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Secondary school students' responses to epistemic uncertainty during an ecological citizen science inquiry

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Abstract

Uncertainty is endemic to scientific research practices; therefore, it is also an important element in learning about science. Studies have shown that experiences and management of uncertainty regarding the epistemic practices of science can support learning. Whereas the common strategies of supporting students in handling uncertainty rely on the teacher knowing the preferred outcomes and answers, few studies have explored settings in which *no one* can give the right answers to students. In this study, we explore how Finnish, suburban secondary school students (aged 13–14 years) respond to epistemic uncertainty during an ecological citizen science inquiry, in which the aim is to produce novel scientific knowledge. Drawing from qualitative interaction analysis of video and interview data, we articulate three responses to uncertainty that arise when students try to make optimal choices during the inquiry: they (a) envision alternative narrative scenarios and hypothesis; (b) accept and maintain it as part of their argumentation practices, and (c) flexibly reframe their research activities and goals. The findings indicate that the citizen science setting can allow students to reframe epistemic uncertainty in ways that are typical of scientific practices even without deliberate scaffolding by the teacher. We suggest that incorporating experiences of uncertainty that are shared by students and teachers in pedagogical design can support doing and learning science in different settings.

KEYWORDS

argumentation, authentic inquiry, citizen science, nature of science, scientific practices

1 | INTRODUCTION

Science is characterized by uncertainty. The scientific research process entails iterative management of uncertainty: researchers choose research questions based on their knowledge gaps within a topic and find the best methodological solutions through trial and error (Latour, 1987; Pickering, 1993). As Firestein (2012) concludes, " … the very notions of incompleteness or uncertainty should be taken as the herald of science" (p. 44). The answers for research questions always have a level of tentativeness and often lead to new questions and investigations. Sometimes the research process leads to a dozen new questions while the original questions and hypotheses remain unanswered (e.g., Dylla, 2020). There can be hypothesized or expected outcomes, but it is not uncommon that a result that is against all expectations or appears as insignificant later turns out to be of great importance (e.g., the pancreatic origin of diabetes by Mering & Minkowski, 1890).

Science education has long faced criticism that it presents a *final form of science* rather than an understanding of *science in the making* (Duschl, 2008; Kelly et al., 1998). Scientific uncertainty unfolds and is managed during the process of generating knowledge, rather than in the final outputs which are considered tentative, but still accepted as the (current) best explanation. Thus, to incorporate experiences of scientific uncertainty into classroom activities, it has been suggested that the focus be shifted from the final forms of disciplinary content knowledge to the development of students' epistemic knowledge (Ryder, 2001; Tiberghien et al., 2014). Critical reflection of the epistemic practices such as devising questions, observations, and interpretations are at the core of *doing* science and an essential aspect of scientific uncertainty. Accordingly, a number of studies have emphasized experiences of *epistemic uncertainty* as key components necessary for students to develop an understanding of scientific knowledge production and its essential scientific uncertainty (e.g., Chen & Qiao, 2020; Hartner-Tiefenthaler et al., 2018; Lee et al., 2014; Tiberghien et al., 2014).

Epistemic uncertainty can be described as learners' "awareness and knowing of incomplete skills or abilities about how to explain a phenomenon, derive trends from muddled data, interpret and represent raw data as evidence, and put forth scientific arguments" (Chen & Qiao, 2020, p. 2147). Rather than knowing or not knowing specific scientific content knowledge, those who practice epistemic uncertainty refer to a degree of confidence of knowing how to generate such knowledge. Epistemic uncertainty arises during an evaluation of arguments and explanations of a phenomenon based on interpreted data (Chen & Qiao, 2020; Hartner-Tiefenthaler et al., 2018). Epistemic uncertainty of science learners is congruent with uncertainty that scientists experience and cope with during the research process. Whereas professional scientists have more resources and can more easily draw from the norms and traditions of the scientific community to address the uncertainty, they experience epistemic uncertainties during scientific research, nevertheless.

Many studies on the ways to integrate epistemic practices of science in classrooms have focused on the role of uncertainty. Research has shown that students' conceptual understanding of science develops and becomes more coherent when they are encouraged to identify, manage, and eventually overcome uncertainty during classroom discussion (Chen & Techawitthayachinda, 2021; Watkins et al., 2018) or scientific practices such as argumentation (Chen et al., 2019) or modeling (Chen, 2021). A common characteristic of many strategies to scaffold and support epistemic uncertainty is that the teacher knows the right solution and attempts to adjust the amount and form of uncertainty that students experience (Chen & Techawitthayachinda, 2021; Manz & Suárez, 2018). However, such approaches omit an aspect scientific uncertainty: during the research process, no one knows the answer or the optimal choice beforehand, but everyone is in the process of generating new knowledge. Students' responses to uncertainty that arise during an authentic knowledge production of scientific research might differ compared to pedagogical designs that build on reproducing existing knowledge.

The norms and goals of scientific research practices are not easily transferable into school settings (e.g., Abd-El-Khalick, 2008). There are few studies on students' uncertainty during such a process; instances that may eventually lead to new scientific knowledge are rare in science classrooms. In this study, we focus on a citizen science activity in which the students participate in the process of generating new scientific knowledge in collaboration with the researchers (see e.g., Trumbull et al., 2000). Unlike most science learning activities, citizen science projects can offer students an opportunity to participate in the collaborative production of new scientific knowledge even with limited skills and resources. Thus, citizen science activities can provide participants with opportunities to engage in scientific uncertainty in ways that are different from typical classroom tasks that aim to reproduce existing knowledge.

We use the citizen science setting to explore how epistemic uncertainty unfolds and is responded to when no one knows the desired outcome. The central research question guiding the study is: how do students respond to epistemic uncertainty during a science inquiry when no knowledge about optimal choices and right answers is available?

To answer the research question, we draw from data from an ecological citizen science project, in which eighth grade students were immersed in scientific research in the urban area surrounding the school. We analyzed field work situations, in which students needed to make choices similar to those that professional scientists would need to make. These choices would not have been trivial even for a professional scientist. Thus, the qualitative nature of epistemic uncertainty that the students experienced resembled that of those engaged in scientific inquiry, even though an experienced ecologist might have experienced less epistemic uncertainty and made the choices more quickly and confidently. Before the empirical part, we elaborate on the nature of uncertainty in science learning and outline how citizen science projects might shape the premises of epistemic uncertainty for the participants.

1.1 | The role of uncertainty in science learning

Students often experience different kinds of uncertainty during learning activities. These uncertainties include lack of confidence regarding interpersonal relationships within the classroom (Jordan & McDaniel, 2014; Knobloch & Solomon, 2002) and uncertainty regarding the disciplinary content knowledge (Darnon et al., 2007). When properly managed, experiences of uncertainty can support the learning process as they push students to re-evaluate their present knowledge and practices and resolve the uncertainty (Kapur, 2016; Warshauer, 2015).

Beyond content knowledge, it is considered critically important that the students understand discipline-based epistemic frameworks, so that the school science is situated in the context of scientific knowledge generation (Duschl, 2008; Hammer & Elby, 2003). Accordingly, science education researchers have focused on epistemic uncertainty as a resource for understanding science as a process (e.g., Chen & Qiao, 2020; Hartner-Tiefenthaler et al., 2018; Lee et al., 2014; Tiberghien et al., 2014). Studies have shown that identifying, maintaining, and eventually reducing uncertainty during the scientific practices of argumentation (Chen et al., 2019) or modeling (Chen, 2021) support students in understanding science in more sophisticated and coherent ways. Watkins et al. (2018) showed that deliberately enabling and encouraging students to position themselves as uncertain positively contributed to classroom dynamics in doing science inquiry.

There is abundant research on how experiences of scientific practices that entail uncertainty and choice-making can be brought into science classrooms. Suggestions on how to make uncertainty tangible for students include supporting students in discussing several possible explanations from complex data (Berland & Reiser, 2011; Chen et al., 2019), discussing the categorization of objects with ambiguous traits that allow for different solutions (Varelas et al., 2008), encouraging even very young students to make choices on how to proceed in inquiries and refine the practices (Manz et al., 2020; Metz, 2008), and engaging in defining variables and modeling phenomena based on them (Chen, 2021; Lehrer & Schauble, 2012).

Integrating epistemic uncertainty in classroom practices is not an easy task. Teachers often perceive epistemic uncertainty as unpleasant and avoid it in their pedagogical strategies (Babrow & Mathias, 2009; Beghetto, 2017; Jordan & McDaniel, 2014; Lee et al., 2020; Tiberghien et al., 2018). Likewise, students tend to avoid experiencing uncertainty during learning activities (Chen et al., 2019; Lee et al., 2020). As students' vernacular understandings of the world are different from that of canonical science (Aikenhead, 2001; Lyons, 2006), they can experience uncertainty as failure to comply with the requirements of science. Hence, this tends to stir emotions of disappointment and frustration particularly when students fail to provide the correct solution (Bellocchi & Ritchie, 2015; Bellocchi, 2018; Kervinen et al., 2020a). Regulating such negative emotions is considered to be an important part of science learning (Tomas et al., 2016).

