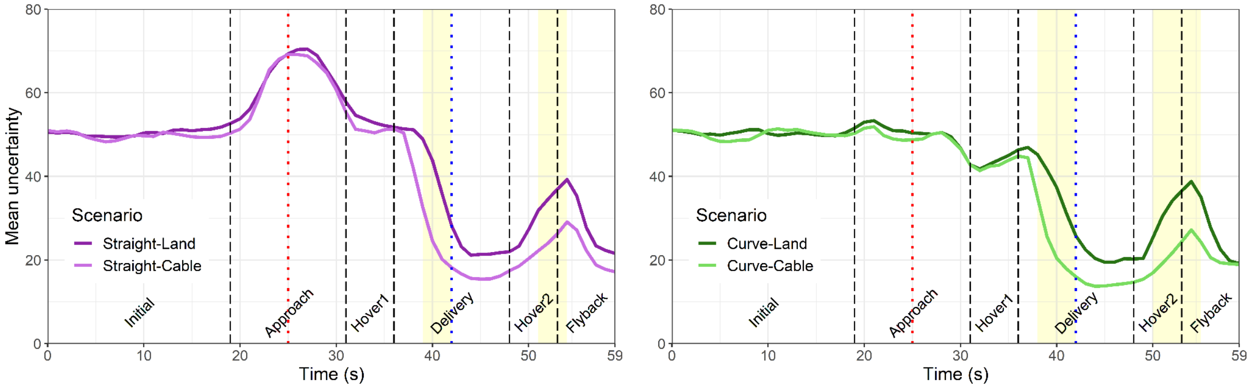

Figure 9: Mean uncertainty for Land versus Cable delivery method for the *Straight* (left) and the *Curve* (right) approach trajectory. The yellow region indicates a significant difference between the two scenarios for the respective 1s interval from the t-test, $p < 0.005$. A vertically red dotted line at 26s and a vertically blue dotted line at 42s represent the *above-head* moment and when the package is delivered on the ground, respectively.

ANOVA was performed to evaluate the effects of approach and delivery methods on TMU. The results indicated a significant main effect and larger effect size for the delivery method (F(1, 44) = 11.86, $p < 0.001$, ηp2 = 0.22).

Figure 10 illustrates that participants in the *Straight-Cable* and *Curve-Cable* felt minimum uncertainty earlier compared to the *Straight-Land* and *Curve-Land*, respectively. The post-hoc test suggested that TMU was significantly lower for *Cable* than *Land* method.

