



Crowdsourcing Environment Data with Gamified Augmented Reality Mini-Games

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Remote sensing for observing and recording our surroundings is becoming mainstream. Technologies, such as light, detection, and ranging (LiDAR), are now part of consumer mobile devices and provide a variety of novel interaction opportunities with the environment. Mobile remote sensing also provides affordances for crowdsourcing through location-based applications such as games and gamified systems. While such use cases today are technologically feasible, there is a lack of understanding of how and what kinds of interactions and applications would be both (1) engaging and motivating for users and also (2) maximize the volume and quality of the data being gathered. In this study, we investigate these challenges by developing and testing four gamified augmented reality prototypes that use LiDAR for collecting point cloud data during location-based gaming. Through field testing, interviews, and surveys with 21 participants, followed by reflexive thematic analysis, we identified five themes of dynamics, which exemplify tensions and challenges to designing gamified AR crowdsourcing. The findings primarily point to hazards in design that may undermine user motivation as well as constraints of the environments themselves in facilitating and affording meaningful and rich (gameful) interaction.

CCS Concepts: • **Information systems** → *Mobile information processing systems; Multimedia information systems; Collaborative and social computing systems and tools*; • **Human-centered computing** → **Ubiquitous and mobile devices**.

Additional Key Words and Phrases: Location-based media, augmented reality, crowdsourcing, user-generated content, LiDAR

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1 Introduction

Decision-makers in urban planning, navigation, natural resource management, forestry, and virtual tourism, among others, are looking for ways to collect data from the places and areas they are interested in managing, developing, and/or showcasing [5, 80, 81]. This data can be text-based, image-based, or numerical, and it can be collected through various means, such as satellite or unmanned aerial vehicle (UAV) imaging, on-location sensors, or in-person observations [8, 16, 71]. With the latest advances in hardware and software for image reconstruction and the use of location-based data, the general interest in improving methods for collecting location data has been growing [11, 38]. The success of geo-data-based services such as Google Maps [48] and Pokémon GO [31] has further stimulated interest in exploring the possibilities for gathering such data [57]. In this study, we focus on a particular approach for locative data collection: crowdsourcing, which is defined as involving and motivating laypeople to gather and contribute desired data to a system (i.e., harnessing the wisdom of the crowds) [51, 52].

Location-based crowdsourcing has become increasingly popular as smartphones, satellite navigation, and mobile internet access have become more commonplace [38, 57]. Today, the latest high-end smartphones (such as iPhone models from 12 Pro onward) are equipped with a wide range of sensors that can be used to collect useful geospatial data, with perhaps the most important sensors being LiDAR and camera [57]. Since people carry their phones with them wherever they go, this provides great opportunities for harnessing people's time and expertise to gather data from the real world. However, there are two main challenges here. First, how can we motivate participants to engage in geo-data crowdsourcing, and second, how can we facilitate the data gathering process in a way that we obtain useful data for the purpose [2, 59, 60, 71, 83].

The issue of motivation is multi-faceted, and can be understood through various theoretical lenses [61] such as self-determination theory, which divides motivation into intrinsic and extrinsic motivators [19] or motive disposition theory, which focuses on individual differences in motivation arising from dispositional motives [62]. A recent literature review noted that in addition to motivational mechanisms relevant to most digital products, location-based applications have unique characteristics related to the spatial dimension that should be considered [37]. These can include, for example, users' ability to physically move around, their safety, and where they live. In this study, we approach crowdsourcing motivation, particularly through the perspective of gamification, which is a field of study dedicated to the application of playful elements and dynamics typically found in games in non-gaming contexts [24, 55, 82]. Gamification approaches can provide both extrinsically and intrinsically motivating elements for participants [68], and this approach is often seen as a scalable alternative to more straightforward forms of participant motivation in crowdsourcing, such as simply paying the participants [34, 51, 52].

The challenge of effectively structuring crowdsourcing processes to yield useful data is highly context-dependent and varies based on the specific type of data being collected [8, 16, 71, 84]. For example, measuring the temperature at a specific location requires that relevant temperature sensors be placed in the right place at the right time. Wildlife sightings can be collected through strategically placed cameras or documented and submitted directly by participants [83]. In this study, we focus on collecting point cloud scan data using the iPhone mobile devices' LiDAR-sensors [45]. These sensors enable the creation of point cloud scans of the environment but require users to be in close proximity to the targets they are scanning [78]. An exemplary point cloud scan visualization is provided in Fig. 1. These kinds of scans can be used for multiple purposes, including the mapping of trees and measuring their height [78], creating digital twins of real-world objects such as statues [84] or mapping objects in a broader area, such as a cultural heritage site [88]. The resulting data can then be used for, e.g., virtual tourism and architectural design [85]

or decision-making in the forestry sector. However, in order to obtain this data via crowdsourcing, we need to direct users to points of interest and guide their behavior to gather data optimally. This is a major challenge identified in previous work [57, 78] and something we also investigate in this study.

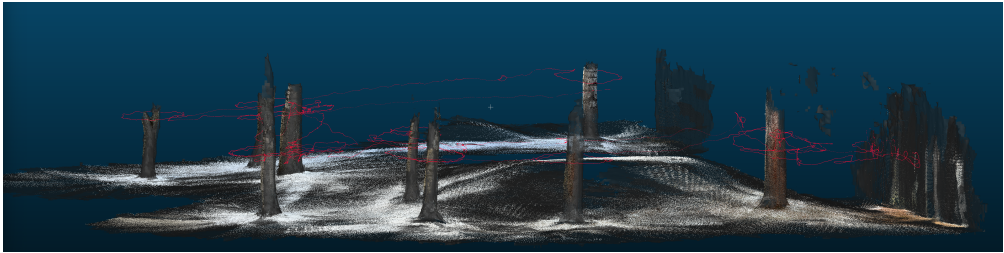


Fig. 1. A visualization of a point cloud scan of a forest environment. Captured using an iPhone 14. Data collected and screenshot captured by the authors.

