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See it, hear it, feel it: an explorative virtual reality study to identify factors determining public acceptance of drones in different city environments

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Abstract

This paper reports an explorative approach to research factors influencing how people experience urban drone traffic. The study used a virtual reality environment to show people what future drone traffic could look like. A total of ten people took part in the survey. They experienced different types of drones with varying purposes in four urban areas: an industrial area, a city center, a residential area, and a park. Various types of data were collected in the study, focusing on qualitative data from interviews. The goal was to collect a rich and comprehensive data set that thoroughly understands acceptance factors related to drones, recommendations on how future research scenarios in high-fidelity simulation should be designed, and which factors should be included or need more investigation. The findings reveal that drone acceptance is determined by a complex interaction of numerous factors, which need more investigation and validation in future research.

Keywords Acceptance · Simulation · Virtual reality · Uncrewed aircraft systems (UAS) · Drones · Urban air mobility (UAM) · Qualitative · Explorative

1 Motivation

Unmanned aircraft systems (UAS), also commonly known as drones, are gaining much interest from industry, research, politics, and society. With technological advancements in autonomous air vehicles and fully automated flight guidance, use cases such as parcel delivery and passenger transport in populated environments are on the research and development roadmap. In parallel with this technological and conceptual development, questions regarding the social impact of urban air mobility are becoming more critical. Are these services accepted by people living in cities or metropolitan areas?

Therefore, social acceptance of drones is investigated and is seen as a critical parameter for developing operational concepts. General models of technology acceptance claim that perceived benefits should outnumber perceived risks. Current studies show that use cases with clear benefits for society are more likely to be accepted than commercial use cases. Nevertheless, when investigating perceived risks in more detail, the challenge is that most people do not have experience with that technology, and these use cases are not likely to rate specific concepts and can express general fears or attitudes towards technology.

Thus, this paper introduces an approach to using Virtual Reality (VR) to let people experience future UAS traffic use cases in different urban focus areas. Using the VR environment, an explorative study was conducted to identify factors that influence the acceptance of UAS flights in different urban scenarios and shed light on aspects that require further investigation in future studies.

2 State of research

The social acceptability of drones is a research field of utmost interest. Numerous studies have explored the public opinion on drones and perceived risks and concerns about this new kind of air mobility. A recent survey investigated

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the acceptance of drone applications in highly urbanized environments and found that drones for search and rescue missions, disaster management, monitoring, or preserving certain areas have high support. The lowest support has been identified for using drones for passenger transport, photography, and videography [1]. The main concerns about drones raised repeatedly in studies are violation of privacy, potential misuse, and annoyance [1, 2]. Related to the perception of drones, the fear of congested skies [2, 3] and noise pollution [3, 4] were also found to be an essential acceptance factor in recent research.

The context of use plays an important role, as surveys showed that drone flight acceptability differs in various urban areas. A study by Tan [1] detected the highest acceptance levels for drones flying in industrial areas, whereas it is low for residential areas. As a possible explanation, the study found that fears and concerns were a more salient factor for drone use in residential areas, while perceived potential benefits could be a more critical consideration for non-residential areas. It needs to be kept in mind that the survey was conducted in Singapore. Citizens might be more open to new technological advances than other countries [1]. A study carried out in Germany came to similar results related to the context of drone use. As in Tan's study, findings also indicated more approval for drone flights in industrial areas compared to residential areas and city centers. Moreover, the study participants expressed a higher acceptance of drones overflying sparsely populated areas, whereas acceptance drops significantly for heavily populated regions [3]. This was also confirmed by Yedavalli and Mooberry's research [4].

One challenge about studies in the field of drone acceptance is that most people have yet to get in touch with drones, for example, having never seen, heard, or flown a drone [3]. Since the technology has yet to be widely introduced, research findings are probably limited to the imagination of participants [1]. Therefore, study designs provide an acoustic and visual impression of drone traffic to help measure annoyance or discomfort related to drones. There are already several studies using an experimental approach in this way. A psychoacoustic investigation of small uncrewed aerial systems (sUAS) conducted by Christian and Cabell [5] compared drone noises to road vehicle noises. Their findings reveal that the annoyance of drone noises is not only a matter of flight altitude but also may be influenced by other flight characteristics, such as flight maneuvers. Furthermore, the study's findings showed that there may be a systematic difference between the annoyance response generated by the noise of the sUAS and the road vehicles [5]. Further psychoacoustic studies reveal that drone noise leads to small changes in perceived loudness, annoyance, and pleasantness in high-road traffic noise soundscapes. In contrast, soundscapes with reduced road traffic noise lead to higher changes [6]. Another study identified loudness, sharpness, and fluctuation strength as significant factors affecting drone noises' annoyance [7]. Research from Chang et al. [8] and Aalmoes and Sieben [9] focused on psychoacoustics and considered the visual perception of drones. In the study of Chang et al., participants were observing real drones in a room. Aspects affecting annoyance identified in the experiment are noises, higher amounts of drones, color and shape of the drone, and fast and jumpy movements [8]. The study of Aalmoes and Sieben investigated the visual and audio perception of drones using a VR simulation. Key findings indicate no differences in annoyance between audio-visual and audio stimuli. Results also showed no difference in annoyance between a louder and a quieter street. Drones in a hovering mode were rated as more unpleasant than flyovers. Personal factors like preexisting attitudes towards drones significantly predict general noise annoyance [9].

3 Research approach

The subsequent research aims to identify aspects essential for the public's acceptance of UAS. A VR approach was selected for this study, similar to some of the experiments mentioned in the previous chapter. Studies using experimental, hypothesis-testing designs make up most of the research.

Conversely, this study aimed to use an explorative approach and collect data to generate hypotheses. Therefore, the focus of the study was primarily on collecting qualitative data. Qualitative research, deeply rooted in psychology, seeks to unravel how individuals make sense of their world and experience various events. It delves into the 'what,' 'how,' and 'why' of phenomena, typically utilizing small samples and employing focus groups, interviews, and observation methods to gather rich, non-numerical data. Unlike quantitative approaches, qualitative research doesn't rely on statistical analysis but instead aims to explore and understand the complexities of human behavior and experiences. This method fosters a hypotheses-generating approach rather than hypothesis testing, allowing for flexibility and spontaneity in interactions between researchers and participants. Open-ended questions and probing techniques empower participants to articulate their perspectives freely, enriching the depth of the findings [10–14].

This study aimed to gain an in-depth understanding of how people in urban areas experience flying drones. As the urban setting in which UAS are flying has been highlighted as a significant factor in previous surveys [1, 3, 4], participants experienced UAM within four different urban environments in this study. They involve an industrial area, a part of a city center, a residential area, and a park scenario. The scenarios involved various UAS types, flight altitudes, and speeds to give the audience a manifold impression. The qualitative data were collected through interviews. Although the focus was on the qualitative methodology, subjective data from questionnaires and objective data were also collected. The aim was to generate results that provide a comprehensive picture of the acceptance of drone flights. The findings should reveal which factors are crucial for the public acceptance of UAS and identify aspects that still need to be covered by existing research and need more investigation. This results in the following research questions:

RQ 1: Which factors determine the acceptance of UAS flights in urban environments?

RQ 2: Which aspects related to the acceptance of UAS flights in urban environments need (further) investigation in the future?

4 Methodology

4.1 VR-lab

The study was conducted in Brunswick's DLR MoSAIC (Modular and Scalable Application-Platform for Testing and Evaluating ITS Components). The recently updated research infrastructure [15, 16] contains a state-of-the-art pedestrian simulator. Its main components are a motorized, omnidirectional treadmill (Omnifinity OmniDeck) with a diameter of 4.70 m, a VR headset (HTC Vive Pro Eye) with a 1440 × 1600 resolution and a refresh rate of 90 Hz, and corresponding controllers (see Fig. 1). All components connect and communicate through a Virtual Reality (VR) PC using SteamVR. The treadmill receives the user's head position via the calibrated VR glasses and, if necessary, activates the surrounding motorized roller segments, progressively returning the test subject to the static center of the platform. This ensures that the test person never approaches the limits of the available physical space despite its movement. Without the limitation of physical space, the subject can move freely in the virtual world.

4.2 Visualization

In designing the virtual environment, the challenge was to meet the varied study design requirements and the VR pedestrian simulation requirements, which also had to consider exhaustion and simulation sickness. Therefore, a complex environment with separated focus areas was created based on the outline of Cremlingen, a small city near Brunswick (see Fig. 2). They involve an industrial area/business park (A), a city center (B), a residential area (C), and a park (D). The intention was to make small, self-contained sections that can be fully experienced for 15 min.

The design process itself took place in Trian3DBuilder and Unreal Engine 4. To portray an elaborate and vivid environment, a high-resolution road map of the German freeway A39 was combined with Open Street Map (OSM) data of the city of Cremlingen. For final polishing, the scene was then exported to Unreal Engine 4. The framework was also used to implement various scenarios such as (but not limited to) complex drone behavior and user navigation through interactive objects.

