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Exploring the potential role of citizen science in the warning value chain for high impact weather

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Preparing and delivering warnings to the public involves a chain of processes spanning different organizations and stakeholders from numerous disciplines. At each stage of this warning chain, relevant groups apply their expertise, but sharing information and transmission of data between groups is often imperfect. In diverse research fields, citizen science has been valuable in filling gaps through contributing local data. However, there is limited understanding of citizen science's role in bridging gaps in the warning value chain. Citizen science research projects could help improve the various aspects of the warning value chain by providing observations and evaluation, data verification and quality control, engagement and education on warnings, and improvement of accessibility for warnings. This paper explores the research question: How can citizen science contribute to the warning value chain? Two workshops were held with 29 experts on citizen science and the warning value chain to answer this question from a high impact weather perspective. The results from this study have shown that citizens, at individual or collective capacity, interact throughout the chain, and there are many prospects for citizen science projects for observations, weather, hazard, and impact forecasting, to warning communication and decision making. The study also revealed that data quality control is a main challenge for citizen science. Despite having limitations, the findings have shown that citizen science can be a platform for increasing awareness and creating a sense of community that adds value and helps bridge gaps in the warning value chain.

KEYWORDS
warning value chain, citizen science, high impact weather, warning, warning design

Introduction

Disasters are unexpected events that collectively threaten to disrupt the lives of a populace (Olsson, 2014). Disaster situations come in varying scales and predictabilities and are set within complex contexts where management decisions lead to broad societal consequences (Liu, 2014). The Hyogo Framework for Action (UNISDR., 2005) and the Sendai Framework (UNDRR., 2015) have encouraged the development of Early Warning Systems (EWS) as an integral part of disaster risk reduction. People-centered EWS look to improve disaster management through four key elements: (1) disaster risk knowledge, (2) detection, monitoring, and warning for hazards, (3) dissemination and communication of warnings, and (4) preparedness capabilities to respond to warnings (WMO, 2018). This multifaceted warning process spans many different systems, organizations and stakeholders.

Communication between numerous interlinked people and agencies is complex and can become more challenging during disasters when time is constrained and demand for information grows (Quarantelli, 1997; Andersen and Spitzberg, 2009). Communication gaps in the warning chain can be exacerbated during severe events and have costly impacts. Some case examples of communication failure include the public's underestimation of the warnings provided by authorities during the 2013 super typhoon Haiyan in the Philippines (Otto et al., 2018) and the communication breakdown between the National Weather Service and core partners during the tornadoes in 2011 and 2013 in Oklahoma, USA (Ernst et al., 2018). Conversely, good relationships and strong communication links between warning stakeholders, such as between a national weather service and emergency managers, improve their capacity to respond to disasters (Ernst et al., 2018). These interconnections are crucial; it is important to understand that the warning message from an EWS is only one part of larger mechanisms of information processing and decision making (Otto et al., 2018).

Golding et al. (2019) introduced a value chain approach to understanding the inputs, data, processes, stakeholders, contexts, outcomes, and various relationships to deliver effective high-impact weather warnings. The warning value chain includes observations, weather forecasting, hazard forecasting, impact prediction, warning generation, and decision making (Zhang et al., 2019; Golding, 2022). In its simplest form, this can be thought of as a sequential process; in reality, connections occur between many elements of the warning chain. The warning value chain also reveals the gaps that need to be bridged to deliver more effective warnings. Therefore, the value chain approach facilitates the assessment of the service design and delivery process and identifies options for improvement as part of an ongoing value cycle (Golding et al., 2019; Golding, 2022).

Many sources of data and information are valuable and applicable for use in the warning value chain by different sectors for various purposes. For example, hydrometeorological observations and measurements can come from instruments such as rain and river gauges, satellite and radar imagery, and weather databases and may be collected by official bodies such as meteorological and hydrological services and institutions. However, public surveys, historical records, eyewitness accounts, photos and videos from citizens, among others, can provide data, and these can come from alternate and unofficial data sources such as social media, online databases, and citizen science projects (Harrison et al., 2021).