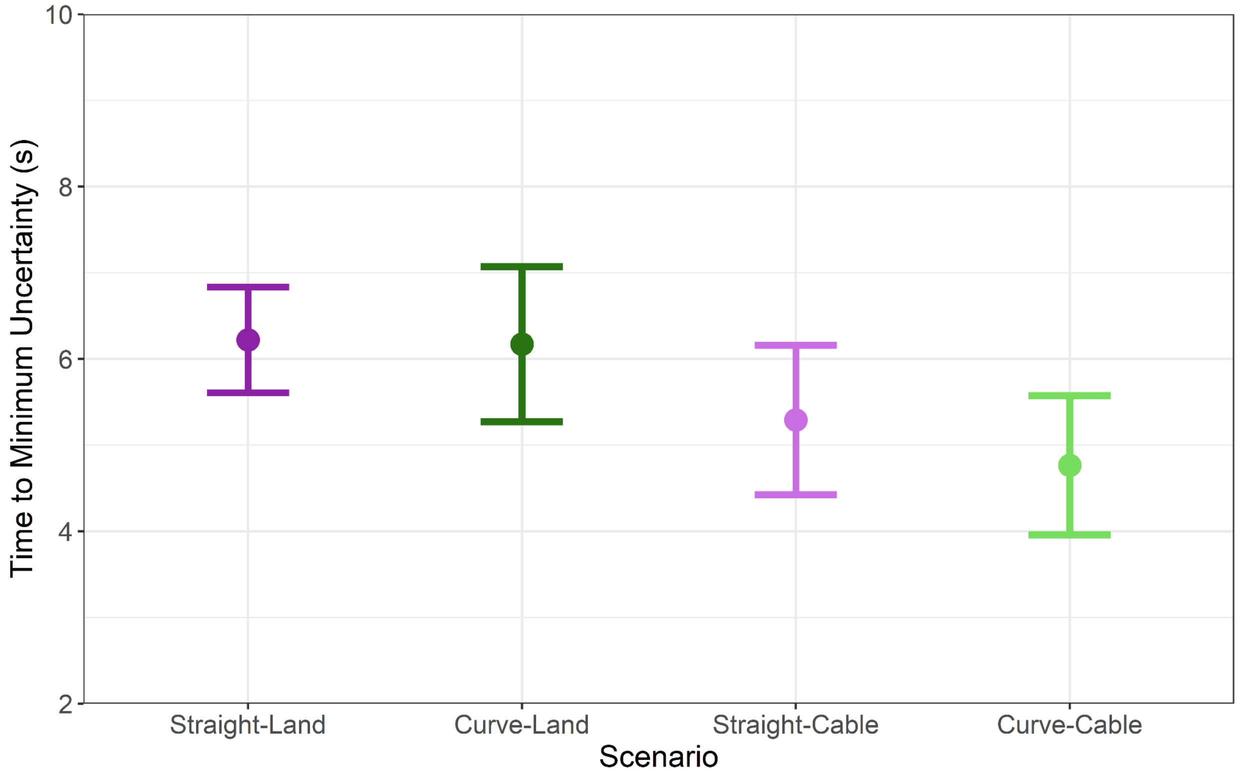

Figure 10: Mean and error bars (CI ~ 95%) of the Time to Minimum Uncertainty for the 4 scenarios in the Delivery phase.

Questionnaire

ANOVA was conducted to evaluate the effects of approach and delivery methods on the Likert scale measures, namely certainty, predictability, trust, and uncertainty evaluated after each scenario. The means and error bars for the 4 Likert scale measures are presented in Figure 11 below.

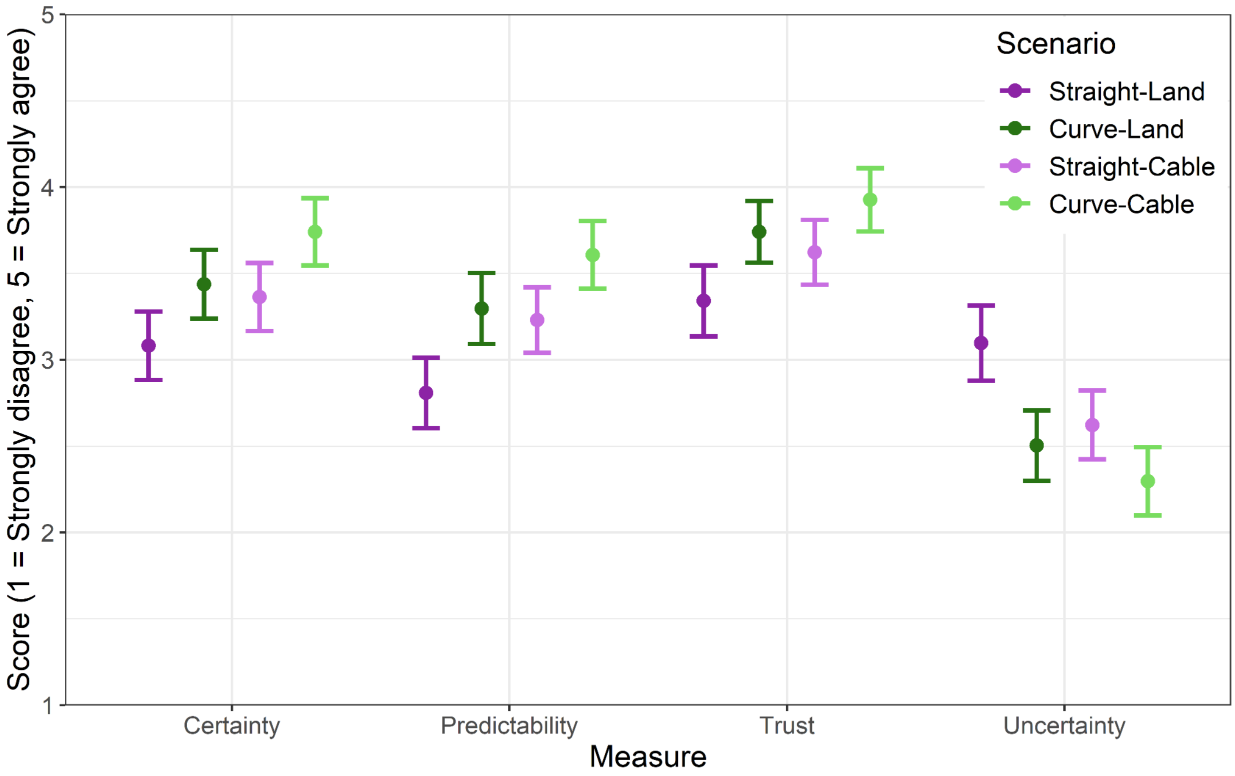

Figure 11: Mean and error bars (CI ~ 95%) of the certainty, predictability, trust, and uncertainty measures for the 4 scenarios