Fig. 1 The pedestrian simulator of the MoSAIC

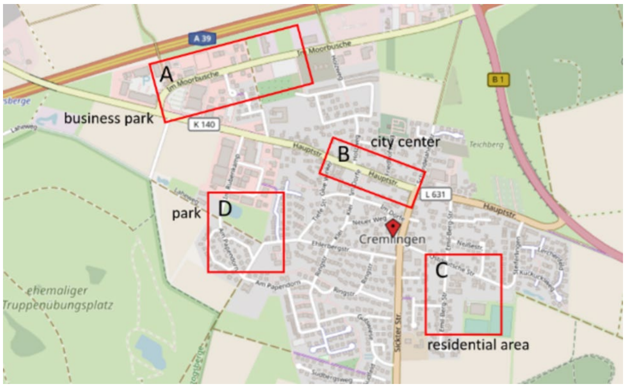


Fig. 2 Focus areas in virtual Cremlingen

4.3 Acoustics

Noise is a critical factor that influences the acceptance of drones. For this reason, the drone's noise was also integrated into the simulation study. However, it should be noted that the focus of the study was on something other than the exact acoustic modeling of drone noise. Instead, attention was paid to the fact that the drones differ fundamentally in their sounds, as they have different sizes, structures, and flight behavior, to determine rough differences in acceptance. Therefore, the reproduction of the drone noises is not exactly realistic, but this was sufficient for the study's objectives, as the aim was to get an impression of what lower air traffic could look like and how this is experienced from the individual point of view of the participants. The following describes which sounds were used for the drones and how they were integrated into the simulation.

Different UAS types and use cases were presented in urban scenarios, including air taxis, rescue drones, quadcopters with private or commercial missions, and delivery drones. For the quadcopters and delivery drones, suitable open-source sound samples were used. As open-source noise samples could not be found for air taxis and rescue drones, the sound was taken from a video of a flying octocopter. The GoPro camera, which was located directly on the UAS, recorded the video within the frame of a flight demonstration in the project City-ATM [17–19]. The flying Octocopter was the DexHawk, a self-built research drone of DLR with a weight of 14 kg [20]. The DexHawk flew 20 m above a river near the Köhlbrand Bridge in Hamburg. In the video, a 15-s sound snippet was extracted during level flight. The noise samples used in this study are attached to the paper.

In postproduction, the background noise of the snippet was reduced using the Adobe Audition software. A dynamic sound component was created for each UAS, containing a start, landing, and idle phase, which are triggered according to the status. This way, so-called sound automats were created, and depending on how the particular UAS behaved in the simulation, the corresponding sounds were played back dynamically and merged into each other. In addition, influencing factors such as size, speed, flight altitude, rotor diameter, number, and type of motors are included in the calculation. Each UAS in the simulation has a dynamic sound linked to it that follows it around every bend and alters based on the UAS's speed. The sound was given a vertical capsule shape for sound dispersal because noise decays with increasing distance and affects UAS differently according to the rotor blades (see Fig. 3). The tiny capsule causes the volume to drop to the sides very quickly. It stretches downward for this purpose and carries the sound directly beneath it. The vertical capsule shape was chosen based on the results of a literature review on drone noise emission characteristics. According to this review, drones exhibit a pronounced vertical angular radiation, while on the horizontal plane a uniform radiation is assumed for reasons of symmetry [21]. Three different capsule sizes were chosen for the referring UAS. Buildings nearby have been altered to block noise appropriately. For all drones, the attenuation function was defined as logarithmic in Unreal.

Figure 4 shows spectrograms of the different drone noise samples used in the simulation. The spectrograms were generated with the Python library "librosa" [22]. They indicate the frequency spectrum during the flight for all drone types. In addition, plots for takeoff and power-down are also presented for the logistics drone, as the drone experienced different flight phases. The spectrograms of the logistics drone, racing drone, and small quadcopter show a horizontal line structure to varying frequencies during the flight. The small quadcopter and the logistics drone tend to be dominated by lower frequencies, while very high frequencies characterize the racing drone. The sound profile of the air taxi and the civil protection drone appears periodically in the plot, whereby the right and left areas are symmetrical, and there is a short transition phase in between. Frequencies in the lower mid-range are the most intense here. During takeoff, several frequencies from the lower to middle-frequency spectrum are most intense for the logistics drone from one second

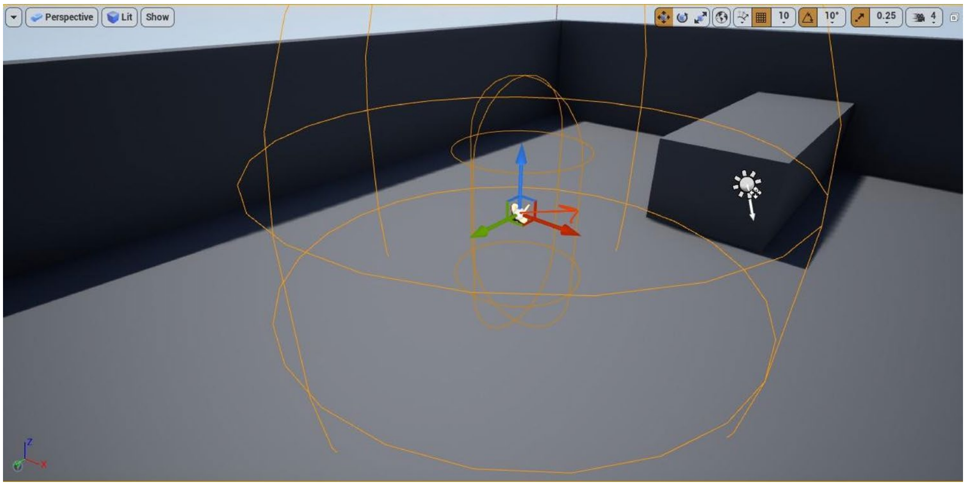


Fig. 3 Vertical capsule sound attenuation in Unreal 4; Source: https://docs.unrealengine.com/4.27/en-US/WorkingWithAudio/DistanceModelAttenuation/ [23]

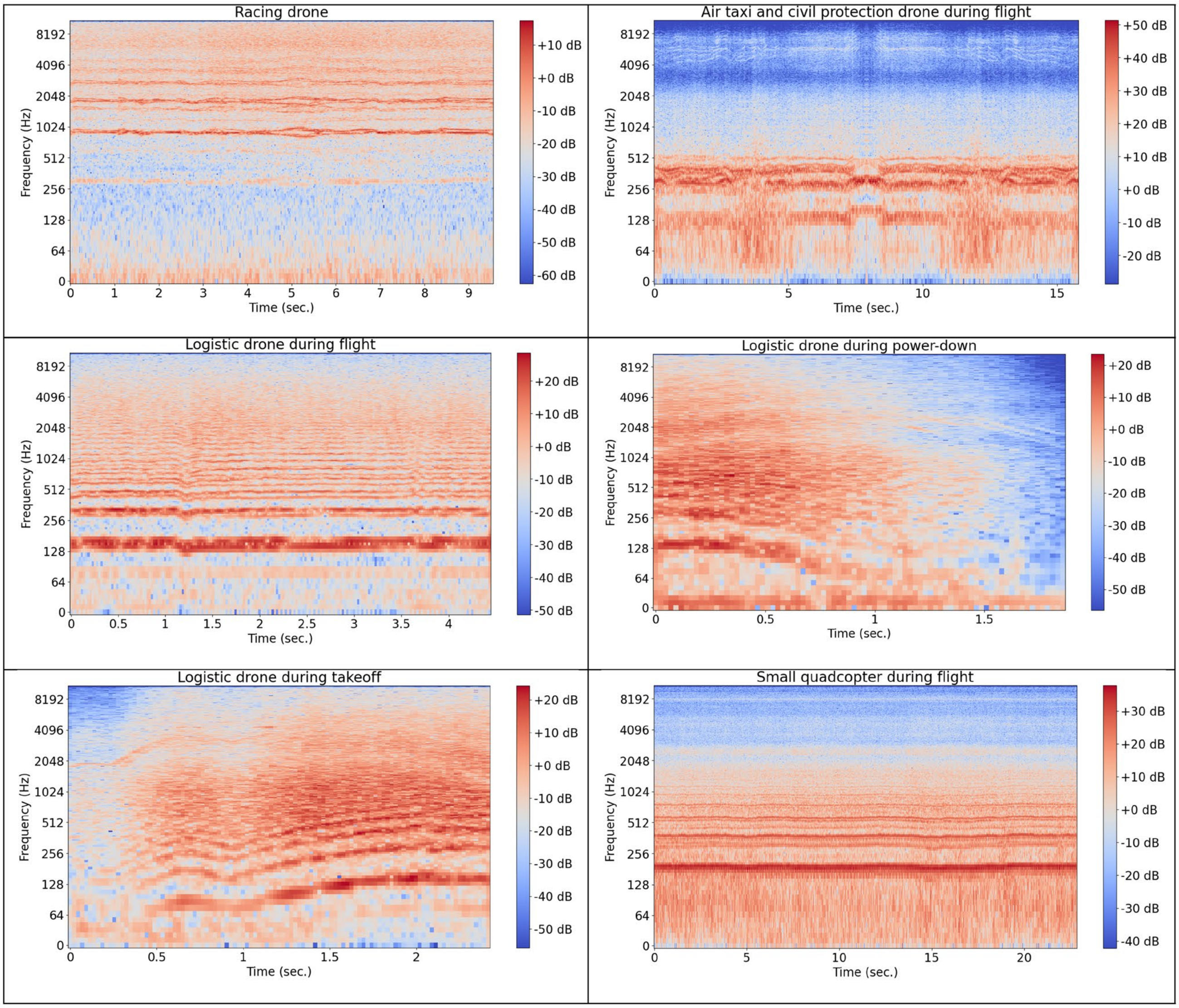


Fig. 4 Spectrograms of the drone noise samples used in the simulation

onwards. Similar spectra are also present for half a second during power-down, after which all frequencies are only very weak. In terms of volume, air taxi and civil protection drones have the loudest frequencies, around 50 dB, while all other drones have significantly lower ones.