Citizen science is valuable in contributing local and on-the-ground data for research (Shirk et al., 2012; Haklay et al., 2018; WMO, 2021). It has been beneficial in various research fields as it can provide information for hard-to-access or remote locations (Stevens et al., 2014). Individuals and communities can also gather and share rapidly perishable data (Wartman et al., 2020). However, there is limited understanding of how citizen science can contribute to bridging the communication gaps in the warning value chain. Marchezini et al. (2018) literature search found that only 15% of articles on citizen science and disaster management linked participatory early warning systems with citizen science. Our study explores this gap by asking: How can citizen science contribute to the warning value chain? The topic is investigated from a *high impact weather* perspective. This paper is an exploratory study of the potential role of citizen science in the warning value chain, and it is not an extensive review of existing citizen science projects in the high impact weather space.

The paper first provides a brief background on the high impact weather context, warning value chain, and citizen science. The paper then outlines the method of using a joint workshop to bring together citizen science and warning value chain experts to explore the question. The findings and discussion sections follow, highlighting the role of citizen science in the warning value chain.

Background

The term *high impact weather* puts emphasis on the consequences of severe weather (Taylor et al., 2018). High impact weather events include flooding, drought, severe wind, thunderstorms, hailstorms, heat waves, blizzards, tornadoes, and cyclones (Vinnell et al., 2021). In 2016, the World Meteorological Organization (WMO) and the World Weather Research Programme (WWRP) established the 10-year High Impact Weather (HIWeather) Project "to promote cooperative international research to achieve a dramatic increase in resilience to high impact weather, worldwide, through improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications" (Murray, 2021). The HIWeather Project uses the warning value chain concept to understand and improve the elements involved in successful warnings (Zhang et al., 2019; Vinnell et al., 2021).

Warning value chain

The value chain concept finds its origin in economics. It characterizes the full range of activities involved in product conceptualization, production, and delivery to its final customers (Kaplinsky and Morris, 2000). The chain describes linked processes and connections between them where value is added at each step to make an initially seemingly unusable product (e.g., timber) valuable for the customer (e.g., table), resulting in optimized cost and efficiency.

The generation of weather warnings and climate services is complex, both technically and organizationally. The value chain concept has become a popular tool for describing and assessing the production, use and benefits of such services that are often established through co-design, co-creation and co-provision with the common goal of enabling timely action to reduce risks (WMO, 2015). This basic idea of generating value along an interconnected chain of processes can be translated into a hydrometeorological context (Lazo et al., 2008; Lazo and Mills, 2021). In this case, the value is in the information created and transmitted through the chain, leading to better decisions and, ultimately, user benefit through (primarily) reduced damage and losses from hazards through warnings.

For describing the co-production of warnings before and during an event, the warning value chain can be visualized as a sequence of peaks and valleys where the peaks represent expertise, and the valleys represent communication gulfs between different areas of expertise (Figure 1, adapted from Golding et al., 2019). Each part of the chain, such as hazard monitoring, modeling and forecasting, risk assessment, communication and preparedness activities, is typically associated with an expert community that delivers that function. However, communication between those communities comes with many challenges. The challenges may at times seem like roadblocks, so communication (represented by the bridges in Figure 1) is vital to link the expert communities and enhance the flow of information and data to inform models and decision processes.

Value is added when data and expertise are combined to generate new information. This information is edited and disseminated through various channels and used for informed decision-making, e.g., by the public or civil protection (Perrels et al., 2012). The warning value chain has multiple associated data inputs and outputs for each component where hazard, vulnerability, and exposure data are needed in the various stages of the warning chain to ensure it operates effectively (Harrison et al., 2022). Further value can be added by improving the tools and communication used by weather services and their partners, leading to increased lead-time, confidence, local accuracy, and engagement.

Value can also decrease since each stakeholder in the chain has its own set of objectives, resources, and constraints and, therefore, may not use all available information (Golding et al., 2019). Challenges include lack of data availability, access, and limited data processing and management capabilities, which can become roadblocks in the warning value chain (Potter et al., 2021; Harrison et al., 2022). As experience is gained, new knowledge is produced and incorporated, and more people contribute to the design and operation of the system, these improvements constitute the value cycle. These reviews and design/revision activities mainly occur before and after high impact events and on slower timescales than warning timescales.