New approaches to support the integration of uncertainty into science classroom activities could prove to be useful. This article focuses on one of the main characteristics of uncertainty in scientific research: that the uncertainty is *shared* by everyone. A typical way to integrate epistemic uncertainty in the classroom is that the correct or the best possible solution is available to the educator who then deliberately withholds it. This might happen by carefully scaffolding the classroom discussion (Chen & Techawitthayachinda, 2021) or designing the learning activities in ways that encourage students to manage with the uncertainty (Manz & Suárez, 2018). In contrast, little research exists on how students respond to uncertainty when the desired outcomes are equally unknown to the teacher. As an exception, Lenzer et al. (2020) examined how chemistry undergraduate students participating in authentic research projects cope with uncertainty. The authors showed that moments, when students recognize the failures and uncertainties in their research process, were particularly important in developing their domain-specific awareness, such as understanding of tools and representations relevant to their discipline. The students responded to uncertainties by seeking feedback and attempting to solve the problem through trial and error. In cases where they did not identify uncertainty, external feedback, and mentoring was needed retrospectively.

Whereas science learning cannot and need not fully imitate scientific research (Abd-El-Khalick, 2008), students' experiences of epistemic uncertainty and opportunities to cope with it may be different depending on the availability of the correct answer and solution. It has been suggested that science education activities in which the questions arise within the learning community and no knows the answers ahead of time, or even if they can be answered at all are particularly important in building a meaningful relationship to science (Roth et al., 2008). Knowledge of how epistemic uncertainty unfolds and can be coped with in such a setting can provide important understanding for designing classroom activities that approximate the practices of science. To address this gap, the present study investigates how uncertainty appears and is responded to in a citizen science project in which the shared goal is to eventually produce scientific knowledge that is new to everyone.

1.2 | Citizen science as an opportunity for authentic science experiences

The concept of citizen science was developed in the 1990s to describe the aim to better engage citizens in science discourse and build a more trusting relationship between science and the public (Strasser et al., 2019). Citizen science projects are viewed to serve a dual goal to gather larger data sets with the help of public participation and promote public understanding of science (Trumbull et al., 2000). There are several classifications of citizen science projects, where typologies are built from different points of view. An influential classification has been by created by Bonney et al. (2009) and revised in Shirk et al. (2012), which divides projects from the citizen *participation* point of view to (1) contractual; (2) contributory; (3) collaborative; (4) co-created, and (5) collegial in the increasing order of participation. The definition of participation here is driven by project design aspects: in which parts of the project do citizens participate. A similar approach is taken by an influential classification by Haklay (2012). In turn, Strasser et al. (2019) developed a taxonomy of different knowledge practices that citizens may or may not take part in during participatory science projects. The authors distinguish five such epistemic practices: (1) sensing; (2) computing; (3) analyzing; (4) self-reporting, and (5) making.

Recently, more and more citizen science projects have been conducted in collaboration with schools. In these projects, the educational aims of citizen science are often emphasized. Both affective factors like interest in science and epistemic understanding and skills of the doing science are proposed as arguments for integrating the citizen science projects in formal education (Phillips et al., 2018). Studies on educationally focused citizen science projects have suggested that participation in citizen science can increase students' knowledge of the content (Alexander & Russo, 2010), motivation and interest (Aivelo & Huovelin, 2020), and support the development of scientific literacy and pro-environmental attitudes (Kim & Lee, 2019).

In this paper, we set our focus on the potential of citizen science projects as authentic science experiences for the participating students. The authenticity of an educational task derives from various dimensions, such as (a) how much the content resembles real world content; (b) how much the activities and skills needed for the task resemble real-world activities; (c) how much the outputs of the task impact entities outside the education environment; (d) how much the activity resembles students' personal lives, and (e) how much students' own questions are answered and needs satisfied during the task (Barab et al., 2000; Strobel et al., 2012).

The requirements for authenticity can be more or less met in various science learning activities, as long as the activity resembles the real scientific process. This is so because the similarity at the cognitive level is more important for the experience of authenticity than the actual physical resemblance of the two (Roach et al., 2018). Citizen science tasks are likely to meet many dimensions of authenticity, particularly regarding the similarity between the task and the process of science. Specifically, citizen science projects include one specific aspect of authenticity that is usually not present in science classrooms: the aim to produce new scientific knowledge.

The goal of citizen science projects to generate new scientific knowledge presents a unique opportunity regarding the goals of science education. Indeed, it has been suggested that educational activities in which the questions arise within the learning community and no knows the answers beforehand are best for realizing the authenticity of science (Roth et al., 2008). Furthermore, citizen science projects are suggested to provide opportunities for citizens to not only follow the process designed by professional scientists, but also think for themselves and make their own decisions within the set framework (Bonney et al., 2016; Rautio et al., 2022). Indeed, the description of the research protocol cannot be so exhaustive that there would be no decisions left for the students at all. The relevant question here is what kind of open-endedness in the research protocol would allow students to bring their own knowledge into the project, while minimizing the eventual effect for the validity and reliability of the research data. In the case of the citizen science project in this study, the students were instructed to follow the detailed process to collect data; thus, this can be seen as a contributory project. Nevertheless, it should be noted that most citizen science project taxonomies are not based on participants' epistemological processes, but rather project design. Thus "contributory" label might not fully describe the role of the students in this project: students are also required to make several decisions on their own instead of just mechanically repeating what they have been told by the professional researchers. Within a taxonomy of the epistemic practices of the citizen science project (Strasser et al., 2019), the current project involves students in two epistemic practices: *sensing* (collecting observations) and *analyzing* observations (identification of rat tracks). It is likely that during both of these practices, the students face questions and uncertainty about the epistemic process of the inquiry, something which is desirable in terms of engaging in scientific thinking (e.g., Hartner-Tiefenthaler et al., 2018).

However, the setting of this study is different from typical science classroom activities in two ways. First, the knowledge-producing aspect of citizen science means that no one knows beforehand what will result from the inquiry, but students' choices and actions are an essential part of achieving this knowledge. For example, not only might the students be uncertain of how to interpret the data, but they may also share that uncertainty with everyone involved to the extent that no one knows the data beforehand. Second, partly because of the previous reason and partly because the students work mostly apart from the teacher, no one can guide the students to optimal and correct choices during the task. We hypothesize that for these reasons, the citizen science context shapes how epistemic uncertainty unfolds for the students and how they cope with it. In the following parts, we describe our citizen science setting in more detail and draw from empirical data to analyze how the students respond to epistemic uncertainty.

2 | METHODS

This study was designed to analyze how students handle epistemic uncertainty that arises during an inquiry task where no one knows the desired outcomes beforehand. We draw from data from an ecological citizen science project in which student groups worked in collaboration with professional researchers to study the presence of urban rats close to the schools. The student groups were video-recorded as they worked independently in the vicinity of the school and interviewed. As the students did not have professional researchers or teachers as a resource immediately available to them, students' own responses to uncertainty became particularly visible for empirical analysis.

2.1 | The ecological citizen science project

The study was carried out as a part of the larger citizen science project that explored the rat presence and multispecies encounters in urban environments (Helsinki Urban Rat Project: https://www.helsinki.fi/en/projects/urban-rats and CitiRats: https://citirats.wordpress.com/). The ecological aim of the project was to investigate the spatiotemporal population dynamics of rats (*Rattus norvegicus*) by collecting data on rat presence or absence in the city of Helsinki and later link this information on different ecological and sociocultural variables. The ecological research process and the role of the citizen science activities within it are presented in Figure 1.

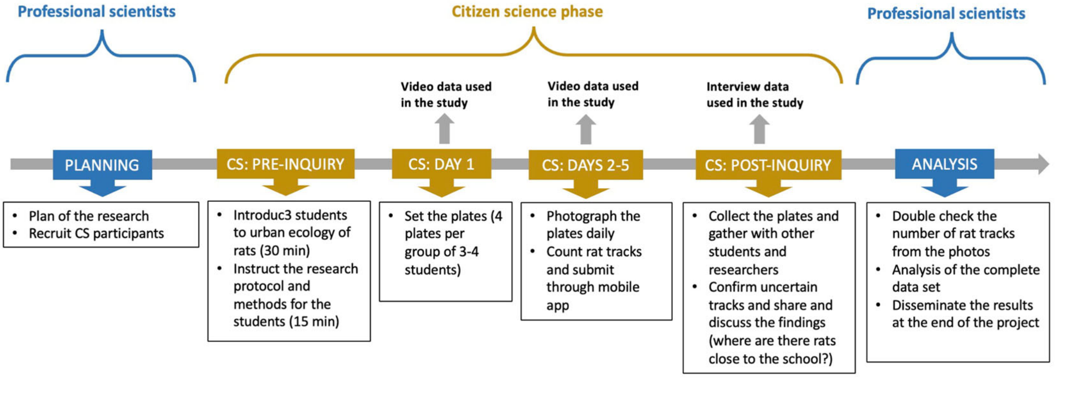

FIGURE 1 Timeline of the research project.

As part of the data acquisition, students from secondary schools gathered data on rat presence in the environments close to their schools. To explore rat presence, the students used track plates, which are 20x20 cm white plastic plates that are painted with lampblack (Hacker et al., 2016; Figure 2). If a rat walks across the plates, its paw prints are left to be identified and counted by the students. Thus, the students did not need to encounter rats during the study, but it was possible to identify the places in which rats had recently moved.