Before the study began, two seasoned UAS operators verified that the noises sounded realistic. According to their feedback, the noise of the small UAS was too quiet. Thus, a pitch multiplier of 1.5 was set for them. Additionally, the noise of the racing drones was multiplied by 0.5. The volume multiplier was set to 0.75 for the other drones. The newly established volume levels were adopted for the study after being assessed as reasonable in a subsequent sound check. In the study, the sounds were played back via the headphones integrated in the VR glasses. The volume was set to 100 percent in the simulation computer.

4.4 Scenarios

Four different urban environments were simulated in the study, including a city center, a part of the residential area, and a park. In each scenario, different UAS types representing different use cases were shown. The events in the scenarios did not follow any systematic variation of factors. Instead, we aimed to give participants diverse impressions of various UAS and events. Additionally, we kept the scenarios' occurrences plausible because drones might genuinely exist soon. To do this, we selected UAS types for each scenario based on what may be expected there, and we designed variables such as flight altitude, speed, and flight path as they might be in practice. Various types of drones with different purposes were depicted in the simulation. These included a small quadcopter, an octocopter, a UAV helicopter, and a VTOL with two seats. In this way, the participants were shown different purposes and various sizes of drones and types that differ visually from each other. The flight altitudes were highest for commercial drones, i.e., air cab and logistics drones, as well as civil protection drones. These were between 50 and 150 m. However, the logistics drone also took off and landed in industrial and residential areas, so the flight altitudes could also be very low. Otherwise, there was no variance in the flight altitudes of these drones, but they maintained a certain cruising altitude in each case. The situation differed with small quadcopters for filming, industrial inspections, or hobby use. The flight altitudes were more dynamic and varied between three and 50 m. The hobby drones fluctuated wildly in their flight altitude and tended to fly in a criss-cross pattern, as they are often controlled manually. The other drones followed more specific routes, as the missions for these types were planned in practice, and predefined routes were flown automatically. The flight routes of the air cab, the logistics drones, and the civil protection drone always followed a straight line. The speeds also varied depending on the type of drone. Smaller drones, therefore, had lower speeds than larger drones. Table 1 overviews the use cases, UAS types, and flight parameters in the referring scenarios. A screenshot of the simulation's environment (left table side) and an image of the flight paths in Open Street Map (right table side) are displayed for each scenario. The numbers in the flight path column refer to the numbers in the street map images (Fig. 5).

4.5 Procedure

The study took part in the VRU lab. First, participants were welcomed and briefed about the procedure. They declared their consent to take part in the survey. Following that, they answered a questionnaire related to Simulator Sickness. Participants received a briefing about the OmniDeck and conducted two training scenarios to familiarize themselves with the virtual environment and the hardware and to manage walking on the OmniDeck. At the same time, simple mechanics such as grabbing objects with controllers are trained. The training lasted between 30 to 45 min.

Afterward, participants were instructed to imagine that it is 2030 and that urban traffic has changed. Traveling takes place on the ground and in the air. They are in Cremlingen, a

Table 1 Overview of use cases, UAS types, flight altitude, and speed in the different scenarios

Scenario	Flight path	Use case	Flight altitude (m)	Speed (m/s)	UAS type
Industrial area	1	Logistics	50	8	Octocopter (14 kg)
	2	Logistics	60	8	Octocopter (14 kg)
	3	Logistics	80	8	Octocopter (14 kg)
	4	Logistics	100	8	Octocopter (14 kg)
	5	Logistics	70	8	Octocopter (14 kg)
	6	Air taxi	150	25	VTOL with two seats (450 kg)
	7	Civil protection	100	15	UAV helicopter (14 kg)
	8	Industrial inspection	20	8	Small quadcopter (1.2 kg)
City center	1	Logistics	50	8	Octocopter (14 kg)
	2	Civil protection	100	16	UAV helicopter (14 kg)
	3	Filming	5–20 (varying)	8	Small quadcopter (1.2 kg)
	4	Filming	20–50 (varying)	8	Small quadcopter (1.2 kg)
	5	Air taxi	150	25	VTOL with two seats (450 kg)
Residential area	1	Filming	5	8	Small quadcopter (1.2 kg)
	2	Filming	5–20 (varying)	8	Small quadcopter (1.2 kg)
	3	Civil protection	100	8	UAV helicopter (14 kg)
	4	Logistics	50	8	Octocopter (14 kg)
	5	Hobby	5–20 (varying)	16	Small quadcopter (1.2 kg)
	6	Air taxi	150	25	VTOL with two seats (450 kg)
Park	1	Civil protection	100	16	UAV helicopter (14 kg)
	2	Hobby (racing)	2–3 (varying)	21	Small quadcopter (1.2 kg)
	3	Hobby (racing)	2–3 (varying)	21	Small quadcopter (1.2 kg)
	4	Hobby	3	1	Small quadcopter (1.2 kg)
	5	Hobby	5–20 (varying)	16	Small quadcopter (1.2 kg)
	6	Air taxi	50–100 (landing)	8	VTOL with two seats (450 kg)
	7	Logistics	50	8	Octocopter (14 kg)

Fig. 5 Flight paths and impressions of the scenarios (row 1: industrial area, row 2: city center, row 3 residential area, row 4: park)

smaller city with 5000 inhabitants located 15 km away from Braunschweig with 220,000 inhabitants. They are supposed to follow a route in different areas of Cremlingen and fulfill some tasks. They are supposed to behave normally as they would do as a pedestrian. Before each of the four scenarios, participants saw a map with the route they should take and were instructed on their tasks.

The subject was given several secondary tasks during the experiment, which varied depending on the sections. The tasks served several purposes at the same time. On the one hand, they should encourage the test person to interact with the environment, increasing the sense of presence. On the other hand, the tasks shifted the user's mental capacities. The subject should not focus on walking but on interacting with the simulation. The intention was to achieve a more natural gait pattern, increase the feeling of presence, and navigate the subject through the environment by strategically placed objects. These tasks were designed to capture some of the participant's attention to simulate a more realistic occupancy level. In the industrial area, the task was to count all the blue cars you spot along the way. In the residential area, the task was to count Easter eggs. In the park and the city center, the task was to collect garbage from the street that you see along the way and throw it in the nearest garbage can. The presence of drones in the scenarios was masked to participants.

The four urban scenarios were presented to the participants in a randomized order to prevent sequence effects. In each scenario, participants had a time window of 15 min to complete their tasks. They could exit the scenario earlier if they completed the task before the allotted 15 min had passed. Time was limited to avoid simulator sickness. Within each run, participants were instructed to press a trigger whenever they felt uncomfortable in the virtual scenery they experienced. Furthermore, participants were advised that they were allowed to share all thoughts and talk to the investigators.

After each run, participants answered questionnaires and ran through a semi-structured interview. After the completion of all four scenarios, a debriefing was conducted. It consisted of an individual brainstorming session on urban air traffic. Afterward, an interview was conducted, and finally, a questionnaire with demographic items was filled out. At the end of the study, participants were explained the goals and research question of acceptance of drone traffic in urban areas. The whole procedure lasted between 2.5 and 4 h.

4.6 Data collection

The study covered a wide range of aspects to address our research approach. Table 2 provides an overview of the topics and methods of data collection that have been used. Topics include various parameters related to how UAS has been experienced in different urban areas and this technology's general benefits and risks. Questionnaires and interviews were conducted after each scenario and at the end of the study. The post-scenario questionnaire includes eight items. Some were adapted from the Technology Acceptance Questionnaire for Video Surveillance (TAM-VIS) and the Technological Acceptance Questionnaire 3 (TAM 3) [24, 25]. The researchers formulated the others. The items used are listed below:

Table 2 Topics addressed in the study and methods of data collection

Topic	Methods of data collection
Acceptance of UAS in different urban environments	Questionnaire, interview
Confounding factors	Trigger presses, interview
Focus of attention	Interview
Perception of flight altitude	Interview, questionnaire
Perception of visual density	Interview
Perception of UAS noise	Interview
Perceived usefulness of UAS	Questionnaire, interview
Perceived risks related to UAS	Questionnaire, interview

1. The scenario made me feel nervous. (TAM 3)
2. I felt scared in the scenario. (TAM 3)
3. To me, the scenario's events appeared to be unforeseeable. (by researchers)
4. In the scenario, I felt as I was being watched. (TAM-VIS)
5. I felt disturbed in the scenario. (TAM-VIS)
6. In the scenario, I felt restricted in my privacy. (by researchers)
7. I felt safe in the scenario. (by researchers)
8. I felt comfortable in the scenario. (TAM 3)

Participants rated these eight items on a categorial scale (totally disagree, somewhat disagree, rather agree, totally, agree, not sure). Items seven and eight were reversed for the analyses because, in contrast to the other items, they are formulated positively. During the simulation runs, participants marked situations they perceived as disturbing by pressing the trigger of the handheld controllers. Trigger presses were recorded within the simulator log files. Each scenario time and position of each trigger press per participant was derived, representing a disturbing situation.

5 Results

5.1 Sample

The sample involves participants from different departments of the German Aerospace Center. In total, ten people participated in the study. One person was excluded from the analysis due to sound problems during the simulation. Seven of the remaining nine participants are men, and two are women. A majority of seven persons live in cities with between 100,000 and 500,000 inhabitants. The other two participants are residents of smaller towns. The attitude on UAS, in general, is mainly positive within the sample. Furthermore, most participants already experienced UAS in a private or occupational context (see Fig. 6). The participants have been recruited via an e-mail distribution list. Participants received financial compensation when they wanted.