The results (see Table 2) for the 4 Likert scale measures indicated significant main effects and larger effect sizes of the approach and delivery methods; and no significant interaction effects. Post-hoc tests indicated that the certainty, predictability, and trust scores were significantly higher for *Curve* than for *Straight* approach trajectories; and were significantly higher for *Cable* than for *Land* delivery methods. Post-hoc tests showed that the uncertainty scores were significantly lower for *Curve* than for *Straight* approach trajectories, and were significantly lower for *Cable* than for *Land* delivery methods.

Table 2: ANOVA results for the 4 Likert scale measures, namely certainty, predictability, trust, and uncertainty. *p*<0.001 ***, *p*<0.01 **, *p*<0.05 *

Measure	Effects	*F*	*p*	partial η2
Certainty	Approach	18.53	<0.001***	0.3
	Delivery	10.66	0.002**	0.2
	Approach * Delivery	0.03	0.876	<0.01
Predictability	Approach	23.87	<0.001***	0.35
	Delivery	13.95	<0.001***	0.24
	Approach * Delivery	0.57	0.453	0.01

Trust	Approach	26.07	<0.001***	0.37
	Delivery	8.24	0.006**	0.16
	Approach * Delivery	0.78	0.381	0.02
Uncertainty	Approach	19.93	<0.001***	0.31
	Delivery	11.13	0.002**	0.2
	Approach * Delivery	3.27	0.077	0.07

With regards to the approach trajectory, post-experiment results indicated that 91.11% of participants preferred *Curve*, 8.89% preferred *Straight* and none selected no preference. Regarding the delivery method, 55.56% of participants preferred *Cable*, 31.11% preferred *Land* and 13.33% selected no preference.

Sketches

Figures 12 and 13 illustrate the categories of sketches, with examples, as perceived by participants for the *Straight* and *Curve* approach trajectories, respectively. The three categories of the *Straight* approach comprise sketches where the drone was (i) perceived at a lateral distance of 7m (N = 13), (ii) perceived at a lateral distance of less than 7 m (N = 30), and (iii) rationalized at a lateral distance of 7m but felt to be less than 7m (N = 2). Within category (ii), the drone was perceived to descend to the Hover1 position either (iia) without a vertical straight approach (N = 24) or (iib) with a vertical straight approach (N = 6). The two categories of the *Curve* approach include sketches where the drone was (i) perceived at a lateral distance of 7m (N = 40) and (ii) perceived at a lateral distance of less than 7m (N = 5).

Interviews

This section presents quotes from the thematic analysis, accompanied by sketches, and organized by participant numbers in the order of their recruitment (1 to 45).

Reflections on the Curve approach trajectory

Majority of the participants preferred the *Curve* approach and perceived it as natural, predictable, and safe.

- *“I prefer (the) arc path (Curve) because it's more natural (...) When you see the skydivers land or birds landing or when you throw a stone into the air, that's more like the parabolic flight and not straight ahead.” (P11)*
- *“Arcs (Curve) are just visually easier to read.” (P22)*
- *“I felt safer watching the drone descend (as a Curve) than the other, straight line.” (P39)*