To explore the dimensions of crowdsourcing (1) motivation and (2) guidance in LiDAR-based geo-data gathering, in this study, we created four gamified LiDAR-based augmented reality (AR) prototype "mini-games", or gamified data collection scenarios, which we invited altogether 21 participants to test and provide feedback on. Through an exploratory study with these prototypes, we investigated the following research question (RQ):

RQ *When designing gamified AR-based crowdsourcing applications that collect point cloud data, what are the key dynamics that influence (1) user motivation and (2) the effective guidance of data-collection?*

To address this research question, we asked all participants to complete a survey after they had tried the four LiDAR prototypes. Ten of the participants also joined us for interviews to provide more in-depth insights. We analyzed the data using reflexive thematic analysis [15], a widely used approach in qualitative HCI research [14]. Through this analysis, we make two key contributions. First, we provide new insights into the dynamics emerging in location-based crowdsourcing with LiDAR sensors that can be helpful for designers looking to create such systems. Second, we contribute new empirical knowledge to the scholarship of locative crowdsourcing. This paper is structured as follows: we begin with a review of the background research on location-based crowdsourcing, augmented reality (AR) games, and gamification. Next, we present our empirical research design, including the four prototypes, data collection, and analysis. Finally, we present our findings organized by key themes, followed by discussion and conclusion.

2 Background

2.1 Location-based Crowdsourcing

Location-based crowdsourcing has seen success in both academic field experiments (see, e.g., [52]) as well as practice through examples such as Pokémon GO, Ingress and OpenStreetMap [10, 23, 34]. While various map platforms still involve expert data generation, automatic data gathering via sensors, and systematic mapping by professionals, crowdsourcing has now become a prominent part of modern map information systems [51]. Crowdsourced information supports applications ranging from urban planning [43] to detecting optimal routes and navigation barriers [21, 86], with data collection ranging from passively generated data to active contributions [54].

In academia, location-based data collection processes are typically discussed in two categories: (1) remote sensing and (2) close-range sensing, where the two are distinguished from each other by

the distance between the observing device and the target [18]. Remote sensing typically involves large-scale bulk collection of point cloud data from afar (e.g., satellite imagery), while close-range sensing focuses on in-situ observations characterized by higher precision and accuracy [18]. While both methods collect data in non-invasive ways through cameras, LiDAR, and other sensors, they serve different purposes and scales [42]. The focus of our work is on close-range sensing [57]. This approach can be particularly useful for capturing more details from the environment [78] or for making notes of dynamic elements in the environment [83]. For example, in nature, there are seasonal changes in plants, trees, and mushrooms, as well as in the movement patterns of wildlife. Such details might be difficult to capture with satellites but can be obtained through close-range sensing [18]. As opposed to manually making close-range observations by driving around with cars [5], crowdsourcing harnesses the wisdom of the crowds by empowering them to make observations and contributions [51, 52].

Examples of popular crowdsourcing-focused commercial products include Wikipedia [6, 33, 39], Amazon's MTurk platform [4] and in the realm of location-based products, OpenStreetMap [17, 23], iNaturalist [7] and Niantic's Wayfarer platform (previously known as Operation Portal Reckon) [34]. Out of these, Wikipedia and OSM are based entirely on users' intrinsic desire to contribute. In MTurk, participants are rewarded with monetary compensation, and with the Wayfarer platform, participants can get in-game benefits such as obtaining a new interactable point of interest to their desired location, getting their name immortalized as part of the game world or accumulating points to a badge that allows them to show off to other players [34]. The heterogeneity in successful motivational approaches in crowdsourcing endeavors is evidence that crowdsourcing in itself is a valid approach that is able to produce high-value products and services. In some sense, also the open-source software communities that produced products such as the Linux kernel and GNU software are evidence of the potential of crowdsourcing [77]. Unsurprisingly, advances in consumers' smart devices and internet connectivity have sparked interest in exploring new frontiers in spatial crowdsourcing [78].

There are examples where crowdsourcing initiatives backfire when their motivational mechanisms produce unintended outcomes [27, 89]. A notable example occurred when the popular location-based game Pokémon GO switched from using Google Maps to using OpenStreetMap, prompting Pokémon GO players to make malicious edits to OpenStreetMap in order to manipulate Pokémon spawn points [27, 89]. This example also highlights the inter-connectivity of modern geographical information systems, where projects using open crowdsourced resources may inadvertently motivate people to contribute to related crowdsourcing projects, not always in a positive manner. Because of this, it is important to design location-based crowdsourcing efforts with care, particularly when adding motivational layers, beyond users' intrinsic desire to help, to boost participation [27]. Therefore, next, we discuss the approach of gamification and AR gaming in crowdsourcing.

2.2 Gamification and Augmented Reality Games

By incorporating gamification into crowdsourcing processes, it is possible to guide and motivate users, not only improving engagement but also improving the accuracy and frequency of the data collection [51, 52]. Gamification has been widely applied across domains such as education, cultural heritage, and rehabilitation, where it has demonstrated its potential to sustain engagement and improve learning and behavioral outcomes [24, 30, 32, 41, 53, 55]. For location and environment-related interactions specifically, AR can further enrich user experiences by fostering interaction with the local physical content [49]. Examples include systems where the environment is visualized to participants as it is, examples where it is augmented with historical or cultural layers, or where it's transformed through AR into a fictional new layer of reality [8, 9, 26, 44]. This augmentation of

the local experience has many benefits for crowdsourcing, specifically. Morschheuser et al. created a location-based game augmentation for detecting parking spots and implemented a layer of social competition on top of the activity, boosting user motivation [52] and companies such as Niantic have made entire games around crowdsourcing problems, with perhaps the most well-known example being the game Ingress where users would submit points of interest following specific criteria, which would then be added to the game map [34, 72, 73]. This data was then used as a backbone to create the world's most popular location-based AR game to date, Pokémon GO [8, 38].

The addition of LiDAR sensors to consumer handheld devices now enables more precise AR experiences, as LiDAR enables the real-time detection of surfaces, providing the technical capability to position AR content more realistically in the real world [28, 57]. However, LiDAR does have limitations, e.g., in terms of effective range, and it can struggle with uneven surfaces. In addition to these limitations, a larger issue is that LiDAR sensors are still new, and most consumer mobile devices are not shipped with these sensors [79]. This narrows down the market and directs developers' attention towards alternative solutions, such as purely camera-based mapping and camera-based AR [84]. Relatedly, there has been some work on gamifying the crowdsourcing of images, which, through photogrammetry techniques, can be used to construct 3D models [56, 63]. Recently in the field of locative crowdsourcing there has been work on "3D scanning", which is a term used to describe taking a moving video of an object [84]. Through Gaussian splatting, such video footage can be used to construct a 3D model of the environment, and in some cases, even for geometry editing, and physical simulation [87]. The advantage of LiDAR over these approaches is that it (1) affords more precise measurement of objects, and (2) works better in poor lighting situations. It is also possible to combine the two for even better accuracy and structural consistency [64]. Additionally, LiDAR allows the capturing of large areas without the need for resource-intensive image processing, such as would be required with photogrammetry solutions. Overall, LiDAR sensors can be seen as an up-and-coming technological enabler of more realistic AR experiences [83], and particularly suitable for crowdsourcing tasks requiring precise data, e.g., on tree heights [57].