5.2 Acceptance of UAS in different urban environments

Figure 7 shows the analysis results of the eight items related to how participants experienced the four different scenarios. The most positive answers were given for the industrial area. For all items, most participants, ranging from seven to nine, gave answers in the positive spectrum of the scale, meaning rather than disagreeing with the single statements. For the last two statements, which capture how safe and comfortable

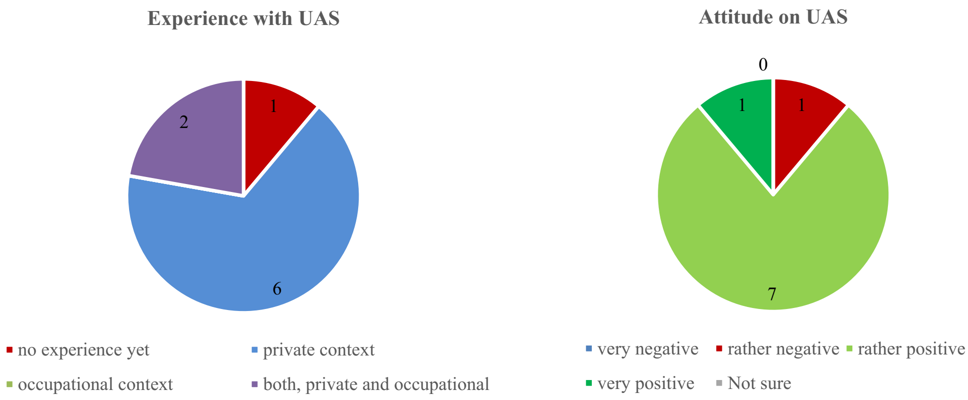


Fig. 6 The right pie chart indicates participants' attitudes toward UAS, and the right one shows their experience with UAS. Both charts present absolute frequencies

participants felt during the scenario, rather than disagreeing, the positive answer spectra are the following: the second most pleasant scenario is the city center, respectively, the main street. Five items were answered positively by at least six participants, more than half of the sample. Aspects rated more negatively in this scenario are the unpredictability of the event and the feeling of being watched and disturbed.

The most negative scenarios are the residential area and the park. For the park scenario, the unpredictability of events and the feeling of being watched, disturbed, and comfortable were rated more negatively by at least half of the participants. For the residential areas, even all items were answered negatively by the majority of the participants.

A Friedman Test reveals significant results in all items (felt comfortable: $\chi^2(3)=9.98$, $p=0.019$, $n=8$; felt safe: $\chi^2(3)=12.49$, $p=0.006$, $n=9$; felt restricted in privacy: $\chi^2(3)=13.02$, $p=0.005$, $n=9$; felt disturbed: $\chi^2(3)=15.12$, $p=0.002$, $n=9$; felt like being watched: $\chi^2(3)=9.21$, $p=0.027$, $n=9$; events seemed unpredictable: $\chi^2(3)=7.93$, $p=0.048$, $n=9$; felt scared: $\chi^2(3)=9.46$, $p=0.024$, $n=9$; felt nervous: $\chi^2(3)=11.16$, $p=0.011$, $n=9$). However, post hoc (Dunn–Bonferroni-tests) pairwise comparisons only turned significant for four items (felt restricted in privacy: $z=-1.67$, $padapted=0.037$, $r=0.56$; felt disturbed: $z=-2.00$, $padapted=0.006$, $r=0.67$; felt like being watched: $z=-1.61$, $padapted=0.049$, $r=0.54$; felt nervous: $z=-1.61$, $padapted=0.049$, $r=0.54$). In all items, differences are significant between the industrial and the residential area. The effect sizes in all post hoc tests correspond to a strong effect.

In the final questionnaire answered by the participants after the simulation, approval for drones flying in specific city areas and participants' concerns related to drones were asked. Results indicate that drone flights are mostly tolerated in business and industrial areas, as most participants gave positive ratings. In city centers, at least six of the participants would agree to drone flights. According to the ratings, drones would not be acceptable in housing areas and parks (see Fig. 8).

5.3 Disruptive factors and situations

Participants could press a trigger in situations where they felt disturbed or uncomfortable. Data from nine participants were recorded. Two participants were excluded from this analysis, one due to an incorrect configuration during the measurement and one due to incorrect trigger usage. However, the two participants were only excluded from the trigger analysis and not from the others, as the problems with the trigger presses are unlikely to have any influence on the other results. Overall, data from seven participants could be used. The simulator provided logfiles where relevant parameters, including the press of the trigger, were recorded at 50 Hz. These log files were processed with Python scripts to select time points where the left or right trigger parameter was unequal to zero and to merge these times to events, using libraries numpy, pandas, and matplotlib for visualization [26–28]. A threshold of one-second difference between time stamps was chosen to merge rows into a single trigger press event. The identified trigger press events were plotted and visually checked for plausibility (e.g., to validate the threshold chosen and the number and occurrence of trigger presses).

One hundred eleven trigger presses were gathered with a minimum of zero and a maximum of 13 events in one scenario. This result indicates that feeling disturbed is a rather individual evaluation. The average number of trigger presses per scenario was calculated (see Table 3). Results show that, on average, participants encounter seven uncomfortable situations in the residential area compared to three and four situations in the park and city center and two events in the industrial park. At the same time, participants also spent the most time on average in the residential area scenario.

To further detail the reason for the disturbing situations, a plot of all trigger presses with the position of the UAS for the scenarios is given in Fig. 9. Each white dot represents one trigger press; within the plots, the triggers of all participants are combined. The colored lines indicate the flight route of the UAS. What becomes apparent is that in