The representation of high impact weather warnings as an end-to-end value chain reflects the traditional top-down view in place in most countries, which emphasizes providing services by authorities to stakeholders. Improvements tend to be technology-focused, usually on the left-hand side of Figure 1, while communication and response capability (the right-hand side) are the weaker links (Garcia and Fearnley, 2012; Baudoin et al., 2016). On the other hand, people-centered early warning systems take a bottom-up approach, starting with the needs of the users (UNISDR., 2005; UNDRR., 2015). Multiple stakeholders are involved in all stages of the design and operation of warning systems that consider the many social dimensions, vulnerabilities, and capabilities of the people (UNDRR., 2015; Baudoin et al., 2016). Improvements in people-centered early warning systems generally focus on the right-hand side of Figure 1.

All parts of the value chain need to operate well to get the full benefit of early warnings. Ideally, the value cycle addresses gaps in warning systems wherever they may exist, whether in the technology or the people aspects. This paper shows that citizen involvement can provide valuable contributions to all parts of the warning value chain and value cycle, especially through citizen science projects and activities.

Citizen science

Citizen science is defined as a "type of science in which the general public contributes to the production of scientific knowledge, either alone, or more often in collaboration with professional scientists and scientific institutions (Strasser and Haklay, 2018, p. 32)". Citizen science may also be known under different names, such as community science, participatory assessment, community-based monitoring, volunteer monitoring, and others (Shirk et al., 2012). The key importance of citizen science is that the public participates in one or all of the various stages of the scientific process, including but not limited to collecting, categorizing, transcribing, and analyzing data (WMO, 2021). Moreover, citizen science projects have a relational aspect between citizens' and scientists', and their roles are supplementary to each

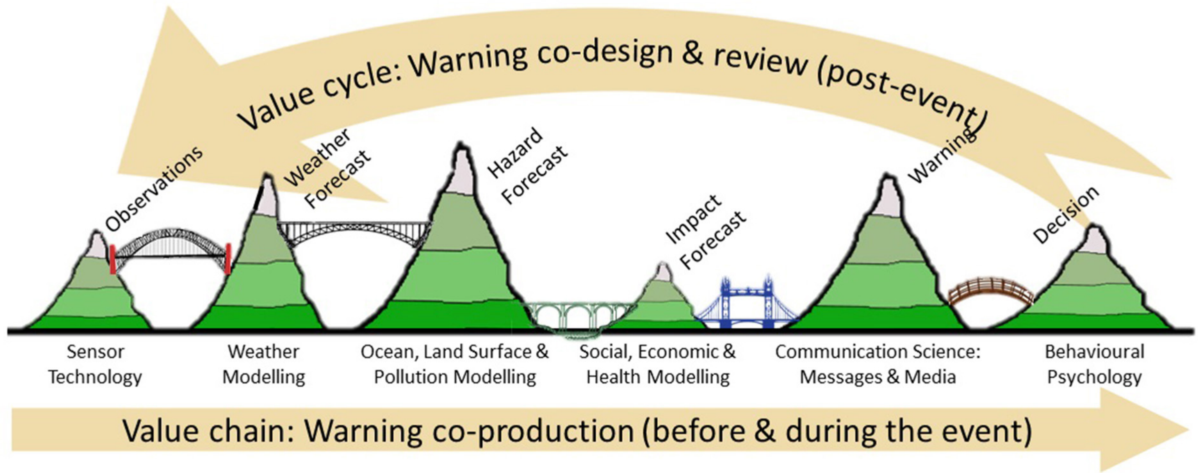

FIGURE 1
The warning value chain concept proposed by Golding et al. (2019), adapted.

other, contributing to the project dynamics. A recent Citizen Science Guidance Note by the WMO (2021) summarizes both the influence of citizens (as sensors, interpreters, engagers and collaborators) and scientists (instructing, collaborating, or co-creating) on different types of citizen science projects (Figure 2).

Citizens can act as sensors to observe and gather data for the projects; citizens can also be interpreters and take a more active role from data collection to analysis; citizens can be engagers in the problem development and design; and citizens can be collaborators, taking a co-production role with scientists to tackle questions (WMO, 2021). Similarly, scientists also can have varying influences on citizen science projects. Scientists can take a more instructive role and primarily lead the project, which may be designed top-down but integrated with citizens' participation, or have a more shared role where projects are co-created with citizens (WMO, 2021). The project design depends on the citizens' and scientists' level of engagement. Citizen science has contributed to various scientific disciplines and has been proven to be a valuable tool in ecology, water, air quality and conservation. Examples can be seen in roadkill studies (Périquet et al., 2018), ecological monitoring of mammals (Parsons et al., 2018), ecology and conservation (Kobori et al., 2016; Harebottle, 2020), drinking water research (Brouwer et al., 2018), and earth observations in general (Fritz et al., 2017; Rubio-Iglesias et al., 2020). As seen in examples from these different research fields, citizen science projects yield many benefits, including financial, social capital, reciprocity, and increase in trust. Studies have investigated the financial value of citizen science in environmental sciences and found significant contributions, for example, US$2.5 billion in biodiversity-related projects (Theobald et al., 2015).