The relationship between gamification and AR appears to be a complex one. On the surface level, one of the highest-grossing mobile games of all time, Pokémon GO, is an AR game [24, 66]. However, previous empirical research suggests that players mostly ignore the camera-see-through AR mode of the game, only engaging with it occasionally, while the bulk of the playing happens through interactions with the map interface and related mini-games (catching, hatching, trading raids, Team GO Rocket battles...) [35]. In Figure 2 we display two popular location-based AR mini-games, both of which only minimally utilize the environment in their design. This suggests that in practice, there is room to study how to create more engaging AR experiences. Indeed, while scholars throughout the years have projected major increases in AR adoption (see, e.g., [65]), major AR game investments such as Minecraft: Earth and a location-based AR game [75] in the Witcher franchise [74] have quickly gone defunct after launch. These developments raise questions about whether AR games and gamified AR are fundamentally non-engaging to wider user populations. Scholars have pinpointed the clunky user experience of a mobile phone's camera-see-through AR as one possible culprit [35], and sales figures for head-mounted AR displays, such as Apple's Vision Pro, show great promise [47]. Reportedly, one struggle that head-mounted AR displays now face is the lack of content [47], which calls for increased efforts on the research and development front. Although this study's focus is not on head-mounted displays, we aim to contribute to the field of AR design by exploring dynamics in LiDAR-based AR scenarios.

Collecting data via gamified location-based crowdsourcing raises questions regarding ethics and participant safety. Previous scholarship on the ethics of crowdsourcing practices has highlighted these issues as complex and multilayered, with no clear and easy go-to solutions [70]. Issues such

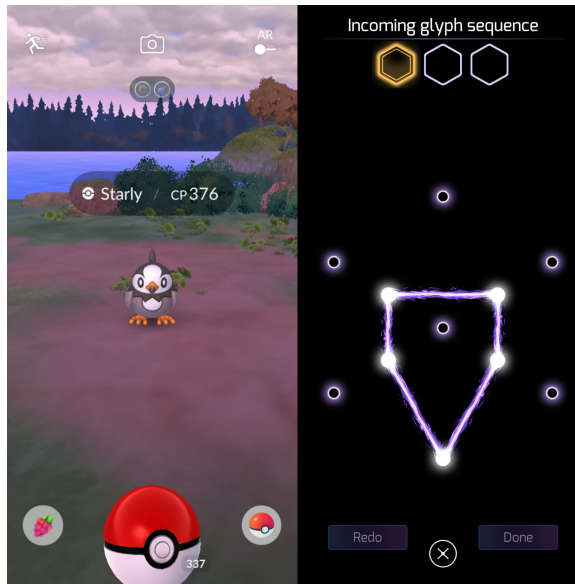


Fig. 2. Screenshots taken by the authors from mini-games in location-based games: Pokémon GO (left) and Ingress Prime (right).

as fairness, transparency, contributors' relationships, freedom, and boundaries need to be acknowledged [70]. In the context of location-based crowdsourcing in particular, participants' safety must also be considered [46]. Moreover, there have been cases where location-based games have inadvertently motivated people to vandalize resources such as open map databases [27]. To avoid unwanted outcomes and ensure that contributors are treated fairly, crowdsourcing solution designers need to constantly monitor how their systems are used in practice [1]. In our empirical study, the focus was not on the ethical issues beyond ensuring compliance with institutional ethical guidelines for research. However, the topics of ethics and contributor safety remain important considerations when developing an holistic, practical implementation of LiDAR-based AR crowdsourcing.

3 Materials and Methods

3.1 Augmented Reality LiDAR Prototype Design

We designed and implemented four prototype applications that could be used as probes [3] to explore the research question. All four applications used the iPhone's LiDAR sensor to detect surfaces and position content onto those surfaces using distinct interaction mechanics specific to each game concept. At the same time, the generated point cloud scans were recorded, stored on the device, and then later transferred to external storage. In our design, we focused on in-situ AR experiences, and did not involve location data or satellite navigation in any of the four AR scenarios. The scenarios were implemented using the Unity3D engine and then compiled for iOS devices. The scenarios were tested locally by the researchers to identify and address any potential bugs or usability issues that could be found. Next, we present and briefly describe these prototypes.

The first design is a spider-catching game where the player uses a spider vacuum to collect spiders that spawn into the environment. The spiders are designed to climb on surfaces like walls or tree trunks. To catch spiders, the user must move their mobile device around, press the screen to activate a vacuum, and keep the mobile device pointed at the spiders. Through this scenario, we

ensure that players not only keep their device stationary but also move it around in a way that maximizes the spatial coverage of the collected point cloud data. This way, the scenario guides users to (1) walk around the area where they are playing and (2) move the device both horizontally and vertically. Furthermore, catching spiders can be considered a potentially fun activity in itself, something that users may wish to engage in voluntarily. A screenshot of the spider-catching game is provided in Figure 3.



Fig. 3. A screenshot of the first GamiLiDAR design: the spiders.

The second design is a spray-painting activity, where the user can spray virtual paint onto any surface. There is no specific task in this design, and as such, it was created with artistic expression and freedom in mind. The purpose of this design is to leverage participants' desire for autonomy [68] and self-expression. At the same time, the movements required to draw things on surfaces require users to move their mobile devices, effectively scanning the environment in the process. We anticipated that this design would result in less movement around the immediate environment, but more careful manoeuvring around particular objects, as participants would be engaged in painting. We provide a screenshot of this design in Figure 4.

The third design is a game where the player pilots a flying spacecraft (which we call a UFO) that can be used to collect "robotic spiders" and "sensor trucks" from the environment. The collection targets get sucked into the ship once they enter its area of effect. This design differs from the spider mini-game in that the UFO is controlled via an on-screen joystick, and surfaces detected by the LiDAR sensor impact its movement and position. In the spider game, the mobile device had to be pointed at the spiders, whereas in this UFO game, the device and the UFO had to be aligned to collect the game objects. This design was meant to emphasize the intrinsic need for competence [68]. We anticipated that the on-screen joysticks would reduce the physical movement of the device itself whilst encouraging participants to explore their physical surroundings more by moving around on foot. We show a screenshot of the design in Figure 5.