Before the inquiry in each school, the second author, who was also responsible for the ecological research, visited the classroom remotely and gave a 30-minute lecture on urban ecology and rats and explained how the students could participate in the research. The experience from the earlier project rounds had shown that even a short ecological introduction gave the students enough knowledge to successfully conduct their part of the inquiry (Aivelo, 2022). The most important knowledge of rat behavior that was needed to set the plates in good spots was that rats tend to avoid open and crowded places and rather move in cover, for example, close to walls. In addition to rats' ecology and behavior, the complexity of human-rat relations in cities was described to motivate students to explore rats in their everyday environments (as most of students also lived close to their schools). The students' motivation to participate in the project was increased by the fact that a researcher outside from the school gave the task and the task differed from typical classroom activities (Aivelo & Huovelin, 2020). After the ecological introduction, the students were introduced (15 min) to the research equipment and instructed in the research protocol, that is, what to do with the plates, how to identify and count rat tracks, and how to send the data.

Students worked in groups of three to four students. When setting the plates on day one (Figure 1), the students were instructed to think of a place where they would like to study rat presence close to the school (around 5 min' walk at most). Further, students were instructed to think of where and how a rat might move in the chosen area to set each of the four plates in such a spot that rats would likely move across them if present. After setting the plates, the students photographed them for four subsequent days and then collected the plates. Students sent the photos of the track plates along with a number of identified (alternatives for confirmed identification or not) rat tracks on the plate into a database through a mobile application EpiCollect5 (Aanensen et al., 2009) (examples of the photos are included in the transcripts). During this phase, students needed to first identify whether there were rat tracks on plates to count them. Here, the data collection and the initial analysis intertwined, although the statistical analysis and modeling were left for the professional researchers. Students were told before the inquiry that the photographs and the rat tracks that they reported would be later double-checked and counted by the authors to confirm the identification. Double-checking is a typical scientific practice, which was also brought out to the students when introduced to the process of generating new ecological knowledge. Furthermore, one aim of talking about double-checking was to give students the confidence to complete the task without fear of compromising the reliability of the research project.

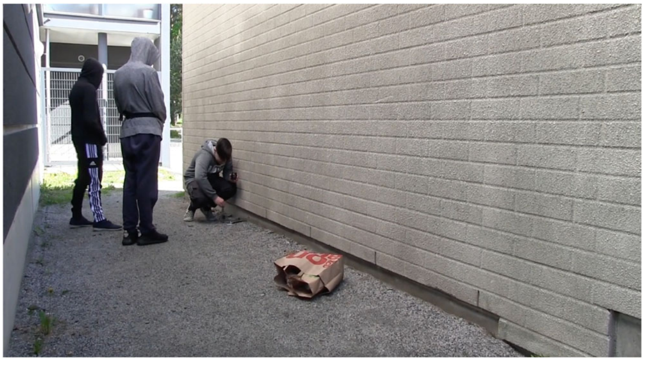

FIGURE 2 Screen capture from the video data. Students (Group 9) painted a track plate placed in a chosen spot close to the school.

At the end of the inquiry in the school, the students gathered to share and discuss their findings with each other and the authors. One purpose of this discussion was to collaboratively discuss and solve uncertainties that had arisen during the inquiry (such as uncertainty of rat tracks or placement of the plates), while still acknowledging the tentativeness of the new knowledge of the rat presence that is being generated. The participants also discussed findings on potential rat presence near their school. The researchers informed the students about how the larger ecological research would continue with all the data around the city. The students' teachers oversaw the process, but stayed in the school yard and did not accompany the student groups when they set and photographed the plates. Due to pandemic restrictions, researchers were not allowed to enter the school buildings. The activities in schools took place outdoors; the students were instructed, and the findings of the inquiry summarized in the school yard.

Whereas the citizen researchers followed a rather detailed protocol designed by the professional researchers, their intellectual contribution was pivotal in the inquiry. To set the plates, the students needed to first decide a potential place for rats in the area that they were familiar with and then decide the suitable spot for each plate based on what they had learned and knew about rat movement. Regarding these decisions, the students worked with a background knowledge that was comparable with what professional scientists would have had. Indeed, the students had moved around and knew more about the area than the professional researchers. When identifying and counting potential rat tracks, an ecologist with experience on rat tracks would have been more confident in the identification. However, even for a trained ecologist, it is necessary to gain first-hand experience with rat (or any animal) tracks to be able to identify them and solve challenging cases. Regarding prior knowledge, the situation was somewhat like a professional ecologist setting their first plates at the beginning of the research project. Whereas a professional scientist responsible for the whole research project would need to deal with uncertainties in many phases of the research, students' activities during the phases of collection and initial analysis of data resembled the cognitive and epistemic aspects of science rather than simply repeating an instructed inquiry; for example, they had to deal with partially conflicting or anomalous data, employ multiple forms of argument and contemplate other variables than originally intended (Chinn & Malhotra, 2002). All in all, the students (similarly to researchers) needed to make choices to set the plates and interpret the tracks with their current knowledge as well as they could, which led to epistemic uncertainty and thus evoked responses to the experience.

2.2 | Participants

Four seventh-grade classes (age 12–13 years) and one eighth-grade class (age 13–14 years) from three schools participated in the project in the spring of 2021. These schools were asked to participate based on the biology teachers' previous collaboration in the same citizen science project. The selected classes were a convenience sample based on schedules, and, depending on the school, the inquiry activity fit better with either seventh or eighth-grade curriculum.

The participating schools were suburban schools in Southern Finland. In Finland, there is a very small variation in academic performance among different schools (OECD, 2016). From the participating classes, nine student groups (altogether 29 students) participated in this study. The participation was voluntary for the students (and the teachers) and is based on informed consent, and the study conforms to the ethical principles of the Declaration of Helsinki. Whereas only the students in the observed groups participated in this research, all students of their classes participated in the citizen science project as it was part of their schoolwork.

2.3 | Data collection and analysis

The data sources used in the study included video- and audio-recordings from student groups that performed the rat presence inquiry and group interviews after the inquiry about their experiences and views on the activity. The video recordings that were used derived from the moments when the student groups either set the plates in the environment on the first day or photographed and counted the tracks on the following days (Figure 1). For the video recordings, both authors used a handheld camera; thus, two groups were simultaneously followed per class. We recorded the audio using external microphones for each student; this allowed the videos to be recorded from some distance; therefore, there was minimal interference with the students' activities (see Figure 2). During the group interview after the lessons, we asked the students about the presence of the researchers and video recording. They reported that they had quickly forgotten about the recording; thus, it had a minimal effect on their activities.

In total, 736 min of recorded videos were used from nine student groups (66–97 min per group). The video recordings included the setting of the plates on day one (total 271 min, 22–43 min per group) and four days of photographing the plates. For one group, only 3 days were recorded due to a technical problem (total 325 min, 23–46 min per group) (Figure 1). The whole class discussions with the second author at the end of the inquiry were also recorded, but this data was not used in this study as our focus was on students' ways of managing uncertainty on their own. The group interviews after the inquiry were audio-recorded (total 113 min, 9–19 min per group).

The video and audio recordings were synchronized before the analysis. Raw transcripts of the lessons were produced using Transana 4.00 software (Craig Rush, 2014). The transcription conventions used are explained in Appendix. The episodes that were selected for the in-depth analyses were subsequently transcribed using a conversation-analytic system (Selting et al., 1998). The conversations among the students originally took place in Finnish (or among one group partly in English as it was the native language for two students), and the fragments presented in this paper are translations by the authors.

The analyses are based on the interactional analysis of students' interactions (Jordan & Henderson, 1995). First, we watched separately through the videos repeatedly and identified occurrences of uncertainty. At this point, we defined episodes of responding to epistemic uncertainty as moments where more than one student was seen to be verbally (and physically) negotiating, describing being unsure, or disagreeing with others regarding an epistemic aspect of their task. Our definition excluded some episodes, in which the uncertainty about using the research equipment arose but was resolved without much elaboration by recalling the instructions that were given before the field work. The following dialogue is an example of how uncertainty unfolded in sequential turns (expressions and reactions to previous expressions) by two students:

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Student 1: yeah but are those rat tracks ((observes the plate))
Student 2: well I don't know they are some tracks aren't they because you can see
           that it has kind of slid maybe (..) [unevenly]
Student 3: [I think] that those are those are not quite rat tracks
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The expressions of and responses to epistemic uncertainty were found to be common throughout the data. We then identified 106 min of episodes (4–24 min per group, 10 s–2 min per episode) that involved negotiating, being uncertain, or disagreeing on what to do during the research process or what conclusions to make based on the data as containing epistemic uncertainty. An episode refers to a continuous phase of interaction centered around the same topic (i.e., epistemic uncertainty). If the interaction shifted to another topic even briefly (e.g., the students talked about using the mobile app), the continuing interaction was coded as a new episode. Thus, the combined length of the episodes demonstrates the frequency of different behaviors better than the number of episodes.

We analyzed the episodes of responding to epistemic uncertainty (106 min) interactionally in joint data sessions (cf., Jordan & Henderson, 1995). Based on the discussions on the emerging sense of what occurred in the samples, we formulated tentative hypotheses based on students' ways to react and cope with the epistemic uncertainty. These hypotheses included ideas such as: "students come up with alternative solutions," "students draw from their everyday lives to elaborate on choices and observations," "students are not disturbed by the continuing uncertainty," "students show disappointment when not finding rat tracks," and "students overcome the disappointment of not having the desired or expected result." We then searched through the entire video database as well as the group interviews to find evidence that either contradicted or confirmed the tentative hypotheses, as required by the method (Roth, 2005). We discussed the emergent understandings generally and any alternative understanding in particular, refined the hypotheses, and articulated three distinct ways of coping with epistemic uncertainty. The findings presented in this report are the result of this iterative process of joint analysis, writing, and discussions (Figure 3).