Citizen science for weather hazards and warnings

Citizen science is also present in natural hazards and disaster research (Marchezini et al., 2018; Hicks et al., 2019; Vinnell et al., 2021). Several citizen science projects have contributed explicitly to weather hazards-related research. For example, a citizen science project in the United Kingdom aimed to understand how weather affects pain; it utilized a smartphone app to get 2,658 residents to report their pain symptoms over various weather conditions (Dixon et al., 2019). The German National Meteorological Service also uses apps to engage with the German populace; through its WarnWetter app[1], citizens contributed approximately 660,000 observations from July to November 2020 (Kempf, 2021). Other citizen science projects engage students and schools. Another German project got students from two high schools in the Bavarian Prealps to build weather stations to collect data and weather impacts (Kox et al., 2021). A citizen science initiative in Hong Kong engaged with over a hundred schools to set up weather stations and investigated the urban heat island effect (Lam et al., 2021). Citizen science can also be used beyond data collection. OpenIFS@home engaged with volunteers to run weather and climate modeling experiments[2], where volunteers across the world ran simulations using their computers at home. These simulations were combined into large forecast ensembles (Sparrow et al., 2021).

Citizen science also has a potential role in providing authorities and scientists with additional observations and

1 https://www.warnwetterapp.de/
2 https://confluence.ecmwf.int/pages/viewpage.action?pageId=212456886

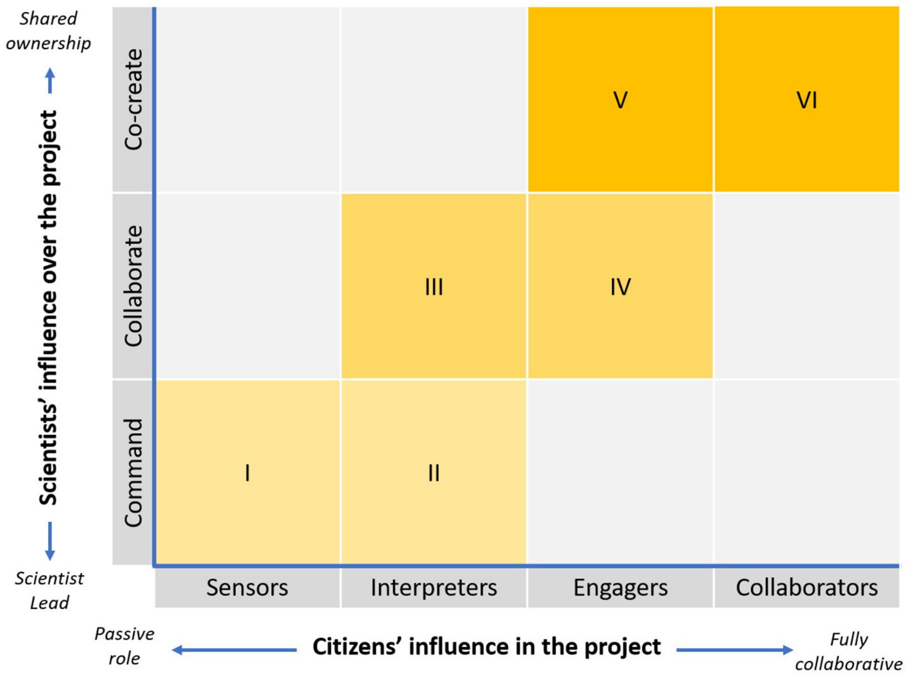

FIGURE 2
Typology of citizen science projects based on citizens' and scientists' level of influence (WMO, 2021).

ground truth to evaluate warnings, especially in hazard-prone situations like high-impact weather events. Citizen science can have a role in the rapid generation and sharing of information (Hicks et al., 2019). OpenStreetMap is a popular online platform for the public and researchers to record and map observations, monitor hazards, and share early warnings (Hicks et al., 2019)[3]. These examples show that citizen science is effectively used in natural hazards research and potentially has a role in enhancing the connections in the various stages of the weather warning value chain.