Finally, we had a fourth scenario, which was simply about visualizing the point clouds as they were generated. This version was not a gamified solution per se, but rather, a visualization of the scanning activity. The idea behind including this in the experiment was to enable the participants to compare and contrast a straightforward visualization with the more gamified version. Since participants could see the point cloud being formed in real time, we had no prior design assumptions



Fig. 4. A screenshot of the second GamiLiDAR design: Painting

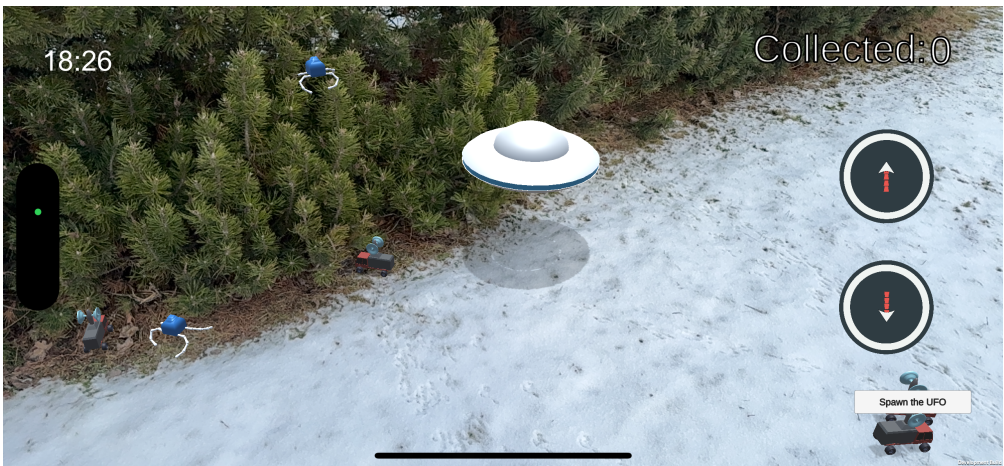


Fig. 5. A screenshot of the third GamiLiDAR design: UFO.

regarding how it would motivate the participants to move. A screenshot of this approach is provided in Figure 6.

These four prototype designs collectively represent diverse approaches to gamifying LiDAR-based data collection with AR, each emphasizing different user interaction patterns and engagement mechanics. These prototypes provided participants with concrete examples of how AR experiences could effectively facilitate LiDAR-based data collection. Following iterative implementation, testing, and refinement by our research team, we proceeded to systematic data collection with participants to evaluate these approaches against our research objectives. Next, we describe the data collection process.

3.2 Data Collection and Participants

Our research participants (N=21) were recruited from Japan and Finland. In the recruitment process, we followed purposeful sampling [76], which, in our case, emphasized having some level of diversity



Fig. 6. A screenshot of the comparison version where users could simply see the point cloud scan as it was being generated by the mobile device.

in terms of education level, age range, AR experience, and LiDAR experience. Thus, the sample is not representative of any particular group but should be understood as a collection of informants with varying backgrounds and levels of expertise concerning LiDAR, gamification and location-based crowdsourcing. This sampling served our aims of exploring the dynamics in locative LiDAR-based gamified crowdsourcing, since the field is rather new and we only had a crude understanding of the field prior to this study. The research was contextualized in the context of scanning forests following previous similar work [57, 78] and to provide participants with a practical setting and a business use case to consider when interviewed about the dynamics in this design space.

From the participant pool ($N=21$), we asked volunteers to join follow-up interviews for additional insights until the authors collectively determined that saturation had been reached, with no new significant themes or insights emerging from subsequent interviews. The demographic data of the participants is given in Table 1. All participants joined the experiment voluntarily and gave their written consent to use their responses in research. The first 15 participants joined an on-site experiment day held in Japan, while the remaining six participants joined the experiment in Finland. All participants ($N=21$) completed an online survey and provided signed consent forms for research data usage.

Figure 7 summarizes the overall data collection process. To ensure that participants could understand and reflect on the concept of crowdsourced, gamified AR LiDAR data collection, a 30-minute seminar was conducted for most participants, with individual introductions provided for the remainder. In the seminar, this novel approach to data collection was explained, and there was time for questions, discussion, and comments. Participants were shown point clouds from both professional devices and iPhone LiDAR sensors, heard about how location-based gaming motivates players to play in nature [36], and learned about gamification elements of location-based crowdsourcing [52, 57].

Next, it was important that the participants could try out the prototype applications themselves in an outdoor area with trees. So, after the introduction, participants were divided into four groups, each with an iPhone device, so that testing of the AR scenarios could be conducted simultaneously to minimize wait times. A researcher accompanied each participant to answer questions and help with any technical issues. The four prototypes were designed to last for 1.5 minutes, but in a few

Table 1. Demographic information of the participants. We had 15 participants during a seminar day in Japan and 6 additional participants joining the experiment in Finland (total N=21).

#	Gender	Age	Education	AR expertise	LiDAR expertise	Follow-up Interview?
1	Male	50-59	Master	little	little	yes
2	Male	50-59	Master	little	none	yes
3	Male	50-59	PhD	moderate	little	
4	Male	20-29	Master	moderate / high	none	yes
5	Female	20-29	Bachelor	moderate	none	
6	Male	20-29	High school	high	none	
7	Male	20-29	Master	moderate	moderate	
8	Female	20-29	Bachelor	little	none	
9	Male	20-29	Bachelor	moderate	none	
10	Male	20-29	High school	none	none	
11	Male	20-29	High school	none	none	
12	Male	20-29	Bachelor	none	none	
13	Male	20-29	High school	none	none	
14	Male	60-69	PhD	moderate / high	none	yes
15	Male	20-29	Bachelor	moderate / high	none	
16	Male	20-29	Bachelor	moderate /high	moderate	yes
17	Female	30-39	Master	little	little	yes
18	Female	32-42	PhD	none	none	yes
19	Non-binary	20-30	Masters	moderate / high	little	yes
20	Female	50-59	Masters	none	none	yes
21	Female	30-39	Masters	little	moderate / high	yes

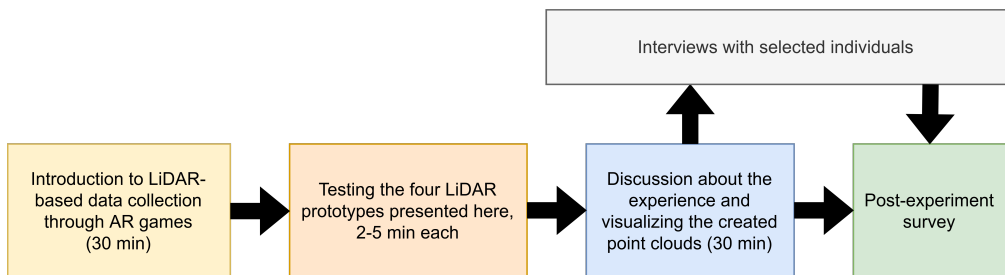


Fig. 7. An overview of the experiment design.

cases, participants could replay a scenario or, due to bugs, play it for longer (up to 5 minutes). Testing of the four gamified AR scenarios took place in a small wilderness area adjacent to the

seminar location. While at the test site, the participants were free to ask questions and encouraged to think-out-loud as they proceeded to try out the prototypes at their leisure.