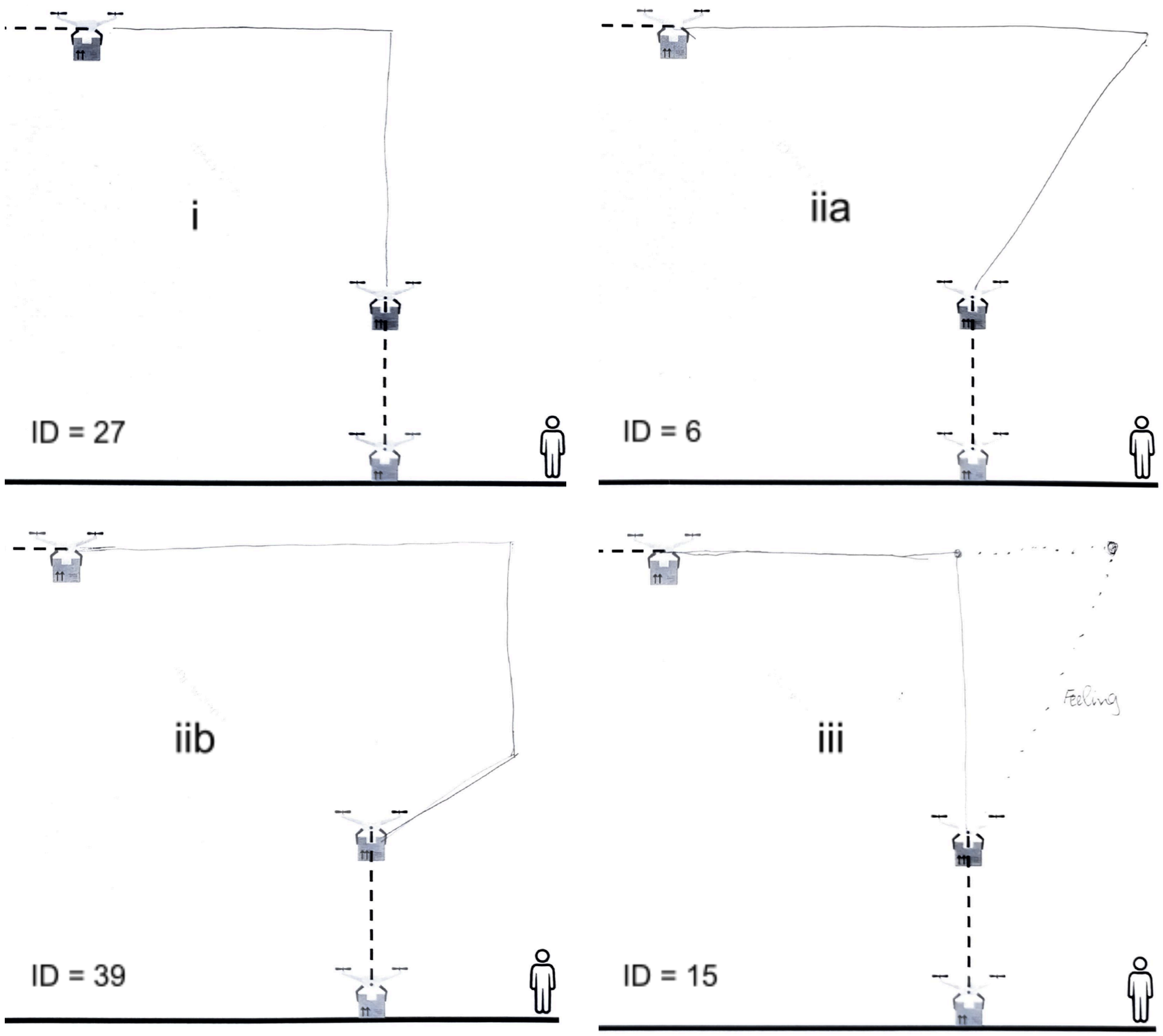

Figure 12: Example sketches of the *Straight* approach, as perceived, for the three categories with participant ID. See categories (i), (iia), (iib), and (iii) in the top-left, top-right, bottom-left, and bottom-right subfigures, respectively.

Some participants explicitly noted that they observed the drone, following a *Curve* approach, within their line of vision (see Figure 14 (left)): *“I don't have to look far overhead” (P43)*.

Uncertainties and safety issues about the *Straight* approach trajectory

In the *Straight* approach, when the drone was about to descend from a height of 45m, most of the participants had to look up, perceiving the drone as above head (see Figure 14 (right)). The *Straight* approach evoked feelings of uncertainty and unsafety.

- *“When it was over my head, I was uncertain what exactly it's going to do?” (P1)*
- *“The straight-line approach made me feel the drone is directly above my head and it felt a bit more threatening.“ (P38)*
- *“What if the package drops on my face?” (P39)*