Members of the public are not merely passive recipients of information but can play active roles in communicating and responding to warnings in times of danger (Schulze et al., 2015; Tan et al., 2017). People look for warning verification and environmental cues from people who are known to them. Even when authorities issue warnings, some people may not fully appreciate the danger unless reinforced by someone known and trusted, such as a family member or friend (Wood et al., 2018). Even when the warning is understood, and people take action, some may require assistance from friends and neighbors to move to a safe location or take other protective action (Boulianne et al., 2018). Furthermore, engaging communities in discussing hazards, whether in person (Abunyewah et al., 2020) or through online channels and social media (Kankanamge et al., 2020), helps to enhance community awareness and preparedness.

The public consumes weather observations and forecasts for decision-making, both for day-to-day activities (Phan et al., 2018) and when threatening weather is imminent (Kox and Thieken, 2017). But citizens also use information from other parts of the value chain, not just the warning. For example, weather enthusiasts take their weather readings and share them with national weather services and volunteer networks (Gharesifard et al., 2017; Krennert et al., 2018). Individuals sensitive to temperature, humidity, and air pollution may need to protect themselves from adverse health impacts even before a warning is issued (Campbell et al., 2020).

Limitations and challenges for citizen science

A researcher or group of researchers, either amateur or professional, can start a citizen science project as long as they have enough motivation to investigate a question (Pettibone et al., 2016). However, researchers should also consider the limitations and challenges of citizen science projects. Lee et al. (2020) and Walker et al. (2021) discuss the benefits but also the issues and challenges of citizen science. Limitations can include costs and negative social impacts, among others. Costs of conducting projects may vary when factoring in the overall project, including the level of training and management and

3 https://www.openstreetmap.org/

control of data quality (Gardiner et al., 2012). Depending on the type of data to be collected or analyzed, some level of expertise may be needed and may require some extent of training and quality monitoring to ensure citizen science data is fit for research purposes (Conrad and Hilchey, 2011). Citizen participation and interests may also change or decline as the project progresses (Sauermann and Franzoni, 2015). It requires time and effort commitment from the public for the benefit of science, which may potentially cause burdening of the citizens, disempowerment, conflict creation, and new forms of inequality (Lee et al., 2020; Walker et al., 2021).

These studies illustrate that citizen science has both benefits and challenges, as with other methodologies and research engagements. Researchers should be mindful of these challenges. Many tools and strategies are available to help citizen science projects acknowledge and navigate the limitations (e.g. Freitag et al., 2016; Pettibone et al., 2016). This study recognizes the limitations of citizen science as it explores how existing or potential citizen science research projects and initiatives can add value to enhance the warning value chain.

A joint workshop

HIWeather is aimed at improving the effectiveness of weather-related hazard warnings. Two of the flagship components of the HIWeather program are the warning value chain project and the citizen science project. The warning value chain project aims to review the practices used to describe weather, warning and climate services to assess and provide guidance on applying value chains in a weather warning context involving multiple users and partnerships. The citizen science project is designed to share information and provide tools to help groups and agencies develop pathways of engagement with the public to undertake scientific research. Each of these flagship projects has expert members on the topics. A joint workshop was conducted to create a dialogue between the two groups to converge on the topics and interact and share their expertise.

The workshop was held with 29 subject matter experts on citizen science and the warning value chain in July 2021 to explore the intersection of the two topics. Few were experts in both topics. This joint workshop pioneers the collective exploration of the warning value chain and citizen science together in the context of high impact weather. The joint workshop received peer-reviewed approval under the Massey University code of ethical conduct for "low risk" research involving human participants (Application ID 400024723).

Participant recruitment

Purposive recruitment was done by inviting the HIWeather flagship project members. The 29 subject matter experts came from different sectors, including meteorological services, research institutions, universities, and commercial weather forecasting services from various counties in both hemispheres, including Argentina (2), Australia (4), Austria (1), Canada (1), China (1), France (1), Germany (2), Ghana (1), Mexico (1), New Zealand (2), Switzerland (1), the United Kingdom (3), and the United States (9). The limitation to this recruitment method is that most participants are from established scientific institutions, and none of the participants is from the public. Therefore, the views provided herein may reflect a top-down institutional perspective rather than a ground-up viewpoint from citizens.