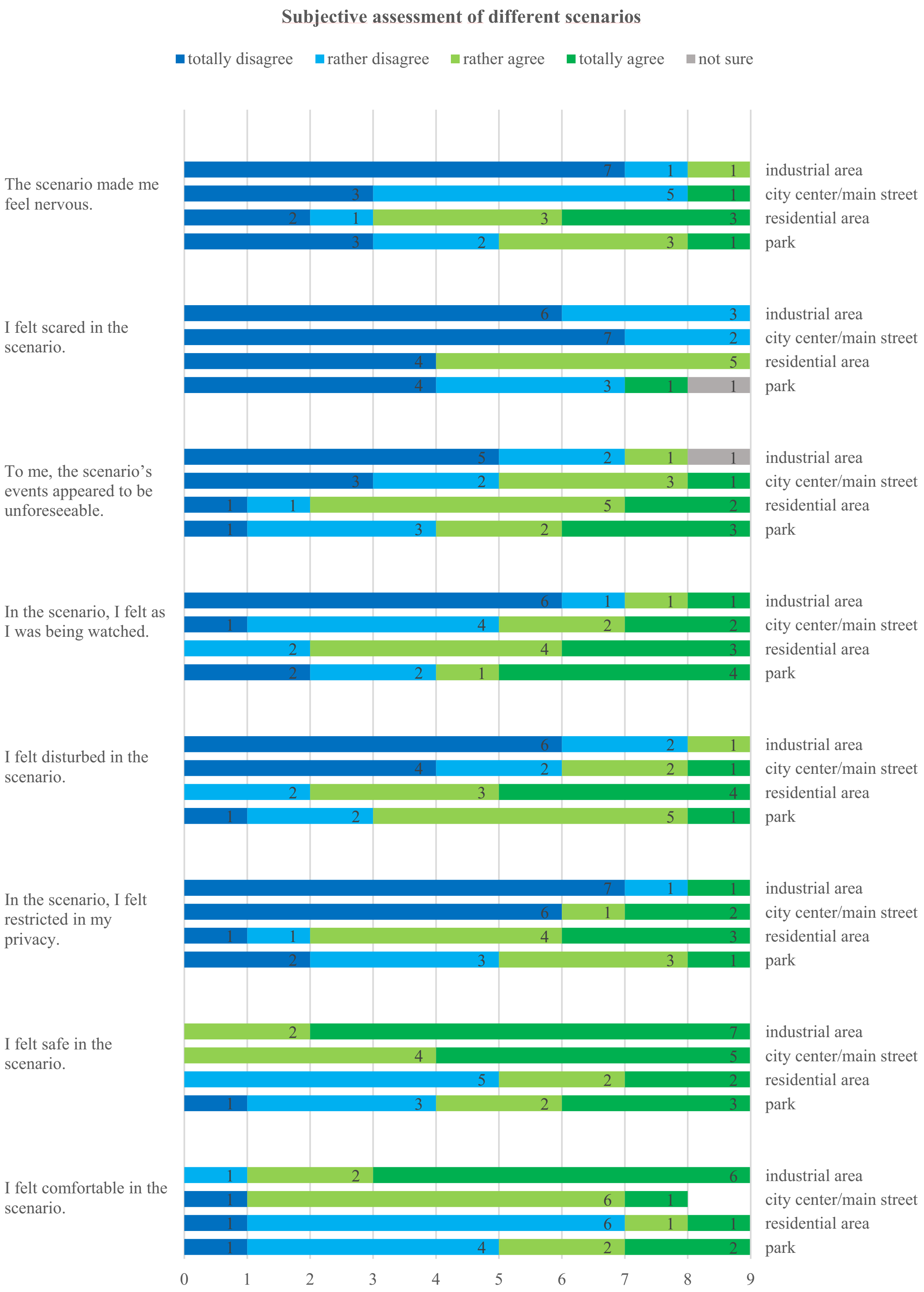


Fig. 7 Subjective assessment of different scenarios in total number

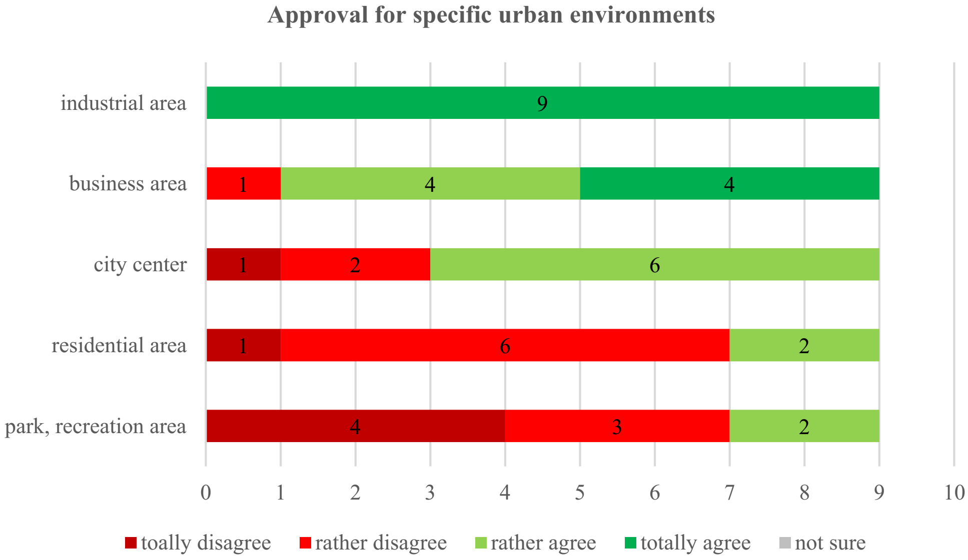


Fig. 8 Approval for specific urban environments in absolute frequencies

the city center, residential area, and park, triggers were pressed, especially when small UAS were nearby. This observation aligns with statements participants gave in interviews after experiencing the scenarios. For instance, eight residential areas stated that their attention was primarily on UAS, especially the small ones flying around one of the houses and in the garden. For these reasons, participants expressed their closeness and noisiness. Contrarily, there is no specific location where trigger presses are clustered more frequently in the industrial area.

Table 4 gives an overview of the factors, participants perceived as disturbing about UAS within the various scenarios. These factors are feedback from the post-scenario interviews. The numbers in brackets indicate how many participants stated the respective aspect. The statements reveal that small UAS, like the one in the garden in the residential area, were especially perceived as annoying. They sometimes convey the feeling of being observed when equipped with a camera. Noise, as well as unforeseeable flight paths and maneuvers, were also frequently mentioned.

Table 3 Number of trigger presses per scenario

Scenario	Mtrigger	Sdtrigger	Mtime scenario	Sdtime scenario
Industrial area	1.7	1.6	287.0	28.0
City center	3.7	2.6	487.3	226.8
Residential area	7.3	5.0	605.1	147.2
Park	3.1	2.5	478.1	140.9

5.4 Focus of attention

Table 5 presents the results of the post-scenario interviews regarding the focus of participants' attention within the different scenarios. They show that the participants in the industrial area mainly focused on the task assigned to them. UAS received the second-most attention. The situation was the opposite in the other urban regions. The UAS was the significant focus there, with the task coming in second.

5.5 Perception of visual density

According to the post-scenario interviews (see Table 6), participants perceived the amount of UAS as pleasant or reasonable in the industrial area. Two persons described the air traffic volume as somewhat higher. With regards to the city center and park scenario, different perspectives can be seen. Some participants perceived the amount of UAS as acceptable and not disturbing, whereas others stated that there was much going on and they felt annoyed. Regarding the residential area, it is evident that the participants tended to think that there were too many UAS present. This especially applies to the small ones.

5.6 Perception of UAS noise

When comparing the responses given in the interviews to each scenario, it appears that the participants found UAS noises in the industrial area to be the most pleasant (see Table 7). One participant cited the environment because one would anticipate an industrial region to be noisy. UAS nearby, such as those taking off or landing, are an exception. This is perceived as uncomfortable in terms of noise. In the city center, the takeoff and landing are unpleasant

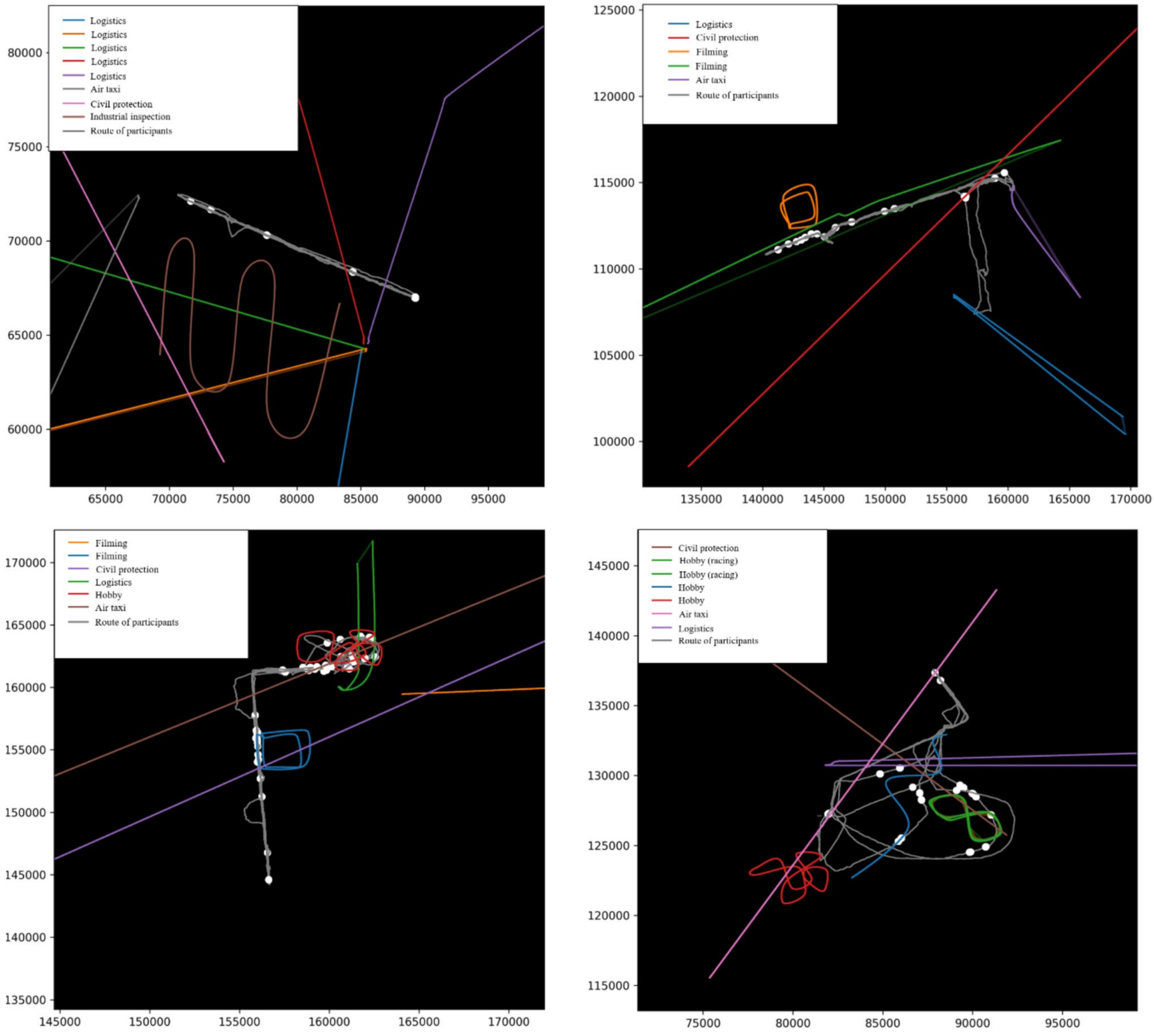


Fig. 9 Plots of the trajectories of persons (grey) in the different areas and positions of trigger presses (white dots). Upper left: industrial center, upper right: city center, lower left: residential area, lower right: park. The axes in the figures are based on the WGS84 geodetic reference system

compared to air taxis. Moreover, in this scenario, some participants perceived small UAS as loud and annoying. The same applies to the residential and park areas, where several participants considered especially small UAS disturbing. Some participants described their sound as aggressive and compared it to bees or hornets. Participants generally noted that it can be unsettling and irritating when UAS are heard rather than seen in some scenarios.

5.7 Perceived usefulness

In an interview after the simulation, participants were asked about their perceived advantages of using UAS. They stated that various applications were coming to their minds. The different use cases indicated by the participants are summarized in Table 8. It also shows the absolute frequencies of each aspect mentioned and how many participants have a more positive or negative view of the respective use cases. As the table shows, air taxis and cartography were stated most frequently. The majority of UAS applications are perceived positively by the participants. An overly negative opinion was expressed on parcel delivery and hobby usage. Regarding monitoring, half of the sample has a positive attitude toward the use case, while the other half has a more pessimistic viewpoint.

Table 4 Factors stated by the participants that were perceived as disruptive

Disruptive factors in the scenarios	*n*
Small drone in the garden	5
Flight path not recognizable, unforeseeable maneuvers	4
Noise	4
Felt observed by camera drones	4
Purpose not clear	3
The purpose of the camera drone is not clear	3
Partly unexpected	3
Small drone	2
Racing drone	2
Landing spot not recognizable	1
Take off/landing at factory hall	1
Behavior not recognizable	1
Delivery drones in gardens might endanger kids	1
Disturbing at some time	1
Flying above sidewalk	1
Flying past	1
Operator not visible	1
Risk of collision	1

n number of participants who mentioned the aspect

The post-scenario interviews also discussed perceived usefulness, referring to the UAS observed in the different scenarios (see Table 9). Most participants' feedback focused on small UAS; virtually all thought they could have been more useful in specific situations. Drone delivery was the subject of a few assertions as well. Opinions on this use case differ. While some participants find them helpful, others do not.