After the participants' hands-on testing of the prototypes was completed, we reconvened with the participants back at the seminar location for a group discussion. Here, they were shown selected point cloud scans they had just created. The purpose of this step was to visually demonstrate to the participants what happened "under the hood" as they engaged with the gamified LiDAR scenarios and to offer them perspectives on how the point cloud data accumulates in the background. As mentioned previously, selected participants were also invited to one-on-one interviews. These interviews were structured based on the following themes: (1) thoughts on the data collection process; (2) advantages of this kind of approach; (3) potential hurdles of this kind of approach; (4) practical use and business value; and (5) future directions. All interviews were recorded and later transcribed in preparation for data analysis.

Finally, the last step of the data-gathering process involved distributing an online survey form for participants to complete. As the seminar and interviews took place in two different countries, the survey was given to participants in English or their native language. The survey was translated into the native language of the two countries by a native speaker author. The survey questions are presented in Table 2. The survey was kept brief, and the questions were simple to prevent survey fatigue and to ensure that all participants completed the survey.

Table 2. Survey and interview questions

#	Question
1	Which one of the four scenarios (spider, UFO, paint, point cloud) was your favorite? Why? Please explain
2	How would you improve the AR game experience? Provide as many suggestions as you can think of!
3	Do you have ideas on how to improve the fit of the AR scenarios into large-scale crowdsourced data collection?
4	Is there anything else you would like to share?
5	Demographic questions (age, gender, education, experience with AR and LiDAR technologies, and participant number)
Interview questions (semi-structured)	
6	What is your opinion and view of this work we are doing?
7	Do you think it has any real-life application potential?
8	What kinds of data could we collect with this? In what cases would this approach be suitable?
9	Who would pay for the data we collect?
10	Who would participate in this if it were available on Google Play and App Store? Would you?
11	Do you see any fundamental or outstanding issues with this approach?
12	What would you say are the most critical aspects to work on or improve next in this kind of data collection?

3.3 Data Analysis

To address the research question (RQ), a reflexive thematic analysis approach was used for the data analysis [15]. The survey and interview responses were analyzed together. Additionally, observations made during data gathering and informal, unrecorded discussions during and after

data collection influenced the interpretation of the data. The analysis proceeded as follows. First, the researchers conducting the analysis read through the transcriptions and listened to the recordings, taking notes and marking down any interesting dynamics they encountered. The notes focused on elements relating to the participants' motivation, interactions between the LiDAR AR games and the real-world environment, and how the prototype systems could best guide users toward gathering useful data. This process partially overlapped with data collection. During the initial analysis, it became apparent that additional interviews were needed to improve the quantity, richness, and reliability of the data. Consequently, more interviews were conducted in Finland, and key observations were extracted from them as well.

Second, following the reflexive thematic analysis approach [15] the authors engaged in interpreting the material by connecting similar findings and collating them into broader themes. This step was iterative, as the themes were developed and refined throughout the analysis process. For example, we removed a theme that was heavily tied to our prototypes since we did not consider such technical details regarding usability issues to provide universal value in this space. We also combined some themes together and added a new one. As a result of this process, we ultimately identified five distinct high-level themes, which we discuss in the next section.

Third and finally, we returned to the data and coded the quotes to match the themes following the example provided in the work of Papangelis et al. [58]. We extracted specific quotes and connected them to specific themes. We then began elaborating on the themes by reflecting on the quotes in light of our evolving understanding of the topic. We used direct quotes from the participants (either from the interviews or the survey) to support the presented arguments. This iterative process, where the content was refined within the themes, continued until all authors were satisfied with the interpretation of the data. Finally, to report the findings, we translated relevant quotes into English.

4 Findings

4.1 Theme #1 Game Scenarios and Gamification Can Undermine Users' Intrinsic Motivation to Contribute

In general, the participants had positive feelings about the game scenarios and the idea of crowd-sourcing data in the presented manner. For example, the participants stated that *"gameplay was fun and exciting"* (P19) and suggested various ways to improve the mini-games (e.g., *"It might be more fun to mix in rare spiders or spiders with high points, such as golden spiders, among the spiders."* (P7)). However, we found evidence of individual differences in which of the four scenarios the participants enjoyed the most. In fact, all four scenarios were mentioned as the favorite by a minimum of two participants, each providing various arguments to justify their preference. Below, we provide two exemplary quotes.

"Spider. It was fun and intuitive to play. The spider's movements looked like the real thing as it walked along the actual ground." (P6)

"The paint part was interesting. This is my favorite because it feels like it's about writing into the real world, it's artistic, and it stimulates my creativity." (P9)

Participants also enjoyed the mini-games for different reasons, and they engaged with them in different ways - some moved a lot while playing, while others remained mostly stationary. While most participants appeared excited and made positive remarks about the mini-games, some (e.g., P1, P2 and P17) were less enthusiastic about the core idea of gamifying the data collection in this manner. For example, P2 stated the following:

"The games didn't draw me in. It wasn't too exciting. Like it wasn't something I would do on my free time." (P2)

When asked further about their lack of excitement, P2 and P17 both mentioned that they do not play games in their free time, to begin with, but were, in fact, quite interested in the idea of mapping nature and of the public helping out through citizen science. P2 mentioned that he would gladly help collect nature data (*"Yea, I actually enjoyed the mapping of the tree part, I like walking outside"*) but would prefer if he could do it by having some necklace or other type of wearable device on him for data collection where he could then solely concentrate on nature and not some additional technology. Similarly, participants P3 and P17 also raised the idea of a mismatch between collecting forest data and incorporating technology into forests, as well as a potential mismatch between engaging in a serious activity (mapping the real world) and coupling that with something fun and cartoonish. The following quotes illustrate this.