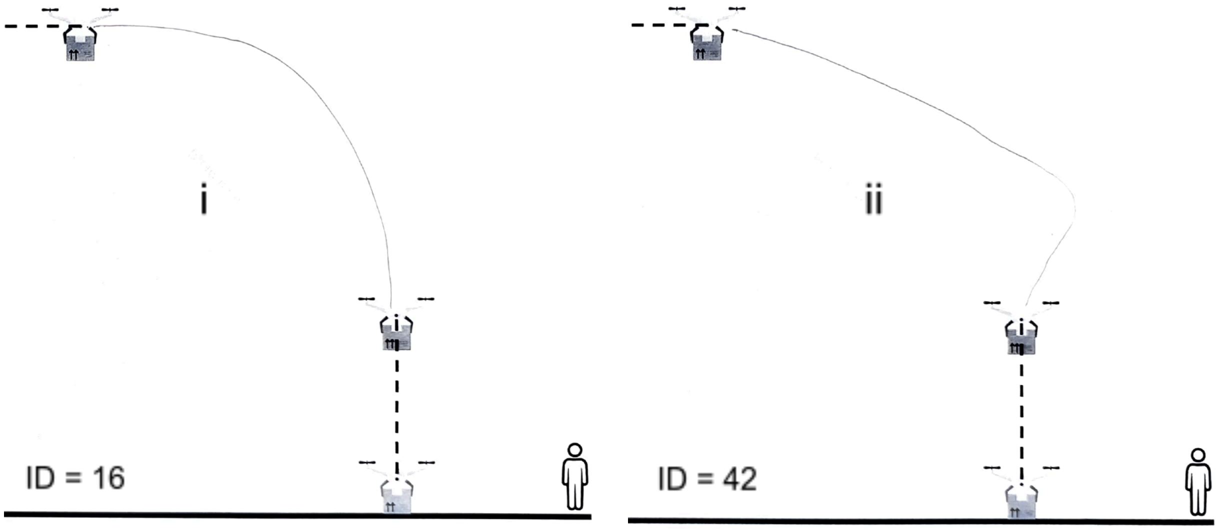

Figure 13: Example sketches of the *Curve* approach, as perceived, for the two categories and with participant ID.

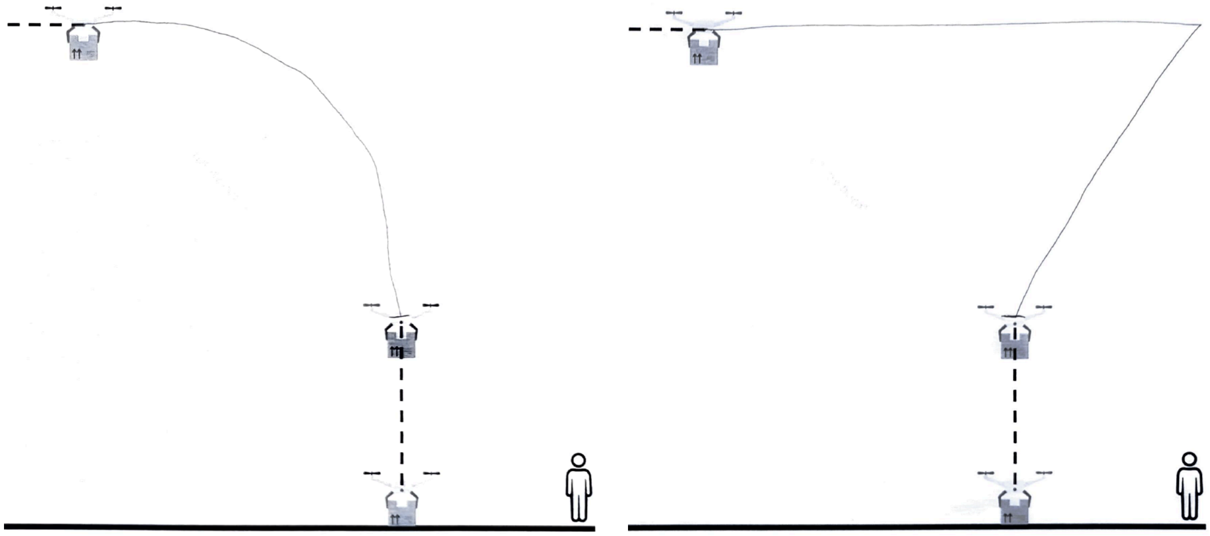

Figure 14: Sketches of *Curve* (left) and *Straight* (right) as perceived by a participant (P28).

Uncertainties about hovering behaviour

The hover phase made the majority feel curious and uncertain about the drone's intentions, especially after the Delivery phase.

- *“When it stays (hovers), I was like, okay, I'm not sure what you're gonna do. Are you gonna attack me?” (P7)*
- *“Hovering made me feel uncertain because I knew that something would follow, but I didn't know what.” (P17)*
- *“Before delivery, stalling (hovering) was mostly fine. But after delivery, (with) stalling (hovering), I was like, what is it going to do? Is it going to do something that I'm not sort of used to seeing so far?” (P38)*

Reflections on alternative approach trajectories

Beyond the current approach trajectories, few participants suggested exploring other trajectories such as circular motion, spiral motion, or approaching from a different direction but within the participant's line of vision.