Many participants said that the aim of the UAS is only sometimes evident in response to whether they found the UAS's purpose in the scenarios to be transparent. According to some of them, the function of small UAS is particularly unclear and suspect. Participants' presumptions regarding the use cases, however, were essentially correct. They frequently believed that small UAS were being used for surveillance, filming, or as a hobby. Large UAS were acknowledged as air taxis. Additionally, some of the UAS were assumed to be carrying cargo.

In a post-simulation questionnaire, participants were asked to rate their approval for different UAS use cases (see Fig. 10). This item was taken from the telephone survey conducted by the DLR in 2018 [3]. The majority of the sample agrees with several of them. The acceptance rate is substantially lower for air taxis, parcel delivery, and shooting pictures and movies for commercial purposes. Only half the participants would accept these applications.

Table 5 Focus of attention on the scenarios

Industrial area	*n*	City center	*n*	Residential area	*n*	Park	*n*
Task	8	Drones, airspace (8)	8	Drones, airspace	9	Drones, airspace	8
Drones, Airspace	5	Task (4)	4	Task	4	Surroundings	2
Drone noise	1	Road traffic, truck (2)	2	Surroundings	2	Task	2
Surroundings	1	Noises (1)	1	Drone noise	1	Pont	1
Look ahead	1	Follow route and curbsides (1)	1	Reach destination	1	Not to tumble	1
				Birds' twittering (1)	1		

n number of participants who mentioned the aspect

Table 6 Perception of visual density in the scenarios

Industrial area	*n*	City center	*n*	Residential area	*n*	Park	*n*
Pleasant, ok	4	Ok, moderate	3	More drones than in the city center	2	Much going on	2
Higher amount	2	Seen 2–3 drones	2	Ok	2	Disturbing	1
Reasonable amount	1	Much more going on	2	Many drones	2	Not disturbing	1
If drones are not visible, the amount can be more flexible	1	Tolerable amount depends on purpose	1	Too many (in the garden)	2	Not so many (2–3 drones)	1
		Significantly less drones	1	Seen up to 6 drones	1	Air taxi not disturbing	1
		Association with "bombing runs"	1	Too many small drones	1	Higher amount was annoying	1
		Disturbing	1	Drones stand out	1	The most in this scenario so far	1

n number of participants who mentioned the aspect

Table 7 Perception of drone noise in the scenarios

Industrial area	*n*	City center	*n*	Residential area	*n*	Park	*n*
Ok, pleasant, quiet	5	Standing/landing air taxi unpleasant	6	Loud, annoying, unpleasant	6	Sometimes not seen, but heard drones	5
Uncomfortable if the drone is close	4	Small drones loud and annoying	4	Small drones disturbing	4	Quieter than residential areas	3
First heard than seen drones	2	Instead heard than seen	2	High flying drones ok	3	Too loud, unacceptable, annoying	3
Noise is to be expected in industrial areas	1	Customization after 1 min	2	Partly sounded like bees	2	Close, disturbing & aggressive (like hornets)	3
Not heard drones	1	Quiet noises	1	Disturbing if too close	2	Small drones negatively present	2
Loud noises not disturbing if close to streets	1	Phone calls still possible	1	Would be ok if noises were like birds twittering	1	Air taxi ok/pleasant	2
Would be too much to live there	1	Strange, unknown	1	Quieter	1	More acoustically disturbing than visually	2
Humming a bit annoying	1	Challenging to localize	1	More pleasant than the city center, but still too loud	1	Too irritating in the park (nature, relaxation)	1
STANDARD drone noises	1	Air taxi sounds like hovering aircraft	1	Uncomfortable if hearing but not seeing them	1	Sounds triggered observation	1
Significantly quieter than cars or trucks	1	Annoying in the beginning	1			Customization	1
		Big drones not disturbing	1				

n number of participants who mentioned the aspect

Table 8 Use cases stated in the final interview

Use case	*n* (total)	*n* (positive)	*n* (negative)	% positive
Air taxis	6	5	1	83
Cartography/ mapping	5	5	0	100
Parcel delivery	4	0	4	0
Hobby	4	1	3	25
Monitoring of infrastructure	3	3	0	100
Transportation in general	3	3	0	100
Film recordings	3	3	0	100
Authorities and organizations with security tasks	2	2	0	100
Emergency aid	2	2	0	100
Monitoring	2	1	1	50
Delivery of medical goods	1	1	0	100

n number of participants who mentioned the aspect

5.8 Perception of flight altitude

Findings related to flight altitude (see Table 10) from the post-scenario interviews show that the participants perceived the altitude of UAS in the industrial area as pleasant. No negative statements were made about it in this scenario. In the other scenarios, participants were primarily okay with the altitude of UAS flying 50 m or higher. These include air taxis and delivery and rescue drones. On the other hand, small UAS flying at lower altitudes were experienced as being too close. In the residential area, this was particularly frequent. Some participants recommend that UAS fly at least 10–20 m above the ground or distinctly above buildings.

In a post-simulation questionnaire, participants were asked to choose the minimum flight altitudes that, in their opinion, are appropriate for privately, commercially, and publicly used UAS (see Fig. 11). This item was taken from the telephone survey conducted by the DLR in 2018 and extended by two additional response categories [3].

Results of a Friedman test reveal significant differences between the tolerated minimum flight altitude of varying UAS applications ($\chi^2(2) = 15.056$, $p < 0.001$, $n = 10$).

Table 9 Perceived usefulness and transparency of UAS in the scenarios

Perceived usefulness	*n*	Perceived transparency of purpose and assumed purpose	*n*
Small drones less useful	8	Small drones: camera, hobby, surveillance	8
Delivery drones useful	3	Passenger transport/ air taxi	7
Delivery drones not useful	2	Purpose not (permanently) Explicit	7
Passenger transport useful	2	Transport (of goods)	7
Surveillance negative	2	Use of small (camera) drones not clear or questionable	6
Hobby drones don't need to be helpful; it's fun	1	Industrial area: delivery, industry, research	5
Use not of interest	1	Only two of the small drones' purposes are clear	1
		Fertilize plants in the park	1

n number of participants who mentioned the aspect

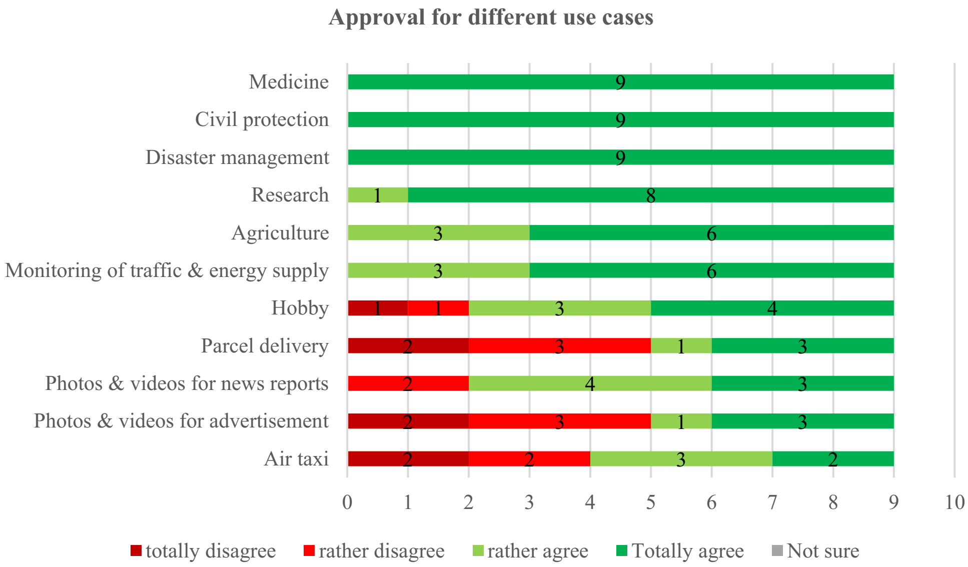


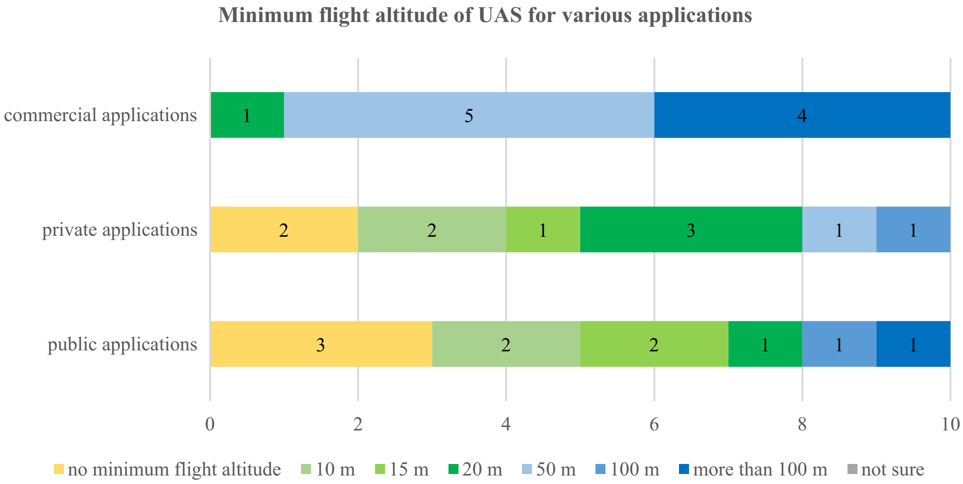
Fig. 10 Approval for different approvals ranging from "totally disagree" to "totally agree" in absolute frequencies