"In the UFO game, if there is a metaphor of picking up trash in the forest, it might help raise awareness about environmental conservation." (P3).

"I know some people who would [want to engage with these apps while in nature], you could certainly engage some people with this, but I wouldn't want to engage with these kinds of apps while in nature." (P17).

It was therefore clear that some people who would otherwise be interested in participating in a citizen science initiative by walking in nature might be alienated by the gamification elements. Furthermore, for some, there was a mismatch between the game elements and the collected data was disturbing. For these user groups, it may be prudent to offer a user experience centered around a non-gamified scanning system or to align the gamification elements more closely with the surrounding environment and data collection objectives. Furthermore, all developments that could help participants visualize their contributions and make them more concrete would likely be well received by, e.g., P1 and P21, as illustrated by the following quotes:

"I understand the aim of the game is not to catch spiders, but to map the trees. Perhaps at the end of each activity, you could have something of the output of the mapping exercise. (...) Something like a 3D image of [what was created]." (P1)

"I find it quite interesting (...) to be able to see the points cloud and if you could, for example, after the experience you [could] download your own point cloud and do things by yourself that would be also pretty [nice]." (P21)

4.2 Theme #2 Physical and Environmental Constraints Remain Fundamental Hurdles

When discussing the practical applicability of LiDAR-based crowdsourcing, participants mentioned physical, environmental, and cultural constraints. There were some constraints, e.g., in the game design, that could be addressed relatively easily (e.g., P3, P5, P8, P9), but others were more fundamental and not easily addressable. Many of the physical and environmental constraints related to our chosen context of nature, where participants noted that people need some form of transport to get to the most remote locations where we might wish to get data from, for example a car or a bicycle, and that it takes a lot of effort to travel a long distance to gather desired data. For example, P4 was skeptical about whether the prototype games would be able to provide a strong enough motivational pull for participants to travel to the most remote places and suggested additional mechanisms, such as hidden on-site QR codes, to increase participants' motivation. However, elements such as the lack of road or path infrastructure, dangerous terrain, sealed-off areas, and the time commitment required will likely remain major obstacles to obtaining data from most remote places, as stated, e.g., by P4 and P14. Participants also mentioned that there could be some social or cultural constraints. For example, P14 noted the following:

"When you go out and do these science-public connections, quite often it's a lecture. To me it's like pontification. We're telling you this information. It's not a two-way interaction. We are the authority, this is what we're telling you. I find this the wrong approach." (P14)

Behind this quote lies an ethos that in crowdsourcing and citizen science projects, it is important to avoid constraining participants and instead harness their wisdom. This relates to the first theme, where P1, P2, and P17 expressed their desire to contribute to the project on their own terms instead of engaging with scanning on the developers' terms through the created prototypes. It also relates to the fourth theme of participant empowerment, where needlessly strong guidance for data collection can, in fact, hinder the participants' ability to make the best use of their talents. However, addressing the constraints of the application is not a straightforward endeavor, as it can lead to having non-unified data (P4) and can create a more convoluted user experience.

In addition to the already discussed constraints, in some areas, a social stigma may be associated with moving around and playing AR games in public. In other places, it could be dangerous to move around visualizing the world through the screen of a mobile device as experienced, e.g., by P5: *"I almost hurt myself."* Participant 8 continued:

"It may be dangerous to concentrate too much on the game, but it would be fun if there was an element of enjoying nature more (running around, walking around). I like walking and enjoying the sounds of nature, wind, and air." (P8).

Thus, while participants were excited about the application of this system in forest and nature contexts, they wished for a less constraining implementation. Furthermore, it remains unclear how well intensive AR game-based crowdsourcing would translate into busy urban spaces, where users are constrained not only by terrain, traffic, and other factors, but also by other people, social norms, and societal expectations of behavior in public spaces.

4.3 Theme #3 Users Seek Meaning, Justification and a Sense of Purpose in Participation

While many participants (e.g., P6, P7, P9, P12, P13, P19) expressed that the individual mini-games were fun, an equally large number (e.g., P1, P2, P4, P14, P16, P17) raised questions regarding the meaningfulness of the mini-games. These comments appeared to stem from a sense that the mini-games were disconnected from broader goals, themes, narratives, reward structures, and purposes other than the data collection. A few participants addressed these remarks in the context of individual games, such as the painting mini-game, as follows:

"And the painting and the color, I didn't see the point." (P1)

"Unless you've got a point, or a purpose, I don't see the point in just waving a brush back and forth on a tree." (P14)

Some participants experienced a misalignment between the expected way the mini-games would play out and the actual implementation, which, in their case, resulted in questions regarding the overall reasoning behind the AR LiDAR prototypes. These concerns arose either from the way individual mini-games were implemented or from the lack of an overall purpose. Related comments are provided below:

"With the UFO, the velocity vector does not decrease over time. You are not controlling it precisely, you are throwing it like a frisbee. This kind of game design can have it's place, but I don't think this is the place" (P4)

"But what's the point? What am I like doing here?" (P16)

"I kind of imagined those data points now being transformed into some digital repository (...) I would imagine that that data could then be repurposed back into that tree maybe"

in a digital version, or [creating] a mapping of that tree somehow. Thinking about that made [the activity] to me made way more interesting." (P14)

The final comment from P14 highlights how the participants were actively looking for a purpose, not only within the individual mini-games but also outside of them. They were not satisfied with just a short burst of "fun" but were looking for reasons why they would engage with the mini-games, what value they were adding to the crowdsourcing endeavor, and how their contributions were helping. Thus, there is a need to provide additional layers of meaning both on the game aspects and the crowdsourcing aspects of the mini-games. These additional layers of purpose could be concretizing the contributions (P14) or having, for example, story and narrative structures. In addition to these suggestions, the participants discussed that a misalignment or poor precision of the AR content could lower the sense of meaningfulness by lowering the sense of immersion. Regarding this, P16 explained as follows:

"For there to be a real-world use case for this, it needs to be precise. (...) The game needs to complement the real world, instead of being at odds [(misaligned)] with it." (P16)

As an example, P16 mentioned that the Swedish furniture company IKEA, which has an app for precisely placing furniture in a room using LiDAR, and that, similarly, LiDAR-based AR games should make use of the environment more precisely. To demonstrate this, he said that in the spider mini-game, the spiders would often disappear or get stuck on surfaces. This was something that clearly bothered other participants, such as P4, who stated: *"But it's to be expected from a prototype at this stage of development."* The seamless integration of AR into various surroundings can be considered a major technical and design challenge, yet it appears to be quite important for creating an illusion of purpose.