In the analyses, we attempt to produce and provide an adequate account of the observed interaction among the students. The value of an utterance in and to a conversation is tied to its social evaluation, which the listeners make available for the analysis in their own turns that follow immediately (Volosinov et al., 1973). Thus, the minimum unit of analysis that makes sense to analyze such interaction is a pair of communicative turns. The nature of the interaction can be analyzed based on the ways to which the utterances are reacted and responded. This approach does not require special interpretive methods; rather, the analyst is required to hear the participants in the way they hear and understand each other (Garfinkel & Sacks, 1986). In this report, we make visible how the unfolding interaction can be heard, as well as the possible (general) cultural premises on which our understanding is based.

In the following sections, students' interactions in the selected episodes are analyzed in this manner to show the ways in which they encounter and cope with the uncertainty during their ecological inquiry. Because the uncertainty of science classrooms and scientific research that was focused on constitutes culturally characteristic and interactional phenomena (e.g., Bellocchi & Ritchie, 2015; Dylla, 2020), they constitute cultural possibilities

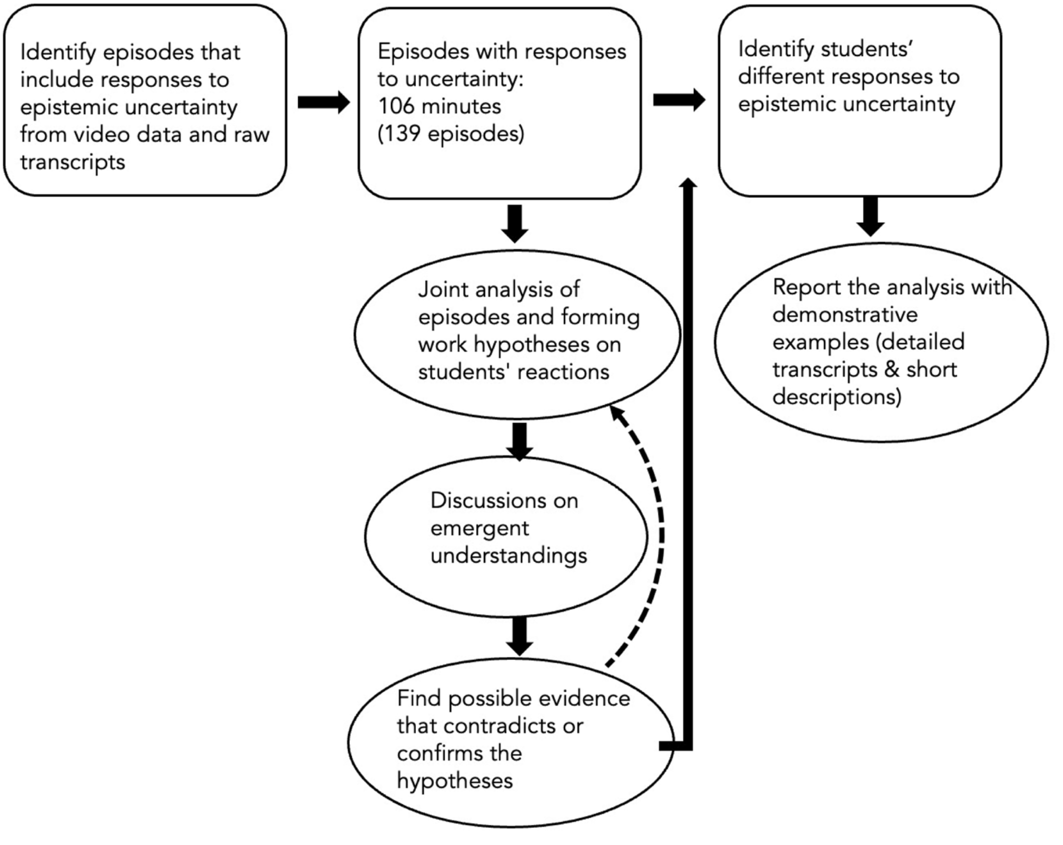


FIGURE 3 Interaction analytical process of the study.

rather than phenomena that are specific to individual students (Rawls, 2002). They are, in fact, observed across the project with several groups, but are highlighted in the selected episodes with certain students.

3 | FINDINGS

The citizen science context allowed the uncertainty to be empirically investigated in a context differing from typical science classrooms. We identified three ways of students handling uncertainty: (a) controlling uncertainty through envisioning alternative narrative scenarios and hypothesis; (b) maintaining and accepting uncertainty by articulating it as part of argumentation practices; and (c) overcoming the uncertainty of having a desired result by flexibly reframing their research activities and goals (Table 1). These three ways partially overlapped and might have been used by the students in the same episodes as these social phenomena unfolded as pairs of communicative turns that can be located far away from each other in time with many actions going on at the same time (Rawls, 2002; e.g., see the analyses of Fragment 3 and Fragment 4, in which students not only maintain and accept uncertainty, but also envision alternative narrative scenarios). Nevertheless, each of them constituted a distinct approach to reacting to and coping with the experienced uncertainty.

3.1 | Envision alternative scenarios and narratives

In this subsection, we show how students reframed the epistemic uncertainty of not knowing the correct solution by creating alternative scenarios and explanations. The citizen science research setting allowed students to replace the requirement of knowing the right answer with the task to envision and evaluate options and outcomes to know the world in new ways, which incorporated their prior knowledge and experiences.

At the beginning of the inquiry, students chose a spot to study rat presence and then decided where to place the track plates in that small area. Plate placing was an important decision, because the validity of the result (rat presence) was partly dependent on whether the plates were in the most probable places (in the chosen area) for rats to move. The students were advised to think of where the rats might move and to remember that rats prefer cover from walls or other structures instead of open areas. However, when choosing where exactly to put their plates, students had to reflect with limited information on where and how rats might move in the area. Other moments of uncertainty unfolded as the students checked the plates for tracks in the following days. They found various tracks and footprints and tried to figure out what had caused them. The traces on the plates were often unclear, which caused uncertainty about whether they had been caused by rats or some other creature. Students had been shown pictures of rat tracks on the plates beforehand, but only a limited time had been spent on practicing to identify rat tracks.

On both occasions, the students typically envisioned and discussed different scenarios of the rats' movement in the area; when observing the tracks, they considered what might have happened. These scenarios were informed by students' knowledge of rats and other species, such as rats' preference of

TABLE 1 The amount of data by groups within the different responses to uncertainty.

Response to epistemic uncertainty	Combined length (minutes; G=group)									
	G1	G2	G3	G4	G5	G6	G7	G8	G9	total
Envision alternative scenarios and narratives	3	6	4	10	5	8	8	4	4	52
Stay with uncertainty as a resource for argumentation	2	3	0	4	1	12	7	0	6	35
Overcome uncertainty of having the right result	1	3	0	1	0	6	9	0	1	21

Note: As the responses can overlap, the total amount (108 min) differs from the length of analyzed episodes (106 min).

walking close to walls, but many times also combined experiences from students' everyday life and of the urban environment. For example, when discussing the plate placement, students visioned how rats would step out of their assumed home (hole in the ground) at night, play parkour on the wall and in pipes, hide behind boxes, walk, or crawl or chill out in the dark places, or possibly be too chubby to fit into a hole. The following fragment shows how various scenarios of what the rats might do are brought up and discussed while a student group is deciding on a place for their fourth (last) plate.

Fragment 1. Student group 4 (all names are pseudonyms).

```
 1 Tomas: let's put it there ((points at something;
          Fig. a))
 2 Pauli: there (..) where
 3 Tomas: under the tree
 4 Leo:   why
 5 Tomas: [under the tree]
 6 Pauli: [why why] would rats go that way
 7 Leo:   why would rats [go there they're not]
 8 Tomas: [I don't know they want if it's raining and]
          they want to go under a tree
 9 Leo:   [we're studying ra
10 Pauli: [well then they go there under the roof
11 Leo:   we're [studying rats not birds]
12 Tomas: [well what if] they don't get it or what if they
          go to that vent and vent away ((points at a vent
          on the wall; Fig. b))
13 Tomas: ((laughter)) [vent away]
14 Leo:   ((laughter)) [I guess now you know] we're
          studying rats [not birds
15 Tomas: [then we know that rats are imposters
16 Leo:   ((laughter))
17 Tomas: or there for example (.) there at the wall
          ((points at the wall, Fig. c))
```


a


b


c

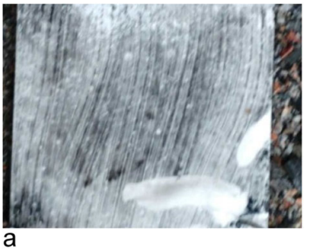
At the beginning of the episode, Tomas suggests putting the plate in the direction indicated by his hand, specified as "under the tree" when asked by Pauli. Leo reacts to this suggestion by asking for arguments, which indicates that they disagree with the suggestion. This is further implied by asking why rats would go under a tree (turns 4 and 7), Leo begins to utter about rats not being something (turn 7). "I don't know" in the beginning of Tomas' response (turn 8) can be heard as him not being certain about his following proposal. Thus, the following argument that rats want to go under the tree for rain cover can be heard more as a speculation of a possible scenario than knowing something for certain. Pauli picks up on Tomas' argument about the rain and utters that rats would rather use the roof as a shelter (turn 10), which can be heard as an alternative scenario. Meanwhile, Leo simultaneously continues and repeats his statement (turns 9 and 11) that they are investigating rats and not birds. The repetition implies that he is waiting for someone to pick up on his words, but receives no answer. Tomas' utterance (turn 12) is most likely a response to Pauli's argument about the shelter. He then brings in yet another option, marked by "or," about the rats going to a vent (visible for all on the wall) and "vent away." Now, all together three alternative scenarios of rat actions have been raised. Reactions from Leo and Pauli following the "vent away" scenario is laughter, which can be heard as if treating it as funny or as a joke. Tomas continues to develop this scenario of rats as "imposters," again greeted with laughter by Leo. The students' reactions indicate that they have a shared understanding of something that is meant by "venting away" or "imposters" that is not evident in the common sense of these expressions as it would make little sense in the unfolding dialogue. This shared understanding turns out to stem from shared experiences of a video game *Among Us*, the name of which the students mention several times during the lesson and in which special meanings are granted for terms "venting" and "imposter." As the analysis of the conversation requires (only) to hear the participants as they hear (understand) each other (Garfinkel & Sacks, 1986), some understanding of a shared video game culture is required to understand how the everyday experiences of gaming inspire an alternative scenario of rat movement. At the end of the episode, Tomas suggests a new spot for the plate close to the wall (turn 15). This is the spot where the plate is eventually placed, similar to an earlier plate that was situated close to the wall.