Table 10 Perception of flight altitude in the scenarios

Industrial area	*n*	City center	*n*	Residential area	*n*	Park	*n*
Pleasant, ok	7	Small drones at street too low	4	High flying drones ok	6	Small drones too close (8)	8
Take off and landing is ok	3	Normal, ok	2	too low: around house and garden	5	Air taxi ok (3)	3
Should fly above houses	1	Appropriate for air taxis	1	Minimum flight altitude should be 10 m	3	delivery drone ok (2)	2
Should only be visible for specific purposes	1	Better than residential area scenario	1	Too low	1	LOW, but far away (1)	1
		Rescue drone unproblematic	1	Uncomfortable, felt observed	1	Uncomfortable if close to people (1)	1
		Delivery drone supermarket: good separation	1	Did not affect perceived safety	1	Altitude challenging to estimate	1
		Separation ok	1	Better than park scenario	1	Big drone should fly higher	1
		Rotary wings shallow (annoying)	1			Drones didn't dodge	1
						Close drones irritating	1
						Distance of 10–20 m ok	1

n number of participants who mentioned the aspect

Fig. 11 Tolerable minimum flight altitude for commercially, privately, and publicly used UAS



Pairwise comparisons with the Conover test and a subsequent Bonferroni correction indicate significant differences between the preferred minimum flight altitude of commercially and privately used UAS ($p = 0.011$) and between commercially and publicly used UAS ($p = 0.009$).

According to Fig. 11, participants would not tolerate a flight altitude below 20 m for commercial applications. For this type of use, most participants rated 50 m or more than 100 m as the appropriate flight altitude.

5.9 Perceived risks

In the final interview, participants could express concerns regarding UAS. Content categories were created from the responses, and the concern-related statements made by the participants were assigned to these categories. Nine main categories and 22 sub-categories were derived. Each main category is further divided into several sub-categories. Table 11 shows the main and sub-categories. The "n_{sub}" column indicates how many statements from the participants were assigned to the individual sub-categories. The "n_{main}" column shows the sum of these frequencies in the respective main category. As a first result, all participants expressed concerns about UAS. The most frequent concerns are associated with harm to social values, such as privacy violations or misuse of organized crime. An insufficient technology maturity level represents this sample's second main concern. In this regard, the safety level of manned aviation was mentioned as a benchmark. Furthermore, the third most common concern is collisions with other airspace users (e.g., manned aviation and birds) or bystanders on the ground. Participants also assumed a negative impact on human health caused by noise or by encouraging unhealthy behavior.

Additionally, the participants were asked about concerns related to UAS in the final questionnaire. This item was taken from the telephone survey conducted by the DLR in 2018 [3]. Results indicate that the presented aspects concern more than half of the sample. The highest concerns are noise and the possibility that UAS might be used for criminal actions (see Fig. 12).

All participants rated noise as a medium to high concern in the questionnaire, but only three participants mentioned noise as a risk in the interview. The results of both methods indicate that misuse of criminal actions, violations of privacy, and safety concerns are relevant risks for the sample.

6 Discussion

The discussion is divided into three sub-chapters. 6.1 discusses the strengths and limitations of the study. 6.2 answers the first research question and thus contains a discussion of the results. The second research question is answered in 6.3. As this question asks which factors should be researched in the future, the answer also provides an outlook.

6.1 Strengths and limitations

In this study, an interactive human-in-the-loop simulation utilizing an advanced pedestrian simulator has proven valuable in providing participants with a realistic and immersive experience of future UAS scenarios. To our knowledge, this was the first approach of a Virtual Reality study in which participants were not only observers but could actively move around, experiencing different scenarios and interacting within them. About the novelty of this kind of interactive VR scenario, it was very pleasing to observe that users showed only a shallow level of simulation sickness. Hence, no test run had to be interrupted or aborted. Simulation sickness is often a significant problem regarding human-in-the-loop (HIL) simulation, so this is a great success. Reasons for this are mainly assumed to be the decelerated simulation design (compared to flight or driving simulation), which also translates the subject's movement directly and without delay into

Table 11 Perceived risks related to UAS

Main categories	n_{main}	Subcategories	n_{sub}
Harm to social values	11	Violation of privacy	5
		Organized crime	3
		Surveillance	1
		Weapon	1
		Eases stalking	1
Immature/unsafe technology	9	Immature/unsafe technology (obstacle detection not accurate, rotor failure)	5
		Damages due to drone crashes	2
		Endangering critical infrastructure by crashes	1
		Short operation time of the battery (crashes due to empty batteries)	1
Collisions	7	Collisions	3
		Collisions with people/injury to people	3
		Collisions with birds	1
Harmful influence on human health	5	Noise	3
		Promotes unhealthy behavior (e.g., less movement, the negative influence of noise on mental health)	2
Misuse of technology	4	Misuse of technology	4
Immature/unsafe operation	3	Easy use of the airspace is threatened by drones	1
		Unsafe handling/operation	1
		Risk due to private use	1
Risk for operators	2	Legal risks for users in current operations	1
		Threat to drones by others	1
Safety	1	Safety in general	1
Shadow cast	1	Shadow cast	1

n number of interview statements assigned to the respective categories

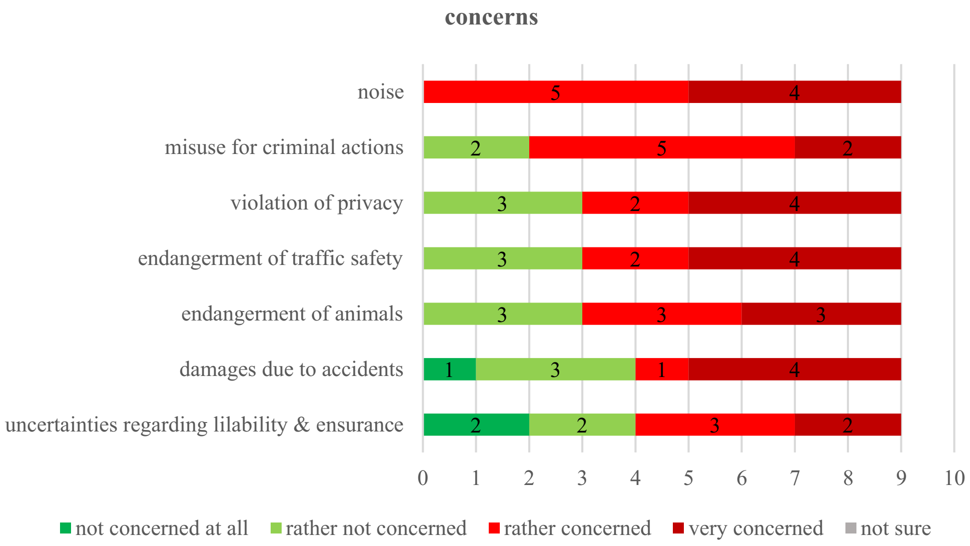


Fig. 12 Participants are concerned about UAM in absolute frequencies

the simulation, as well as the preliminary and comprehensive introduction of the subject to the system through well thought-out training scenarios. Moreover, the different tasks given to the participants during training and in the active scenarios simulated daily situations in which people would pay attention to traffic and continue their everyday activities. This way, it could be investigated to what extent people would recognize or be distracted by drones when focused on other things. Detailed insights were gained about various factors that determine UAS acceptance. Thus, this research's explorative and qualitative approach has proven valuable when exploring the acceptability of novel technologies.

Limitations should be mentioned about the modeling of drone noise. These are based on recordings with microphones directly on or near the drones and consist mainly of open-source samples. More realistic results would undoubtedly be achieved with standardized acoustic recordings and measurements in the field. Furthermore, we are unaware of any good open-source samples of an air cab, so we used the sounds of an octocopter in the study. The modeling of the samples for the simulation is based on the possibilities of sound representation in the game engine and the subjective assessment of experienced drone pilots. An exactly realistic simulation of drone sounds would be much more complex, and more parameters would have to be considered, such as wind conditions or the effect of building and ground materials on sound reflection. However, this study aimed to give an approximate impression of drone traffic and depict various aspects. In addition, the small scale allowed the researchers to test the pedestrian simulator for the first time to investigate drone acceptance. In possible future studies of a larger scale or with a more explicit focus on measuring the auditory impression, sound modeling should be given more space and improved. Another shortcoming might be that participants stayed longer in some scenarios than in others. Consequently, it must be considered that this affected the study's outcomes entirely. Finally, the sample size was small, and participants were very experienced and informed about UAS. The overall attitude toward UAS in the sample is relatively positive. However, in the simulation, participants did not only positively perceive UAS traffic but also reported many disruptive aspects. Due to the small sample size, the results of the Friedman test must also be interpreted with caution. Non-parametric tests, as such, already have a lower statistical power than parametric tests. With a small sample, this power is reduced even more. This must be considered when interpreting the significant results. It must also be mentioned that, due to the study design, the results of the Friedman test alone only reveal a little. They show that specific scenarios differ statistically significantly but do not explain why this is the case, as various factors such as flight altitudes or drone types were not measured in isolation. The interviews provide a more detailed impression of possible reasons, and it, therefore, makes sense to consider the various results from the study in combination. The interviews in the study proved valuable in gaining a deeper understanding of multiple acceptance factors and showed the great added value of qualitative data collection.