Workshop structure and guide questions

In preparation for the online workshops, the participants were asked to consider the intersection between the warning value chain and citizen science. They shared their initial thoughts through an online collaborative platform called Jamboard[4]. The platform provided a virtual whiteboard that provided an illustration of the warning value chain (from Golding et al., 2019) and a workspace where participants could add notes anonymously at any time before the workshops (Figure 3).

Two online sessions were held (at 0700 and 1900 UTC), so members from different parts of the world could attend the session that best suited their time zones. The sessions ran for 2 h each. Each session opened with brief presentations on (1) the warning value chain and (2) citizen science. The presentations ensured that everyone would have a brief overview and a common grounding. The workshop activity consisted of facilitated semi-structured discussions with the attendees. The facilitators (i.e. the authors of this paper) discussed the following questions under three topics:

1. Citizens in the warning value chain
    a. Where are citizens involved in the value chain?
    b. How do citizens engage with warnings?
2. Citizen science on the warning value chain
    a. Where in the value chain can citizen science contribute to enhancing warnings?
    b. How can citizen science contribute to the enhancement of warnings?
3. Added value of citizen science
    a. What's the added value of citizen science in the value chain?

4 https://workspace.google.com/products/jamboard/

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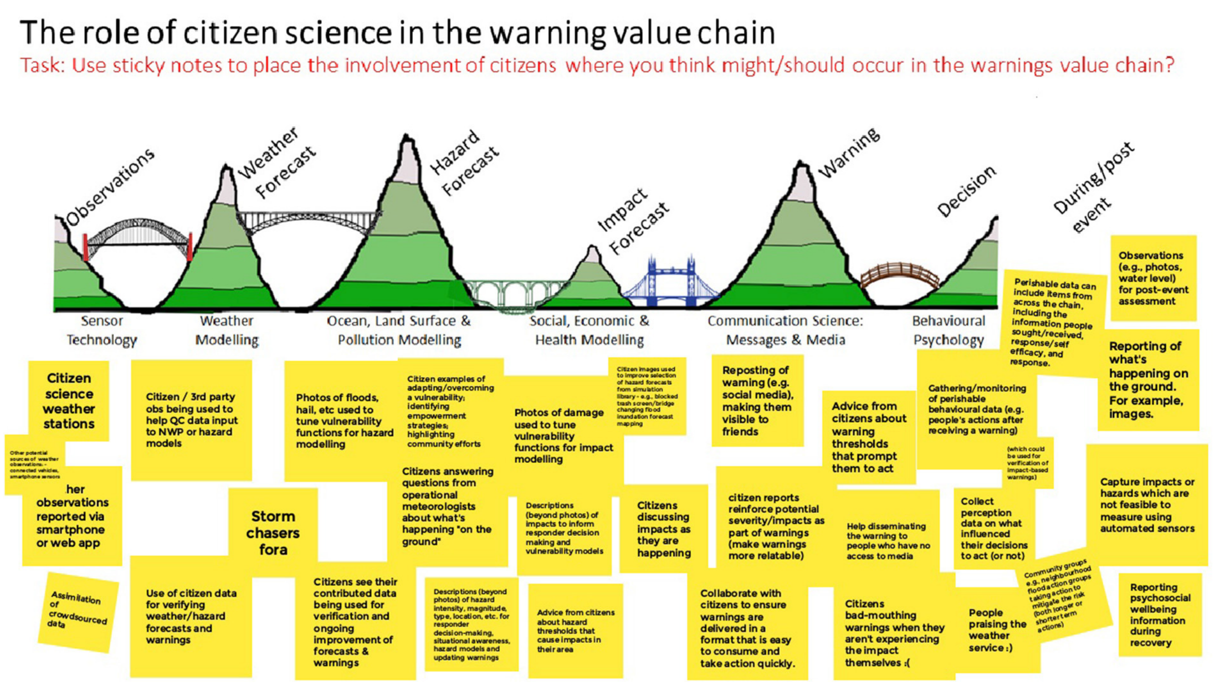

FIGURE 3
Pre-workshop online collaborative board with yellow sticky notes showing the responses provided by participants.

Jamboard was also used to help facilitate the conversation during the online sessions. One board per topic was used. The participants were given a few minutes to post notes anonymously on the board before starting the discussion. As the format was semi-structured, the flow of the discussion was dictated by the participants, and follow-up questions were prompted when necessary.