Altogether three alternative scenarios of what the rats might do have been brought out in the episode: seek cover from the rain under a tree, seek shelter, and go into a vent. The episode shows how the scenarios envisioned by the students were relevant to the task. Some of them, for example, the one about seeking cover under a tree, evoked different opinions and discussion and provoked alternative narratives. We can see how students end up treating the narrative of rats seeking cover under a tree as less viable than seeking cover under the shelter, which was followed by the students' decision not to place the plate under the tree as Tomas first suggested. However, even when the envisioned scenarios did not cause disagreement or debate, they allowed students to represent their ideas and understanding about rat behavior as well as the environment; thus, each scenario contributed to making choices about the placement and advanced the completion of the task.

Like the envisioning of future scenarios when placing the plates, the discussions on what had happened around the plates also incorporated alternative pasts and narratives. For example, the students discussed possibilities of other animals having passed across the plates, pieces of plant having dropped on the plate causing prints in the paint; they tried to differentiate brush strokes from other traces. Many times, the hypothesized pasts extended from rat presence to other (urban) life around the plates. The following fragment shows how a student group observing two of their plates on the first day tried to deduce what had caused the tracks and build a narrative of something having moved the plate.

Fragment 2. Student group 9.

1 Elias: but what can that be that track ((looks at the plate; photo of the plate in Fig. a))
2 Oliver: well probably someone has come to see what that is and then (.) I don't know maybe been drunk and tried to grab that weird tag ((a tag attached to the plate with information about the research)) but then grabbed the plate ((laughter)) and then that kind of [line formed
3 Elias: [yeah isn't a thumb just like ((places his thumb close to the plate; Fig. b))
4 Oliver: yeah
5 Leevi: yeah you said that it is pretty slippery (.) or something like that
6 Elias: well but I don't know [what kind of]
7 Leevi: [or then he just] borrows it for [other purposes
8 Elias: [no look it has moved from there to here
9 Oliver: yeah
10 Elias: someone has come and touched it
11 Leevi: someone has moved it (..) vandalism


a


b

The episode begins with Elias presenting a question about a track. The form of the question ("What *can* that be?") can be heard as asking for *possible* explanations rather than a single certain answer. Oliver's response begins with "maybe," continuing the speculative tone raised by Elias, and presenting his following explanation as a possibility rather than a fact. Oliver's suggestion about a drunken person having moved the plate and caused the tracks is then treated with an agreement interjection "yeah" by Elias, who continues with an unfinished notion of a thumb having to do something with it. Both Leevi and Oliver agree with this (turns 4 and 5), and Leevi continues by referring to their previous experience of the slipperiness of the plate. "Or something like this" at the end of the comment can be heard as maintaining its speculative nature. Following "yeah but" can be heard as a doubt of something previously expressed, after which Elias makes an unfinished expression of not knowing "what kind of" (turn 6). What he refers to cannot be known for sure as no one addresses it, but might well refer to not knowing previous events. Leevi then expresses an idea that the person responsible for the tracks might have borrowed the plate for other purposes, which is rejected by Elias who notes that the plate has only been moved a little bit. At the end, the students agree that someone has touched the plate and moved it; Leevi suggests that it could be vandalism.

The episode exemplifies a typical situation in which students see a mark on the plate and come up with one or several explanations for what has caused it, or, in this case, also the relocation of the plate. The story of a drunken person touching a plate is narrated right after the observation of the mark as a response to the question by Elias. Next, the students evaluate the story based on what they know about the characteristics of the painted plate and what they see. All in all, looking for an answer to the original speculative question about what the mark can be unfolds as a speculative narrative of past occurrences, expanding it based on observations, and finally evaluating the feasibility of what has been suggested.

Two aspects are common to both described occasions of task-related epistemic uncertainty leading to production of alternative scenarios and narratives. First, the students began producing speculations, alternative scenarios, and anecdotal suggestions around the question at hand instead of focusing on finding the correct answer to solve the question and reduce uncertainty. In comparison, an experienced person would have been able to pick the best places for plate placement or identify tracks more easily. However, instead of getting stuck on not having enough knowledge to be certain, the students came up with various possibilities that allowed them to manage their uncertainty and make sensible choices regarding plate placement and track identifications.

Coping with epistemic uncertainty through alternative scenarios and narratives makes sense from the perspective of science practices. The object of scientific research—here ecological citizen science research—is to obtain new knowledge and ways of knowing the world. Because the new ways of knowing did not exist before, uncertainty of what the world (phenomenon) is an integrative part of the process, and new knowing requires employing scientific practices. The uncertainty of not knowing if the rats will be or are present in the chosen location is not treated as a problem that would need to be fixed before continuing with the task, but it appears as producing alternative (future or past) scenarios to be discussed and evaluated.

Existing studies have shown that moments when students knowing or being able to reproduce canonical scientific knowledge or practices tend to evoke frustration (Kervinen et al., 2020a) or lead to seeking answers from the teacher (Bellocchi & Ritchie, 2015). By contrast, resorting to hypothesizing alternative scenarios appears to mitigate such reactions: the students did not exhibit frustration in their interaction and advanced with the task independently. The speculative nature of the scenarios and explanations, in turn, made sense as speculation about what might happen instead of uncertainty about the right answer of what should happen.

The second aspect common to the above-described reactions to epistemic uncertainty is that students drew from different sources of knowledge to envision scenarios and narratives. Not only students' prior knowledge of rat ecology and behavior, but also their knowledge from their previous experiences in urban spaces as well as everyday lives was used to make the narratives of the course of events. For example, Fragment 1 shows how everyday experiences from seeking cover from the rain and participating in a video game become integrated in the scenarios.

In this respect, the ways in which students approached epistemic uncertainty were not only consistent with the practices of scientists but also relevant to themselves. Merely the use of narrative elements—such as temporality and sequence—in their scenarios is a characteristic form of thought and language that enables humans to relate to the cultural world (Ricœur, 1991). Thus, connecting scientific inquiry with the everyday forms of relating to the world could allow the students to students engage in doing science in ways that are meaningful in their everyday lives (cf. Kervinen et al., 2020b; Ko, 2021). The observed actions such as narrating a story of a drunken person having moved the plate or envisioning a rat parkouring in the walls were relevant and meaningful forms of hypothesizing and speculating as they were equally viable routes towards the yet non-existent knowledge of rats than others.

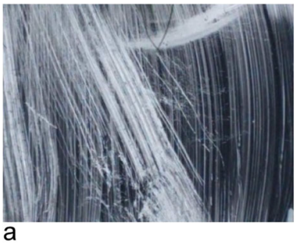
3.2 | Staying with uncertainty as a resource for argumentation

Students' responses to epistemic uncertainty when not knowing the correct answers yielded alternative narrative scenarios and hypotheses for discussion and evaluation, but they rarely led to certainty of the interpretation (knowing what exactly had happened on the plate) or the methodological choice (knowing what the optimal spot for the plate) would be. However, the students did not seem to be much disturbed when these questions were left unanswered. In this subsection, we focus on the ways in which students discussed and evaluated the uncertain observations to show how the maintained uncertainty and even disagreement worked as a resource for doing (participating in) science rather than presented obstacles.

Students were asked to count what they thought of as rat tracks and report them in the application, but they knew that the photos would be double-checked and that they could discuss the findings with the (other) researchers at the end of their inquiry. This led to several discussions, in which the students did not decide or agree what had caused the tracks. In these instances, arguments unfolded about what the tracks could be, but students also maintained the position of uncertainty as they contented themselves with not knowing for certain the origin of the tracks. The following fragment exemplifies a typical discussion around the observations and how students reach an agreement about not being sure about the tracks. The student group is observing their plate on the first day.

Fragment 3. Student group 9.