- *“I have been thinking that the approach could basically be from the side. So you start up, then you will fly straight, and then you move to the left or the right within my vision. (...) If you take it in a circular motion, you actually use multiple points (...) When I look at it, the drone, from my point of view, is in a circular motion, I do incorporate more of the surroundings into its motion, which makes me feel safer.” (P12)*
- *“The drone should identify the subject and then start spiraling around him for at least one turn and then smoothly descend.” (P45)*

Reflections on the cable method

Most of the participants preferred delivery through *Cable* as the drone maintained a safe distance and they felt certain and clear about the drone's intentions.

- *“It makes the intentions of the drone much clearer. You know, there's a package coming down.” (P12)*
- *“With the cable drop, I felt the most certain in the entire experiment.” (P19)*
- *“When it (drone) is far from the ground it feels safe, that it will not touch anyone.” (P28)*

During the Hover2 phase, some participants experienced less uncertainty with the *Cable* delivery, *"because the hovering part was a bit more clear" (P44) and "the hovering isn't that obvious (by itself)" (P18)*, than with the *Land* delivery, as it *"felt abrupt" (P44)* and induced uncertainty about the landing intention: *"Then I was not sure, okay, is it (drone) coming down again? (...) it felt a bit tricky as to what it (drone) is doing" (P44)*.

Uncertainties and safety issues about the *Land* method and parachute method

While some participants found the *Land* method familiar, others expressed uncertainty regarding the delivery intention and safety.

- *“(...) it felt more familiar when it (drone) came down to (the) ground by landing.” (P3)*
- *“While drones come down, they have rotor blades rotating, maybe someone like kids can try to touch the blades.” (P19)*
- *“It's unclear when it (drone) is going to drop the package and when it (drone) is going to stop and how long it (drone) is going to stop, so there was more uncertainty with drone landing.” (P20)*

A few participants acknowledged delivery through a parachute as an alternative method where a drone could maintain a safe distance. The method, however, was not preferred to the other methods due to practical wind challenges and was perceived as unsafe, and unpredictable.

- *“It's so unpredictable and so unnecessary (...) Also, you don't want something falling on your heads.” (P14)*
- *“With a parachute, the package may have a chance to get stuck on the trees, lamp posts or any other things.” (P19)*
- *“(...) in the Netherlands, with the wind, I'm not sure about that one (parachute method). I feel like I'd get hit in the face with a parcel.” (P43)*

Need for explicit information and potential solutions to mitigate uncertainty

Beyond the approach trajectories, hovering behaviour, and delivery methods, the lack of explicit information about the drone's intentions was identified as a factor contributing to uncertainty. The majority of participants emphasised the importance of receiving clear and explicit information regarding the drone's purpose and delivery intentions.

- *“Why and what are you doing and what are you doing now?” (P4)*
- *“It would have helped to have an expectation of where and when it is going to be landing or all of these details like what do the brakes (hovering) mean.” (P5)*
- *“If the package is being delivered near me, then I should know about it beforehand. (...) What is inside the package and who is sending it, the sender information and the purpose of the package.” (P39)*

The design of the drone's appearance and the Human-Machine Interfaces (HMIs), such as lights and sound from the drone or text on mobile phones, were stated as potential solutions to communicate drone intentions and handle uncertainty.

- *“If you consider a medical drone, and if it would go with the medical noise and the medical lighting, that would be very appropriate, then you know what is going on and will happen.” (P12)*
- *“If you can easily identify that the drone is from a hospital, like a specific brand, then I would be less scared of what it's doing. (...) We receive an alert from the Netherlands government, first Monday of every month. Being able to receive an alert like that on your phone would help, if there is somebody that is having a panic attack close by.” (P15)*
- *“When the drone flies at a distance above you then it says “start landing”, when it starts to land, and when it is finished then say “task finished” and fly away. That is more clear to me, instead of the drone doing nothing but stays (hovers).” (P17)*
- *“In case the drone is not dropping the package, there should be a red light and when it is going to come down then a green light to indicate that it is coming down. So it will give an idea of what it's going to do and it will help you to feel certain.” (P19)*

Discussion

This study aimed to understand how the behaviour of a medical delivery drone, specifically in terms of approach and delivery methods, influenced the recipient's feelings of uncertainty. Forty-five participants took part in a VR experiment, observing the drone approach using both *Straight* and *Curve* trajectories and delivering packages either by landing (*Land* method) or using a cable while hovering (*Cable* method). Their uncertainty was assessed through a combination of slider measures, questionnaires, interviews, and sketches. Overall, the results from the mixed method analysis indicated that participants experienced a higher level and larger range of uncertainty and lower level of predictability, trust, certainty, and preference when the drone followed a *Straight* approach compared to a *Curve* approach, and when the drone delivered the package using the *Land* method compared to the *Cable* method. When the participants reflected on their reactions, they mentioned a lack of clarity regarding purpose and intentions as additional factors contributing to uncertainty, extending beyond the explored behavioural characteristics.