6.2 RQ 1: which factors determine acceptance of UAS flights in urban environments?

This simulation study used an explorative approach to investigate how people experience drone flights in four different urban areas. Various factors were identified that influence the acceptance of urban drone traffic. Some results are also consistent with observations from previous studies. It is clear from this and other studies that the acceptance of drones is multi-layered and that various aspects contribute to it. To depict these different aspects in a compact form, a path diagram was developed based on this study's findings and previous research. This diagram is shown in Fig. 13. The acceptance of drones (referred to as UAS in the diagram) is the target variable on the far right of the diagram. The chart involves different stimuli factors that can affect people in the context of drone traffic, as represented by the green boxes. The large blue box represents people and how they perceive and experience different stimuli and react to them. People can perceive certain benefits and risks, or some stimuli can cause annoyance. Perceived benefits are also an essential aspect of the Technology Acceptance Model (TAM), which generally describes acceptance factors of technological systems [29]. Knowledge about drones and experience with drones can also determine what people think of them. The direction in which these different aspects are pronounced ultimately determines acceptance. This is shown by the arrow pointing from the blue box to the "acceptance box" in white. Arrows indicate relations and their direction. The term "relations and directions" is meant here in a descriptive sense based on previous findings. It is not based on statistical analyses such as correlation or regression analyses. The following section will provide a detailed description of the path diagram.

The environment in which drone flights take place is a significant factor in shaping public perception. In this study, participants experienced UAS flights in various urban settings, leading to the finding that UAS flights are more tolerable in certain city areas. They are more acceptable in industrial or business parks and city centers than in residential areas and parks. This finding is supported by the participants' feedback on their experiences in different scenarios. They expressed the most discomfort in the residential area, while UAS flights were least disruptive in the industrial region. Therefore, the environment directly influences acceptance in the diagram. It is also closely linked to noise. The interviews revealed that UAS flights are more expected in industrial parks, and the UAS sound is less disturbing due to the existing noise in such areas. This was also observed in the experiment of Gwak et al., where a higher loudness of UAS was perceived in an environment with low road traffic compared to high-traffic soundscapes [6].

The use cases of UAS significantly influence the perceived benefits and risks, thereby affecting public acceptance. Study results indicate that public applications of UAS are more acceptable to people than private or commercial ones. This finding is also supported by previous research [1, 3]. In the interviews, participants predominantly discussed various use cases in a positive light. This could be attributed

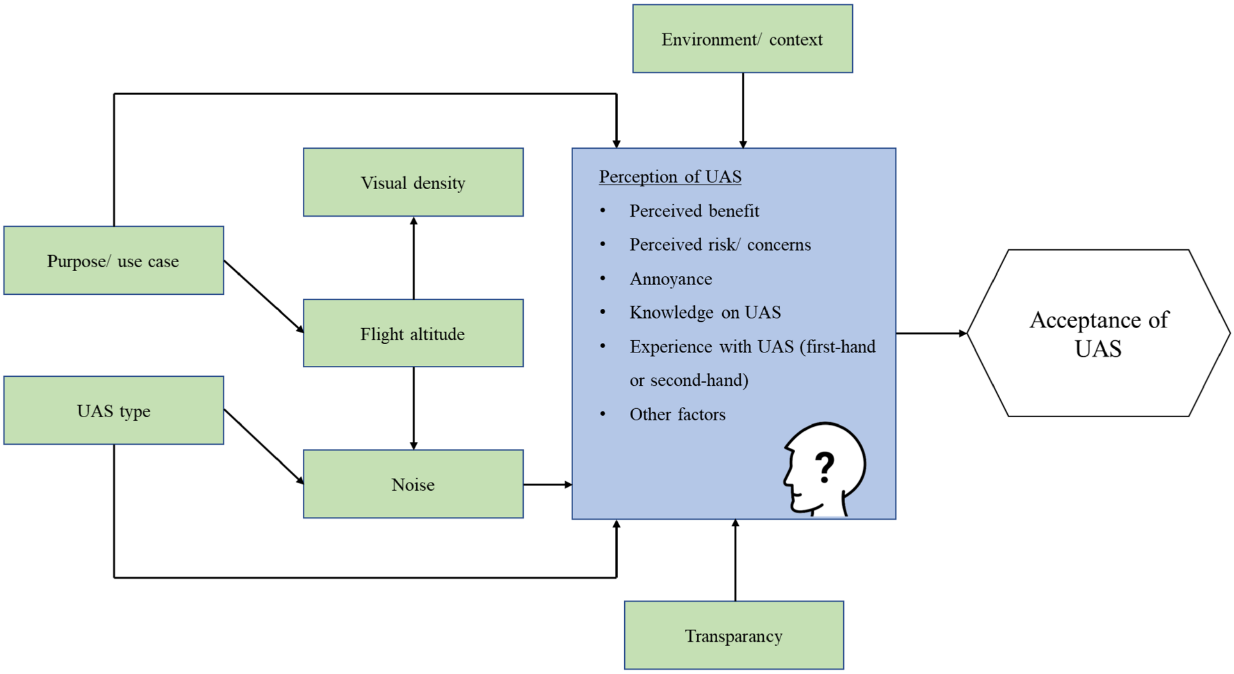


Fig. 13 Path diagram of UAS acceptance based on the study findings and previous research

to the fact that most of the sample is well-informed about UAS and has already had experience with it. Evidence from the literature shows that people who do not use UAS are more concerned about privacy or flights over their property [30]. Moreover, the higher the acceptance of different use cases is, the more people are informed about the benefits and risks related to UAS [31]. Therefore, knowledge and experience on UAS directly influence people's attitudes in our path diagram. Another factor directly related to acceptance is transparency. This can, on the one hand, mean that developers, researchers, or public agencies are transparent in providing information about UAS to society. Therefore, it is connected with knowledge and experience in the diagram. On the other hand, transparency can refer to the purpose of UAS missions. In this study, some participants were bothered by the fact that the intention of UAS was not always clear. Thus, missing transparency might reduce the acceptability of UAS. The purpose of small UAS was significantly often not recognizable to the participants. In addition, because small UAS can be equipped with cameras, the fear arose among the participants that they could observe people. Privacy concerns have also been frequently mentioned in previous studies on UAS acceptance [1, 3, 32–34]. In an experiment by Chang et al., participants required that UAS should give feedback when filming or taking pictures for more transparency.

UAS type and use cases and flight and mission-related parameters involving visual density, flight altitude, and noise are on the left side of the flowchart. There is a connection between the UAS type and its case, as well as flight altitude and noise. Different missions require different altitudes. Furthermore, the findings of this study reveal that the tolerable minimum flight altitude depends on the use cases. UAS with public missions can fly at lower levels than private and commercial usage. This aligns with the results of a survey conducted by Eißfeldt et al. [3]. Concerning noise, its loudness and sound characteristics depend on the UAS type as there are different sizes and propulsion.

Flight altitude impacts visual density and noise. Noise decreases with higher flight altitude and is less disruptive at higher flight levels. Visual density may be more tolerable when UAS are flying at higher altitudes. In the interviews, one participant expressed that the number of UAS can be more flexible if invisible to people.

6.3 RQ 2: which aspects related to the acceptance of UAS flights in urban environments need (further) investigation in the future?

The path diagram described in Chapter 5.1 (Fig. 13) illustrates that the acceptance of UAS depends on various factors that appear to influence each other to some extent. To give an example, connections between noise, purpose of UAS, flight altitude, and urban environment were observed in this study. The identified factors and their relations can be a basis for future research. It has to be noticed that this diagram is the first proposal derived from this explorative study and previous research. The discovered acceptance factors and their relations need further validation and should be proofed in experimental design studies on larger samples. For this purpose, structural equation models (SEMs) [35] could be formulated, as acceptance seems to be determined by a complex interaction of variables. The core of SEMs are path diagrams created to describe a hypothesized set of variables and relations among them [36]. Hypotheses about relations in the model can be tested using factors, regression, or path analyses [37].

One aspect future research should focus on is examining the impact of experience and knowledge about UAS on its acceptability more thoroughly. The sample in this study was highly experienced and informed about UAS and its possible applications. It would be interesting to investigate whether there are differences between people with much experience and knowledge and less informed people. Moreover, further experiments could measure the effect of providing more information to society on public acceptance. Information about the purpose of a UAS flying nearby may also increase tolerance. Participants in this study needed to be more specific about the intention of the UAS in the different scenarios. Future experiments should, therefore, explore if acceptance changes when people get information about the use case, e.g., via company logos on the vehicle or app solutions similar to flightradar24 [38]. Some participants mentioned that they got accustomed to UAS traffic after a while. Thus, it would also be interesting to consider this aspect in future research.

According to the results, the appearance of the scenery and its expectations affect whether UAS are perceived as disturbing or not. Therefore, this aspect should also be considered in future social acceptance studies. In this study, the chosen urban scenarios of Cremlingen are representative of many small and medium-sized towns in Germany, but they do not portray megacities. Thus, further research should also focus on big-city scenarios with higher traffic densities.

Expanding research on how other road users perceive drones, such as car drivers or cyclists, would be interesting in the following studies. As they move faster, quick and jumpy drone maneuvers might be more surprising and unexpected. Therefore, it should be ensured that drones do not endanger traffic safety. Furthermore, other road users and traffic noises should be added to the scenarios. This study focused only on the appearance and noise of drones. Future studies should map all traffic and investigate how it affects people.

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Data availability Open Access funding enabled and organized by Projekt DEAL. The drone noise samples used in the simulation study can be downloaded under the following link:https://zenodo.org/records/14034260.

Declarations

Conflict of interest The authors have no competing interests relevant to the content of this article.

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