1 Elias: this is quite exciting are those leaves or what
are these kind of ((photo of the plate in Fig. a))
2 Oliver: I don’t know
3 Elias: [you can see]



a

4 Oliver: [or some] rat have jumped there and slid from
there haha
5 Elias: cause that’s pretty downhill
6 Leevi: [yeah yeah it could be just tssssh ((a sibilant
sound))
7 Elias: [no
8 Oliver: [well okay that is hardly the case but
9 Leevi: but it looks like someone had scratched it anyway

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10 Elias: yeah scratched ((makes gestures of scratching with his hand; Fig. b))
11 Oliver: hmmm
12 Elias: because
13 Leevi: yeah it looks but it looks like maybe a bird (.) don't birds have kind of long like for example crows ((moves his fingers; Fig. c))

14 Elias: yeeeah
15 Oliver: well I don't know
16 Elias: well don't birds go along the ground too
17 Leevi: yeah yeah
18 Elias: but I don't know if they will go that kind of straight track there ((makes a line with his finger pointing at ground; Fig. d))
19 Oliver: hmm
20 Leevi: hmm
21 Elias: or if they start to slide there ((bends on his knees)) kind of because that cannot that cannot be that slippery really
22 Leevi: I don't know
23 Elias: I don't believe in that myself
(...)
29 Leevi: there (.) and then we will put here that (..) we cannot say that those are rat tracks
30 Elias: but something for example from birds maybe
31 Leevi: Yeah but we cannot put rat tracks we'll put zero in all of these
32 Elias: lets' put that (..) oh noooo


b


c


d

The episode begins with Elias questioning the tracks and suggesting that they might be caused by leaves. Oliver expresses uncertainty and after Elias comments addressing the tracks and what they look like. Oliver begins to envision a scenario with a rat sliding over the plate (turn 4), which Elias and Leevi expand (turns 5–6). Elias' "no" can be heard as rejecting this scenario while Oliver agrees as being "hardly" the case (turn 8). Leevi introduces a new option about someone scratching the plate, which is acknowledged by Elias and Oliver (turns 9–11). Elias utters "because" which can be heard as beginning to explain something. Meanwhile, Leevi continues his suggestion about scratching by contemplating how birds might have caused the tracks. Elias' response "yeah" is prolonged (turn 14), which can be heard as a sign of doubt instead of acceptance, and Oliver's response is doubtful as well (turn 15). Elias' comment (turn 16) can be heard as a counter-argument, addressing birds' possible ways of movement. Students then judge the possibility of bird tracks without taking a clear stand for or against it, and Elias expands the speculation about possible movements (turns 17–21). As Leevi expresses that he does not know and Elias doubts the possibility (turns 22-23), the students do not come to agree on the track being from a bird. A moment later, when filling in the information, they decide not to report any rat tracks, but leave open the possibility for bird tracks (turns 29–32).

Whereas students discuss rats and birds as alternative explanations for the tracks, they are not sure about either and end up reporting no rat tracks. The episode shows how argumentation over different explanations is characterized by uncertainty and estimation of probability. The students use expressions, such as "maybe" and "could this be," that imply likelihood rather than intention of knowing without a doubt. The result of not reporting rat tracks is based on the notion that they "*can't say* that they are rat tracks," rather than knowing that they *are not* rat tracks, which further implies the high risk of error in reporting rat tracks. Argumentation that incorporates the interpretation of evidence and the related error is typical of scientific research that is grounded on empirical observations (Latour, 1987; Martins & Macagno, 2022). The outcome of the research activity can be knowing something with a certain probability or even *not knowing* something at all. Thus, accepting uncertainty and not knowing as a feasible result was in line with practices of science as *no one* knew the answer *at the moment* better than the students. This further allowed the students to maintain the speculative tone in their discussion and conclude with a measure of uncertainty, which is inherent to scientific practices.

At times, the students' disagreement about the tracks was more prominent, and they could not reach consensus that easily. Even then, the uncertainty and disagreement appeared as a resource for argumentation rather than a hindrance to the task. The following fragment shows how disagreement develops throughout an episode of observing possible rat tracks. At the beginning of the fragment, the students are observing one of their plates for the first time after placement.

Fragment 4. Student group 7.

```
1 Julius:  yeah but are those rat tracks ((observes the
           plate; Fig. a; photo of the plate in Fig. b))
2 Max:     well I don't know they are some tracks aren't
           they because you can see that it has kind of
           slid maybe (..) [unevenly]
3 Julius:  [I think] that those are those are not quite
           rat tracks
5 Julius:  [okey we don't] have to count them then
6 Max:     well (..) someone has gone here
           (...)
           ((Carl arrives))
53 Max:    Julius has like a strong opinion that they are
           not rat tracks (..) I don't know because
           surely these are some well someone has gone
           here (..) there you can see that it has kind of
           slid a little there
54 Carl:   might be
55 Max:    something has been jumping there
56 Julius: I still say that they are small rocks
57 Max:    no how can they be small rocks (..) who would
           have come here to throw small rocks (..) and
           why wouldn't they still be on there
           (...)
71 Max:    well we don't know if these are
72 Carl:   confirmed amount [is zero]
73 Julius: [ah] ((reads from the phone)) rat [rat tracks
74 Mike:   [yeah yeah yeah
75 Carl:   yeah
76 Julius: [okay
77 Mike:   [there is that kind of statistics separately
78 Julius: ah nice
```

a


b

At the beginning of the episode, Max and Julius are observing the plate and have agreed that there are some tracks there. Julius questions whether the tracks are made by rats. Max first expresses uncertainty, but speculates how "it has kind of slid" on the plate. What he refers to by "it" cannot be concluded from the interaction for certain, but it implies that some object or entity was able to cause the marks. The way Max refers to "some tracks," and emphasizes in turn 6 that "someone" has moved on the plate, which can be heard as implying that the marks are interesting and caused by a living entity.

The students continue arguing about whether the tracks are caused by rats or not when the other two of the group join Max and Julius a moment later. Max describes the disagreement and repeats his argument of "someone" sliding on the plate indicating a possibility of rat tracks (turn 53). Carl agrees with Max about this possibility, maintaining the speculative tone (turn 54), after which Max continues to envision that "jumping" might have happened. Julius still disagrees with the possibility of rat tracks and provides an alternative explanation of small rocks having caused the traces (turn 56). Max disagrees with this and makes counter-arguments questioning the plausibility of the "small rocks" explanation.

The discussion concerning the origin of the traces soon closes when Max and Carl decide to count the possible tracks and fill in the information in the mobile application. Max states that they are not sure about the tracks and Carl utters that "the confirmed number is zero" while typing on the phone, repeating the words used in the form (turn 72). Julius looks at the phone and utters a sound "aah" and reads the words from the phone partially aloud, which can be heard as if he understands something new or interesting. Turns 74–76 can be heard as agreeing about reporting the separate numbers of confirmed and unconfirmed rat tracks, which is also explicitly stated by Mike (turn 77). Julius' comment "ah nice" can be heard as agreement of their decision of reporting the two numbers and that they have confirmed zero rat tracks. In the end, all the students agree that they are not sure about whether the tracks are caused by rats, but that they can report this finding as tentative and to be later evaluated (and eventually confirmed with researchers).

In the episode, the disagreement about the tracks maintained among the students throughout the argumentation and was finally ended when the students acknowledged uncertainty as a sufficient outcome. Coping with the disagreement did not lead to the discovery of final correct answer, but rather alternative explanations were explicated and argued. In this process, disagreement was not so much about knowing or not knowing the correct answer, but it concerned and needed to be argued in terms of the (un)certainty of knowing. As the results are estimates that might need further investigation rather than final answers, the (prolonged) uncertainty is part of the scientific process. Hence, the maintained disagreement also makes sense as an outcome of engaging in science.

At the end of the inquiry, the students discussed their plates and pictures with each other, the teacher and expert scientist evaluated once more whether there had been rat tracks or not. However, instead of a sense of failure for achieving the correct answers (which nobody had at the time), students could content themselves with not knowing exactly earlier as a form of most precise scientific knowledge at the given point in time, as reflected in Julius' words ("aah nice") at the end of the episode. In the final collaborative discussion, the uncertainty and disagreement had already served as resources for argumentation, evaluation, and articulation of new ways of (not) knowing the world and doing science for the students.

3.3 | Overcoming uncertainty of having the right result

When students placed the track plates, they were very much looking forward to finding rat tracks in their chosen spots. This was evident in their uttered expectations such as "hopefully we get traces there" (Group 1) or as fears such as if "we have very poor spots in the end […] and no rat will walk on the plates" (Group 2). Moreover, when the students were checking the plates on the following days, not finding any (rat) tracks was with every group treated with disappointment ("ah, it's the same stick tracks as the last time" (Group 1); "no rats, damn (…) oh no, and we had such a good spots" (Group 5); "even a mouse would be nice" (Group 1). When asked at the end of the inquiry, students reported that they would have liked to find rats "as it was what we were looking for." Only three of the nine student groups followed found rat tracks during the inquiries, and two of those groups identified the tracks as rat footprints only with the help of researchers at the end of the inquiry. Thus, when checking the plates, disappointment, or neutral reactions of not finding rat tracks were common. By contrast, the few groups that realized that they found rat tracks were excited about the finding. In this subsection, we focus on students' ways of coping with the uncertainty related to interpreting the result of their inquiry. We show how students' expectations and disappointments led to uncertainty of the successfulness of the research, but students dealt with the uncertainty with flexibility and reframed their thinking in ways that are typical of scientific research.

After the inquiry, the students were asked about whether they thought that their research was successful. Almost all groups ended up considering that even though they did not find rats, the study could be considered as successful as not finding rat movement in the chosen places was a result. For example, one student expressed this, including the notion that the plates themselves worked fine as other traces were captured on them:

> well yes kind of in a way that we saw like tracks, but they were not rat tracks (.) so if we study whether there are rats or not, then I can say that not (Leo, group 4)

Students' answers indicate that even if the students were eager to find rat tracks and disappointed by not finding any tracks, they were able to contextualize the activity as solving the question of rat presence in a chosen location. What appeared as emotionally loaded hopes and fears of success (e.g., fear of having chosen “poor” spots) and which can be heard as uncertainty of having *good* results was later reframed as a neutral outcome compliant with scientific approach. As an exception, one group was a bit more hesitant as shown in the following fragment.