The effect of approach trajectory

The mixed-method analysis showed that participants found it challenging to predict the *Straight* approach and felt uncertain about it, especially when the drone was about to descend from a height of 45m. Due to the tendency of humans to overestimate the approach angles of moving objects (Welchman et al., 2004), such as drones, the drone's vertical viewing angle of 81.16 degrees (i.e., $\mathrm{Tan}^{-1}(7/45)$) is perceived directly above the head. This perception contributes to feelings of unsafety and uncertainty regarding the possibility of the package dropping on the head. As a recommendation, drone designers and pilots should consider flying drones at a lower vertical angle when approaching the recipient to instil a sense of certainty and safety.

In contrast to the *Straight* approach, participants perceived the *Curve* approach of the drone to be within their line of vision and some expressed that this was more readable. Consequently, they rarely experienced uncertainty or feelings of unsafety towards the drone behaviour for the *Curve* approach trajectory. The *Curve* approach was the preferred choice and was consistently described as natural, predictable, and trustworthy. This aligns with the findings of Szafir et al. (2014), where the *Curve* approach trajectory in a horizontal plane was perceived as natural, safe, and usable. Interestingly, our results contrast with those of Bevins et al. (2021), where participants viewed another form of the *Curve* approach (i.e., U-shape) as unapproachable and expressed to stay away from the drone. An explanation may be that participants in Bevins' study interpreted the drone's vertical departure at the end of the U-shaped trajectory as a signal to maintain distance. Future research should delve deeper into exploring human perceptions of various forms, including spiral and circular motion as suggested in our interview results, and parameters (e.g., speed, direction, altitude) of the *Curve* approach to identify the most natural and least uncertainty inducing approach trajectory.

The effect of delivery method

Participants favoured the *Cable* and *Land* methods over the parachute method, during the interviews, citing practical challenges related to weather that might impact their ability to interpret where the package would land on the ground and safety concerns. It took more time before participants felt certain during the *Land* method, and they reported lower levels of safety, certainty, and trust compared to the *Cable* method, where the drone's hovering at 7m height and delivery via cable made them feel safe and certain about the drone's intentions. Despite the drone being located 7m away from the participant in both delivery scenarios, the variation in altitude during the drone's descent to deliver the package increased uncertainty. Participants expressed difficulty in discerning the timing of the drone's actions with the *Land* method. They reported feeling unsafe, primarily due to concerns about potential collisions with humans (e.g., kids) on the ground. Our findings are in parallel with previous studies (Bevins et al., 2021; Bretin et al., 2022), indicating that humans express discomfort and tend to move away from drones undergoing altitude changes or those positioned at an altitude lower than eye level (e.g., 1m). To enhance the recipient experience during the interaction, the drone designers are recommended to prioritize the implementation of the cable for package delivery over the drone landing on the ground.

Hovering after the delivery made participants uncertain about the drones' intentions, particularly with the *Land* method. Participants perceived the manoeuvre as abrupt, leaving them uncertain if the drone intended to perform a follow-up task and sparking curiosity. In line with the findings of Bevins et al. (2021), participants interpreted hover as the need for visual attention. We suggest restricting the hovering time to minimize uncertainty for the recipients. If required for external factors (e.g., stabilizing the drone in strong winds), future research should investigate methods to clearly communicate the rationale for hovering.

Other factors affecting uncertainty

In interviews, participants emphasized the significance of clarity regarding the purpose and intentions of the drone as a means to reduce uncertainty. This aligns with the notion that providing information diminishes surprise and enhances the acceptance of drones, as discussed by Szafir et al. (2015). Two methods were discussed for providing explicit information: appearance and Human-Machine Interfaces (HMIs). Based on participants' responses, designers are advised to explore the appearance of medical delivery drones, drawing inspiration from ambulances on the road, to convey their purpose and reduce uncertainty. Participants recommended the use of HMIs to explicitly communicate delivery intentions. The suggested HMIs varied based on the type of information, ranging from lights and speakers on the drone for real-time delivery actions to textual alerts on mobile phones for information on the emergency, drone's arrival, and user role expectations. In cases where it is difficult to execute an ‘ideal’ approach trajectory, HMIs become increasingly vital to inform on the alternative approach trajectory and reduce ambiguity. Previous research on social drones has attempted to explore the use of HMIs like a display attached to the drone to communicate emotions (Herdel et al., 2021a) and sound to navigate a visually challenged recipient (Avila Soto & Funk, 2018), and these efforts were perceived to be beneficial. The intentions of social drones, such as emotional engagement, differ significantly from those of medical delivery drones, which prioritize urgent health aid. Consequently, recipients' preferences for information seeking also differ. For example, none of the participants expressed interest in the emotional state of a drone; instead, they sought information about the actions of the medical drone. Future research should carefully consider the differences, while building upon the existing knowledge on social drones, when investigating interfaces designed to communicate the intentions of medical delivery drones, aiming to reduce uncertainty for recipients.