4.4 Theme #4 Contributors Desire Having a Selection of Ways to Participate

A major theme that emerged in both the interview and the survey data, and which is linked to the second theme, was participants' experience of not having the ability to contribute data on their own terms. For example, P1 and P14 provided suggestions on ways to broaden the scope of contributions so that participants going to nature would not only be providing point cloud scans but could also engage in other data collection activities, such as recording signs of wildlife that they encounter or providing free-form feedback and information on the locations they visit. The following quotes represent these ideas:

"One idea maybe for the distant future would be to have like an add-on with which you could record bird sightings and animal sightings and stuff like that." (P1)

"It's that interdisciplinary nature. If we could do [interdisciplinary collaboration] and reach out to the community, and bring their knowledge to the project. And I say bring their knowledge, rather than us taking to them. I think these kind of projects work out to be much more beneficial to the community." (P14)

Therefore, instead of creating an application for a single purpose (collecting point cloud scans from natural areas), the applications should empower participants to engage more holistically with their surroundings and perhaps also contribute to a broader range of data collection. For example, if a participant suddenly encounters the song of a rare bird, they may have the opportunity to start recording sound instead of engaging with the LiDAR-based data collection. Having more freedom in deciding how to contribute and what to do could also be empowering and motivating in itself. This would better enable users to align with the environments they are in, boosting a sense of purpose and immersion. The following quote supports this.

"I think this should allow people to explore the nature themselves, you know, support being in nature. Now, I think it limits, [pause] it narrows down the experience." (P17).

Thus, increasing users' range of actions can have positive effects through multiple mechanisms. First, it can increase the users' sense of autonomy, making them feel more in control and, through that, boosting their intrinsic motivation. Second, it can empower participants to make the best use of their skills and abilities. As there are individual differences and the real world can present surprising and unexpected events, offering a wide range of crowdsourcing contribution options enables users to select optimal tools and processes to best document the things they encounter.

4.5 Theme #5 Unclear Goals and Feedback Undermine Engagement

Issues hindering the user experience, such as bugs, tended to have a negative impact on players' overall enjoyment as well as trust in the developer, a finding that the data also reaffirmed in this case. While the participants did not pay excessive attention to bugs in the interviews or survey responses, some did mention bugs that they found. Additionally, participants also pinpointed various other usability issues. These included the lack of clarity regarding the purpose of the mini-games as well as confusion regarding the overall aim of the activities. The following quotes illustrate these views:

"I wasn't sure if the aim was only to get the [tree] trunk, or get the trunk and the leaves of the trees and the branches as well." (P1)

"It was easy to just stay in one place. I'm not sure if the goal for me was to move around, I was trying to think about the goal of the app vs just the goal of the game." (P2)

"In each game, I felt that the goals to complete were difficult to understand, so I thought the goals should be made explicit, even if it was just text." (P13)

While the clarity of the goals of both the mini-games and the overall activity was important, some participants also discussed whether it would be economically reasonable to reveal the full extent of the data collection to the participants and also pinpointed the ethical issues regarding this type of crowdsourcing. On the one hand, participants deserve to know what kind of data they are providing, and this could even be a motivating factor if framed as a way to help society by contributing as part of a citizen science initiative. However, if players were fully aware of the data collection activity, their engagement might be negatively impacted. The following quote relates to this issue.

"You're convincing people through a game to do the work for you, which is ok, but morally grey. That's the only concern I have." (P4)

5 Discussion

5.1 Design Considerations

In our empirical research, we discovered five themes describing dynamics that relate to our RQ and, through that, to (1) user engagement and (2) guiding users' crowdsourcing participation. Based on these themes, we have derived 11 design recommendations, which we list in Table 3. These recommendations should be considered as general guidelines for designing LiDAR-based AR crowdsourcing games or apps. However, as games are complex systems with potentially various inter-dependencies, these are but one selection of insights relevant to the overall design of these systems.

Some of the recommendations in Table 3, such as #1 and #3, are about altering the design of the prototypes in this research, while others, such as #5 and #9, are about taking the design further and adding new elements. The recommendations are not listed in order of priority, but in the order of appearance, since, based on the reflexive analysis, it is not possible to rank emerging

Table 3. Design recommendations for LiDAR-based AR crowdsourcing applications for improved user engagement and experience.

#	Recommendation	Source
1	Crowdsourcing participation alone can be motivating, and designers need to be careful not to hinder it with "over-gamifying" their application.	Theme 1
2	Embrace individual differences. Support multiple activities and enable users to find a style they enjoy and feel confident about.	Theme 1
3	Build the AR game elements around real-world activities.	Theme 2
4	Avoid a design that constrains participants by forcing them to overly focus on their mobile devices.	Theme 2
5	Short AR scenarios provide only brief engagement. Larger narrative structures and purpose are needed for long-term engagement.	Theme 3
6	The AR content should be aligned with the environment to boost immersion. Overly whimsical content risks replacing, rather than augmenting, the experience.	Theme 3
7	Precision of the AR content in relation to the real-world environment is critical for the content to feel meaningful.	Theme 3
8	Instead of creating an application for a single purpose (create point cloud scans from nature areas), the applications should empower participants to engage more holistically with their surroundings.	Theme 4
9	Participants should be given autonomy and choice in which activities to engage in with AR crowdsourcing.	Theme 4
10	Ensure participants have clear goals and instructions and that the rules of the game(s) are predictable.	Theme 5
11	Provide clear and fair feedback to participants within the AR games, but also on their crowdsourcing contributions.	Theme 5

recommendations in any particular order. Furthermore, the order of importance is likely context-dependent: in some cases, one recommendation may be more important than another, while in other contexts, the order may be reversed. It is worth noting that the research prototypes had a significant impact on the data, the analysis outcome, and, subsequently, these recommendations. Thus, the recommendations should be viewed as part of ongoing research efforts to enhance the design of LiDAR-based AR crowdsourcing and help build a shared understanding of best practices in this design space.