Fragment 5. Student group 7.

```
1 Researcher: what do you think was this study successful
2 Mike:        no
3 Carl:        [well I don’t know maybe
4 Max:         [hmm hmm (.) maybe
5 Mike:        [or if there are rats here [then yeah
6 Julius:      [well (.) we didn’t find rats but at least we know now like that there
               are not much rats going around that building at least
7 Mike:        or there are just rats that don’t walk on our plate
8 Researcher: well at least your plates were on good spots
```

The fragment begins with the researcher's question about the successfulness of the study. Mike immediately responds “no,” while Carl and Max respond with comments that can be heard as hesitation. Mike then extends his previous answers with an alternative (marked by “or”) that if there are rats present, the study would have been successful, something to which other students do not audibly react and the meaning of which therefore remains unknown. Meanwhile, Julius expresses a positive answer to the original question noting that they now know that there are not that many rats around the building. Mike extends to this notion (marked again by “or”) by suggesting that the rats might just have evaded the plates. The researcher then adds that (according to his past experience) the plates were in reasonable spots, which can be heard as an answer to Mike's suspicion about the reliability of the research method and support for the validity of the result of negative rat presence. Thus, this group also appears to consider the study as successful in the end, as Mike's negative first reaction appears to develop into discussion on the validity of method, which is an evaluation integral to scientific practices.

Framing and reframing the successfulness of inquiry in terms of the scientific process was also exceptionally visible within the same group earlier in the second day of the inquiry. When the students came to notice peculiar tracks in their plates that were placed close to the kindergarten building, the following discussion unfolded in which they dealt with the uncertainty of success by expanding beyond the original research question of rat presence.

Fragment 6a. Student group 7.

1 Mike: oh track tracks (..) hey those are triangles
((photo of the plate in Fig. a))
2 Julius: triangles aha
3 Mike: someone has drawn here
4 Julius: hey there are there are tracks here
((gestures to Max and Carl)) (.) they are
kind of mysterious triangles (.) [hmm
5 Mike: ((Max and Carl arrive)) [are these rat tracks
6 Julius: well what you think
7 Mike: I have a feeling that these are some
illuminati
((laughter))
(...)
10 Max: there are shoe prints in one and one has
((photo of the plate in Fig. b)) (..) been
drawn into
11 Mike: one has a heart (.) one has shoe tracks and
here there is illuminati ((laughter))
(...)
51 Julius: if we ask those to raid the shoe of that one
52 Max: quite (.) yeah (.) small shoe
53 Mike: we must check whose shoe print that is (..)
that looks like very small [like a shoe of a
very small kid
54 Carl: [well hey
55 Julius: no but look (.) we don't need the shoe print
(.) let's just go and rummage the shoes of all
those and like who [has that in the sole then
56 Max: [haha (.) okay
57 Mike: this looks like a very small [kid look
58 Julius: [yeah
59 Mike: the kid must have walked here to hide and
stepped there and then they have played
some game
60 Carl: yeah

a

b

At the beginning of the episode, the students are observing the plates on the first day and find tracks that turn out to be triangles. Mike suggests that they are drawn on the plate (turn 3), and Julius calls the rest of the group from observing another plate (turn 4). Julius' response "what do you think" (in which the lack of rising intonation implies that it is rather a statement than a genuine response) can be heard as a doubtful or negative response to Mike's question about the whether the tracks belong to rats. Mike suggests that the tracks were caused by Illuminati (turn 7), which was followed by laughter by all, that can be heard as acceptance of the previous comment as humorous rather than serious (see Jefferson, 1979). Max suggests again that the observations from two plates are drawings and shoe tracks (turn 10); Mike refers to Illuminati instead of triangles in a humorous manner marked by laughter.

Julius' comment a moment later (turn 51) about asking somebody to raid the kindergarten's shoes can be heard as a reference to the personnel and children, to which the students have referred previously. What unfolds next, can be heard as Max, Mike, and Carl picking up on Julius' suggestion about further actions to investigate the origin of the tracks (turns 52–54). Mike proposes that the students should find out who belongs to the shoe that made the track; both Max and Mike suggest that it is small and might belong to a child. Julius then suggests an approach of searching through all the shoes from the kindergarten and comparing them to the tracks (turn 55). This is agreed upon by Max, who adds "ha-ha," which can be heard as not treating the suggestion very seriously. Mike then proposes a scenario of a child walking on the plate when hiding as a part of a game (turn 59), which is commented by Carl as plausible.

In the episode, students conclude that the tracks on the plates have been caused by kindergarten children rather than rats. However, whereas they might have decided to settle on that conclusion and continue to check the other plates, the students instead develop ideas of how the tracks might have been caused. They propose various ways to find out more about the origin of the tracks. A scenario is presented about what they could learn from the tracks about the environment and who has moved where. Some moments later when the students have checked all their plates, the following discussion about their inquiry unfolds.

Fragment 6b. Student group 7.

1 Mike: this is just awful our research so have others (.) for sure others have had some results
2 Julius: well isn't this research just fine
3 Mike: isn't that a little kind of
4 Julius: could we just change this research like into something under eightyear olds next to plates
5 Mike: I thought that
6 Julius: that would make good research
7 Mike: I overestimated eightyearolds (.) I thought that they had been just a little bit ***

Mike suggests that their inquiry is awful and wonders if other groups have got results, implying that they have not got any. Julius, on the other hand, responds that their inquiry is "quite fine." Mike's utterance (turn 3) can be heard as asking for some clarification on Julius' comment. Julius asks if they could change their study to something about eight-year-olds close to the plates, which can be heard as a reference to their previous discussion about how the children had caused the tracks. Julius answers his own suggestion that it would be a good study, whereas Mike does not audibly accept or reject the idea, but comments on how he had overestimated that it might have been someone eight years old (turn 7). Whereas this might refer to how the children have deliberately caused some of the tracks, it may also be heard as an acceptance of Julius' suggestion about them knowing something more about children in the area.

That the students continue their deduction based on the tracks by children, develop a new understanding of how they have acted in the environment, and even frame this new understanding as if it could be an outcome from another research question does not advance their understanding about the original questions of rat presence in the environment. They are rather building new knowledge about the world through the track plate. Whereas this might appear unrelated to the specific science inquiry at hand, and not lead to scientifically evaluated new knowledge, it actually makes perfect sense in terms of the characteristics of scientific practices. As the (contemporary) observations suggested that the rats were not present in the area, new questions about what was present and moving around in the area became relevant. In science, ending up with new questions about what is happening in the world is as feasible an outcome as having or not having the expected result (Dylla, 2020). In this case, the movements of different species in the area are interrelated and do not occur in isolation; thus, they affect each other. The fragment demonstrates how students expanded their engagement with scientific practices from concluding about rat presence to devising new questions and explanations based on evidence and developing methodologies without any of these actions being contradictory to or counterproductive with their original inquiry.

Reframing the initial hopes and subsequent disappointments regarding finding rat tracks as well as expanding the original research questions towards other new ways of knowing the world both worked as ways of coping with the epistemic uncertainty of having *the right* result. Instead of clinging to the disappointment of not finding rat tracks, students drew from the characteristics of authentic scientific research (within the citizen science context) to create space to revisit the expectations and reconceptualize the aim and result of the study if needed. Accordingly, uncertainty was once again reconceptualized as a resource to be used in scientific practices instead of a hindrance to the process of doing and learning science.

4 | DISCUSSION

In this study, we demonstrate how students responded to epistemic uncertainty of a citizen science inquiry in ways typical of scientific practices. The findings show how the inquiry setting in which no one knows the answers or the optimal choice beforehand can allow students to handle increased uncertainty in productive ways that would be less feasible if the right answers were available. By articulating ways to respond to epistemic uncertainty in a rather unique citizen science setting, this study adds to our understanding of uncertainty as a pedagogical resource: settings in which uncertainty is shared can provide students opportunities to respond to experiences of epistemic uncertainty in emotionally and epistemically productive ways. Instead of frustration from not knowing the correct answers, students may draw from epistemic practices of science such as producing alternative solutions and tentative interpretations. Expanding the idea that teachers support students to manage uncertainty by scaffolding and deliberately withholding certain answers (Chen et al., 2019; Manz & Suárez, 2018), our study foregrounds an approach to introducing uncertainty in science classes by designing settings in which also the teacher does not know the correct answer beforehand.

4.1 | Students reframe uncertainty

Our findings exemplify three specific ways in which students responded to epistemic uncertainty arising in science inquiry: they chose to (a) envision and hypothesize alternative narrative scenarios when facing the uncertainty of knowing the answer; (b) accept uncertainty as a viable result in the argumentation over alternatives; and (c) reframe the research activity and its goals flexibly when facing the uncertainty of having a desired result.

Remarkable to each of these means is that they did not involve students expressing (or treating any expressions as) frustration of not knowing something for sure, although this has been observed in science lessons where they were required to find the right answers (Bellocchi, 2018; Kervinen et al., 2020a). On the contrary, the students did not exhibit in their discourse the need to arrive at the correct answer or seek a resource to know it for sure, but rather settled with *reframing* the uncertainty as a resource that allowed them to pursue their inquiry. In fact, the observed responses to uncertainty were much more typical to the scientific research process than immediately concluding the correct answer or not experiencing uncertainty at all. Even the disappointment of the students that was caused by having undesired results approximated one of the scientists rather than of learners failing to perform.