Implications for drones beyond the medical emergency

The current study, focusing on medical emergencies, may also have broader implications for the delivery of other packages such as webshop packages. Companies can enhance user trust in delivery drones by adopting a curved approach, using a cable for delivery, and avoiding post-delivery hovering. To ensure clarity about the drone's purpose, we suggest designing webshop drones be designed distinct from those used for other applications, such as medical drones. Unlike current models from delivery companies like Matternet, Wing, and Zipline, which have distinct designs and no HMIs on board, webshop drones should adopt a consistent aesthetic principle and incorporate HMIs to improve user interaction and certainty. In order to uphold their branding distinctiveness, delivery companies might consider designing package aesthetics to mirror their branding.

Further investigation is required to understand the relevance of our observations towards social drones flying close to humans. Our findings are in contrast with Yeh et al. (2017), where participants maintained a smaller lateral distance from a drone flying at a height of 1.2m compared to 1.8m from the ground and were comfortable allowing the drone within their personal space (less than 1.2m lateral distance). The difference in use cases (social vs. medical delivery) and the associated expectations humans may have could influence how humans perceive intentions and maintain a comfortable distance from the drone.

Considerations and limitations

Before the experiment, participants received detailed briefings on their roles and the drone's purpose, which helped alleviate potential ambiguity and uncertainty. However, in real-world scenarios, uninformed users may be at risk due to their unfamiliarity with safety protocols. These individuals may also need to transition between roles (see Baytas et al., 2019; Tezza et al., 2019) and manage associated expectations. For instance, a pedestrian may need to understand safety protocols and their role when transitioning from a bystander to a recipient while receiving a medical package and assisting a victim. A lack of clarity on roles and safety protocols could result in uncertainty. Hence, future research should focus on exploring effective methods to clearly and unambiguously communicate safety protocols and user role expectations, thereby minimizing uncertainty.

Participants were instructed that the drone approaches from the front in all scenarios, aligning with preferences noted in Wojciechowska et al. (2019b). It is crucial to recognize that drones might approach from various directions, posing a challenge in their identification within an urban environment. Wojciechowska et al. (2019b) observed discomfort and anxiety when drones approached from the rear, possibly linked to uncertainty (Gu et al., 2020). Future research should delve into HMIs for effectively communicating directional information to recipients.

In this study, one-to-one interactions were tested between the drone and the participants. In a busy urban environment, where multiple individuals may be present, visual or auditory distractions from other elements in the environment can lead to other types of uncertainties regarding interaction protocols. Future research should delve deeper into the impact of approach trajectories and delivery methods in scenarios involving multiple individuals, additional distractors, and congested environments.

Conclusion

The current VR study investigated how the aerial paths and delivery methods of a medical delivery drone impact the uncertainty felt by recipients on the ground. Addressing this is vital for establishing a safe and natural HDI, expediting the introduction of medical delivery drones in public spaces, and potentially saving human lives. The study revealed that recipients perceived curved paths as natural, safe, certain, and predictable, contrasting with feelings of uncertainty and unsafety when observing straight-line drone paths that required them to look up during the descent. In contrast to attempting landing delivery, hovering above eye-level (i.e., 7m above ground) and utilizing a cable for delivery reduced uncertainty and instilled feelings of safety and trust. It is advisable to approach recipients with a curved path and employ a cable for delivery to mitigate uncertainty and promote feelings of safety and trust. Drones should avoid hovering near humans, especially after attempting a landing delivery, to prevent ambiguity regarding drone intentions. Additionally, clear and explicit communication of drone intentions was found to reduce uncertainty in the interaction. Therefore, future research is recommended to explore design aesthetics and HMIs for communicating drone intentions.

Supplementary material

Scenario videos, sketches of approach trajectories, supplementary results, and data supporting the statistical tests are available here:
https://www.dropbox.com/scl/fo/o18u2a7klviuhy0xc88x8/h?rlkey=vlepfkd1oyqa0ues2amluk7ye&dl=0

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