5.2 Theoretical and Practical Contributions

This research relates to endeavors for scanning real-world objects, something that, e.g., researchers from the location-based technology company Niantic have recently also studied [84]. Real-world object scanning can make use of LiDAR [78], or it can be done only with camera sensors [84], but the underlying user dynamics appear to share similarities. In both cases, users are asked to follow specific slow mobile device movements around their target, and it is critical to provide multimodal feedback to the users regarding their movements [57, 78, 84]. In our case, instead of direct feedback, we studied creating games around the problem of guidance and feedback, as well as to motivate participants. This approach can be seen as a novel contribution in this field, and based on our findings, it shows great promise while also presenting challenges. The main benefits appear to be the ability to guide users' interactions with the games seamlessly, providing an

additional layer of motivation to participate beyond citizen science-related motivations and having the possibility of being intrinsically fun to the users. Some of the key challenges are technical, such as accurately positioning content in the real world or creating seamless interactions with the physical world that feel immersive and natural. Other challenges are more design-focused, such as creating gamified experiences that do not undermine participants' existing motivations to contribute to environmental data crowdsourcing.

Our work also contributes to the research area on location-based gaming, a field of study that concerns games that utilise the user's physical location as part of the gaming experience [12, 31]. In our case, our focus was not on map-based navigation [13, 36], but rather on in-situ AR experiences. Participants in our empirical study discussed elements such as how to navigate to desired locations and the need to tie the AR mini-games to a broader narrative. Indeed, from the perspective of the scholarship on location-based gaming [40], our key contributions relate to AR mini-games that can be prompted by navigating and interacting with points of interest on a location-based gaming map. The AR prototypes that we created could be added onto a map-based location-based game platform as mini-games similar to the ones we have in, e.g., Pokémon GO, Jurassic World Alive, and Ingress (see Figure 2). In this way, we contribute to the field of location-based games by investigating concrete map interactions and their related dynamics.

From a theoretical perspective, our work relates to research on user engagement and motivation. Our findings provided some support for popular motivational frameworks, as we observed the emergence of the needs for autonomy and competence, popular dimensions of intrinsic motivation in self-determination theory [61, 68]. Regarding previous research on motivation in location-based crowdsourcing, many similar themes emerged, such as the need for precise goals and feedback [37]. However, most importantly, our findings relate to the field of gamification [24, 30, 55], where our work can be understood as a gameful approach to solving two issues in crowdsourcing: (1) user motivation and (2) user guidance. As a motivational force, gamification provides a scalable alternative to pure monetary rewards because, while it is expensive to initially produce properly, after completion, gamification approaches can be copied relatively cheaply. Thus, it is a more scalable solution and, therefore, a better fit for large-scale crowdsourcing endeavors [34]. However, applications such as iNaturalist appear to be doing well despite having only light gamification at most in the form of cataloging observations [7], suggesting that, perhaps as a motivational force, game-like elements are not always needed. However, gamification also has another advantage besides motivation, which is the capability to guide user behavior and interactions. There is quite a bit of research on how AR game actions modify human real-world interactions [12], and we contribute to this body of research by gathering empirical evidence on how AR scenarios can guide user movement in the physical world.

5.3 Limitations and Future Work

As with all empirical design-based work, our study has limitations that warrant discussion. First, as already discussed, together with the design recommendations, the research prototypes and their design had a fundamental influence on the data that the experiment provided to us. This is a limitation that is acknowledged in design research [3, 25, 29], and it is a trade-off that is accepted when probing knowledge on a new frontier in technology. While LiDAR-based mapping systems themselves are not new, not even in the context of crowdsourcing [45, 78], gamified LiDAR AR games can be considered a new, understudied frontier. Similarly, in the analysis, reflexive thematic analysis trades procedural rigor in favor of interpretive insights, leveraging the strengths of rich qualitative data [50]. This methodological choice was deemed suitable in our case. Still, we encourage future studies to explore alternative methodologies and data sources as well as design prototypes to build robustness and rigor in this field of study. Since data was collected from

specific user groups in two countries, the findings should not be interpreted as representative of the viewpoints of the general population. We encourage scholars to replicate similar experiments in different contexts and with different prototype implementations to enhance generalizability.

Our findings also provide opportunities for future research. Many of the themes and design recommendations relate to advancing the mini-game prototypes towards a more fully fledged crowdsourcing platform (such as recommendations #5 and #9). For example, findings regarding the provision of an overall game narrative, structure, and purpose should be further studied by implementing these elements and then conducting follow-up studies. When comparing our approach to popular commercial products such as Pokémon GO or the now-discontinued Harry Potter: Wizards Unite and Walking Dead: Our World, we notice that these commercial products indeed provide an overall framework and story, with additional AR mini-games to engage in [20, 31]. They have, thus, implemented recommendation #5 to some extent. While we had participants from two countries (Japan and Finland), the sample size was too small to observe differences between the samples either in how they used the app, or what elements they brought forward in follow-up interviews. However, we encourage future research to investigate whether there could be cultural differences in how users approach different AR scenarios across different cultures and locations.

One element that was missing from our prototypes was social play, an aspect that has been identified as a critically important dimension in previous work on locative crowdsourcing [34, 52], and which has been the topic of extensive study in the HCI research community [12, 22, 67, 69]. This limitation was also visible in the research data and subsequent analysis, as multiplayer perspectives and social dimensions were not discussed in detail. We also suggest that future research on LiDAR-based AR games for crowdsourcing should focus on the opportunities provided by social play and investigate the types of social play opportunities and dynamics that could exist in the LiDAR-based AR space, as well as how these relate to crowdsourcing. We also see room to further explore the ethics of our crowdsourcing approach, particularly in contexts where users may not be aware that their AR gameplay is being harnessed for data collection. Finally, future research should evaluate the comparative performance of the prototypes using the collected point cloud data, for example, in terms of the number of collected points or the area covered.

6 Conclusions

In this study, we created four LiDAR-based AR prototypes for crowdsourcing locative data to probe dynamics relating to (1) user motivation and (2) guidance for data gathering. These prototypes could be considered games or gamified mini-experiences, and we had a total of 21 participants try them out and provide feedback. Through reflexive thematic analysis, we arrived at five major themes of dynamics: (1) Game scenarios and gamification can undermine users' intrinsic motivation to contribute; (2) Physical and environmental constraints remain fundamental hurdles; (3) Users seek meaning, justification, and a sense of purpose in participation; (4) Contributors desire to have options and alternative ways to participate; and (5) Unclear goals and feedback undermine users' engagement. Through elaboration on these five themes, we extracted 11 design recommendations for LiDAR-based crowdsourcing built on gamified AR experiences. These findings provide new insights into this understudied but emerging area.

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