Epistemic uncertainty and different ways of handling it unfolded when there were multiple possible options for action that the students could not easily decide on based on their prior knowledge. For a professional ecologist with extensive prior experience of research and rats, it would have been relatively easy to know the most scientifically viable alternative to many questions that arose for the students. Furthermore, a professional ecologist would have been able to draw from past field experiences and literature to better evaluate alternative scenarios, be more confident (or even more uncertain) on some speculations, and come up with new insights and research questions that have more relevance to the current research project or the field in general. However, the task required the students to make choices and use whatever prior knowledge and experiences they had. The students used their existing knowledge to produce knowledge about the rat presence that was new for everyone (and potentially develop into new scientific knowledge as the process continues) instead of re-producing something that someone already knows. Thus, even with some differences to professional ecologists, the students' handling of uncertainty was similarly relevant and authentic regarding the goal of the research. Instead of treating their prior knowledge as incomplete and inhibiting their activity, the students were able to make use of the particular feature of the citizen science setting aiming for new scientific knowledge: the uncertainty, not knowing, and new questions are not only related to the process of inquiry, but also a viable outcome (Dylla, 2020).

The findings of this study also show how students reframed uncertainty through the integration of their everyday experiences in the inquiry processes. Integration of everyday forms of knowing is essential to make science teaching meaningful for the students (e.g., Archer et al., 2010; Ko, 2021), and it has been shown that the absence of a teacher can enable such connections particularly well (Kervinen et al., 2020b). The present study extends the previous work by showing how an authentic research setting allowed students to use their everyday experiences as a resource to cope with uncertainty that is meaningful not only for themselves, but also for the production of new knowledge about the world. Indeed, in both science labs and the field, all ways of thinking and knowing that guide the researcher toward desired knowledge are valuable, and there is no need to distinguish between what is known from everyday life and what is known from existing representations of science; new forms of scientific knowledge often even require stepping away from what is already known and imagining new possibilities (Latour, 1987). Providing such opportunities for students can serve an important purpose of crossing the boundaries of mundane and scientific worlds by demonstrating the power of everyday knowledge in science. Whereas dilution of empirical and objective basics of science could lead to the risk of epistemological relativism (Romero-Maltrana et al., 2019), the student's use of their everyday experiences and knowledge were in line with typical scientific practices. Thus, it helped incorporating students' knowledge creation to a scientific framework rather than obscuring the boundary of science and nonscience in harmful ways.

4.2 | Implications for science education

Uncertainty related to scientific knowledge production has been shown to work as a conversational resource in teachers' questioning behavior that creates room for personal decision-making and grants ownership of activities to participants (Roth et al., 2008). This study shows how the epistemic uncertainty that arose without the teacher or the right answer being present worked as a resource for students' mutual interaction that shifted the focus from knowing the right answer to the *actions* that pave the way for knowing better. The findings provide an important understanding for the development of science curricula and teaching practices where students productively engage with uncertainty in a variety of contexts.

Practices inside and outside classrooms would benefit from intentionally designing settings where no one knows beforehand what will be discovered. Examples of useful classroom activities could include exploratory inquiries on different environmental topics or engineering projects in which the best solution needs to be found, but in which the correctness or feasibility of the answer can be known and evaluated only after having it. In such tasks, students use their knowledge and possible support from the teacher or from other resources to produce new knowledge for them and the teacher instead of re-producing something that the teacher already knows. This study suggests that such a setting can increase opportunities for students to use epistemic practices that are typical to scientific research while decreasing negative emotions from failure to re-produce the correct answer.

Endorsing and foregrounding such shared uncertainty as a pedagogical resource may help educators balance between productive and unwanted forms of uncertainty: whereas teachers need to find ways to engage students with uncertainty without unduly increasing their own uncertainty (e.g., Manz & Suárez, 2018) and students get frustrated when not knowing (e.g., Bellocchi, 2018), uncertainty that is shared by the both can be used as a resource to reframe these experiences to be part of doing science. This idea is in line with the call by Manz and Suárez (2018) for a more nuanced negotiation of teacher and student control over how uncertainty unfolds and is managed. Our findings encourage teachers to deliberately emphasize uncertainty as an accepted part and even an outcome of the inquiry process whenever possible. When uncertainty is accepted as part of doing science rather than something to be avoided and removed, students may find it easier to engage in practices such as speculating and making arguments on different scenarios and coming up with new ideas and questions.

The findings of this study demonstrate how collaborating with professional scientists can provide excellent opportunities to implement authentic inquiries in science teaching. When participating in such projects or transforming such practices of authentic (new) knowledge production in classrooms, it is important to realize that the authenticity of science can be realized in learning activities in different forms. Whereas cognitive resemblance between a classroom inquiry and a professional science inquiry may serve many purposes (Roach et al., 2018), some aspects of authenticity may manifest only when students identify themselves with the motives and goals of the research (Roth et al., 2008). Either way, it appears essential that in both citizen science projects and science classrooms the students can actively make epistemic choices on how to proceed with the inquiry process. In our study, the most essential aspect of authenticity was related to no one knowing the desired outcomes beforehand. When this is the case, the uncertainty ingrained in the scientific process unites the students and the teacher rather than separates them with regard to having the knowledge (and power) of science.

4.3 | Limitations and future studies

This study illustrates the ways to manage epistemic uncertainty during inquiry that approximates scientific research in a sense the aim is to produce new knowledge of the world, and no one has ready answers at hand. Whereas the present findings do not indicate if or how these experiences of doing science led to increased conceptual understanding, the previous studies have shown how management of epistemic uncertainty also support conceptual learning (e.g., Chen & Techawitthayachinda, 2021; Hartner-Tiefenthaler et al., 2018; Watkins et al., 2018). This study showed that the responses allowed continuing with the inquiry and reaching the goal of engaging in doing science. Future studies investigating science learning activities might suggest that emphasis on the uncertainty which is *shared with the teacher* may lead to fruitful opportunities to frame both the science content and the classroom interactions. This might show as improved discussion and argumentation among the students, less emotional stress of failing to provide the correct answers, or increased understanding of the nature of scientific knowledge.

The present study does not address the trends or prevalence of the different responses to uncertainty among different students or instructional settings. However, as these ways present cultural opportunities of doing and learning science, the findings transcend the individual cases (cf., Rawls, 2002). Indeed, similar phenomena were observed widely across the data and different student groups even if they were highlighted within some groups and in the episodes selected for the report.

School science teaching tends to appear as rigid system that is difficult to fully disrupt toward knowledge development in a way that characterizes science (e.g., Aikenhead, 2001; Sharma & Anderson, 2009). Whereas we focused on the interactions in which students reframe uncertainty in line with science practices, we cannot know to what extent the individuals consider the activity as a (citizen) science inquiry versus a school task. The post-activity interviews imply that the two settings intertwined: many students found the inquiry to be fun because it was different from "typical school lessons," but still reported to have thought about the larger citizen science project only occasionally. However, the findings concern opportunities that arise when the task approximates authentic forms of science regarding someone knowing the right solutions beforehand regardless of the setting. As citizen science activities can be valuable contributions to the challenging task of transforming science education towards more authentic practices, future studies should investigate how to design collaboration with professional scientists so that students' choices and uncertainties are relevant part of the research process (cf. Bonney et al., 2016; Rautio et al., 2022).

5 | CONCLUSION

The goal of science education to engage students in *science in the making* entails the inclusion of epistemic uncertainty and practices of managing that uncertainty in classrooms. Whereas unexpectedness and not knowing are easily framed as failures (cf., Roth et al., 1997), the present study demonstrates that an inquiry setting with no correct answers available allows opportunities for students to reframe the uncertainty in productive ways.

Uncertainty that is shared with the teacher and work as a pedagogical resource increases the emotional space for the students to respond to uncertainty. We observed how students who were producing new ecological knowledge responded to arising uncertainty through scientifically relevant activities that relied on maintaining a level of uncertainty rather than quickly ending it to reach the expected or correct outcome. Increasing such forms of uncertainty in classrooms will also increase the uncertainty for the teacher. However, if it can also enable the students to make use of the experiences of uncertainty in productive ways, educators should not shy away from incorporating this aspect of science into classroom contexts. When the uncertainty is accepted as an integral part of scientific inquiry, even as an outcome, it may not hamper the students from successfully completing the inquiries. On the contrary, such emphasis in pedagogical design can allow students to access doing and learning science in more authentic and meaningful ways.

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data are not publicly available due to privacy or ethical restrictions. Requests to access the datasets should be directed to the corresponding author. The datasets presented in this article are not readily available because the participants and their schools may be identified from the data. Requests to access the datasets should be directed to AK, anttoni.kervinen@helsinki.fi.

ETHICS STATEMENT

The research permits were granted by the City of Helsinki on 5th of March 2021. The participation in the study was voluntary and based on informed consent, and the study conforms to the ethical principles of the Declaration of Helsinki.

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APPENDIX: Transcription conventions

[]	Square brackets indicate beginning and end, respectively, of overlapping speech
(.)	Clearly audible pause of less than one second
(..)	Clearly audible pause of more than one second
underline	Underlined text indicates that the speaker is emphasizing or stressing the speech.
***	Inability to hear what was said
((text))	Our own comments and observations