Data analysis

The discussion method was semi-structured based on the topics and sub-questions. The primary data source for analysis was the seven online collaborative boards (one pre-workshop board and three workshop boards per session), with the participants' responses captured *via* online "sticky notes". During the workshop, notes were taken, and each online session was recorded digitally. The sticky notes from the sessions were extracted, compiled, and organized to a table using Microsoft Excel. This allowed for easy reference back to the notes and recordings to capture the participant's insights. The short quotes presented in this paper are gathered from the participants' sticky notes.

A qualitative thematic analysis was conducted from the insights gained from the workshop, where the main process for analyzing the qualitative data was through naming and classifying (Flick, 2007). This study follows the thematic analysis approach by Braun and Clarke (2006, 2012) to identify, analyze and report themes from gathered data. For the initial coding process, the responses from both sessions were collated and mapped using the Golding et al. (2019) warning value chain. Then the codes were reviewed to identify underlying patterns to form themes. A 'theme' for this study reflects a pattern of shared meaning – a core concept (Braun and Clarke, 2012). Where necessary, the responses were aggregated by collapsing and combining the themes and then the various themes were defined and named. Using the themes, the research team then built a visual summary of the insights on the potential role of citizens and citizen science in the warning value chain.

Findings

The participants of the joint workshop had different expertise and came from various institutions. Through the workshop, they shared their experience and knowledge on citizen science, participatory engagement, science outreach, warning value chain, warnings, communication, meteorological research, and others. Given the range of expertise, the workshop provided a successful platform for shared learning on the topics where participants were able to ask questions and provide their perspectives on citizen science and the warning value chain. The analysis of the workshop shows two broad themes on citizen science and the warning value chain: (1) citizen involvement and (2) citizen science contributions.

Citizen involvement in the value chain

Consistent throughout the workshop is the theme that citizens are involved throughout the warning value chain. Figure 4 is a visual summary of the findings from the workshop on citizens' involvement in the value chain during high impact weather events. The involvement of citizens does not necessarily follow a linear sequence; findings from the workshop show that citizens' involvement can happen at any time, either pre, during, or post high impact weather events. The warning value chain itself does not follow the temporal chronology of an event but rather is presented as a succession of expertise that supports the delivery of the warning, with citizens interacting with various parts of the warning chain at different times. Figure 4 reimagines a condensed warning value chain portrayed in a cyclical process moving between expertise in (1) observations, (2) weather, hazards, and impacts, including their forecasts, (3) warning communication, and (4) decision making and response. The cyclical representation shows that each part of the warning value chain affects the other parts. For example, the upper right quadrant indicates that as citizens experience weather and the associated hazards during an event, such information from citizens can potentially contribute to the forecasting of weather, hazards, and impacts.

Snippets gathered from participants' sticky notes in the workshop showed opportunities for citizens' contributions:

> *"photos of flood, hail, [and others] to tune vulnerability functions to hazard modeling."*
>
> *"descriptions (beyond photos) of impacts to inform decision making and vulnerability models."*
>
> *"Citizen/3rd party observations [can be] used to help quality control data input to numerical weather prediction or hazard models."*
>
> *"citizens [can answer] questions from operational meteorologists about what's happening on the ground."*
>
> *"gathering/monitoring of perishable behavioral data (e.g. people's actions after receiving a warning) – which could be used for verification of impact-based warnings."*

Through the workshop discussion, participants also identified several ways citizens could participate and provide observations on the warning value chain. Weather observations from home or school-based weather stations can provide valuable data streams to national weather services to enhance the situational awareness of forecasters and emergency managers. Observations can also be shared online with the broader public through the Weather Observations Website (WOW)[5], Weather Underground[6], or other websites. Aside from weather stations, other mechanisms may be able to capture data, such as devices like smartphones and connected vehicles. People could also manually report weather observations using dedicated apps. App examples given in the workshop were MPing in the United States of America[7], WeatheX App in Australia[8], and WarnWetter App in Germany[9]. Other citizen observations were mentioned, including photos and videos of weather and hazard phenomena by storm chasers, for example, who are rich sources of intelligence in severe weather. Crowdsourced data through social media can also provide on-the-ground, real-time observations of hazards and their impacts.

Citizens' involvement can range from a personal level (e.g., experiencing an event) to community interaction (e.g., sharing warnings to friends); this is also highlighted in Figure 4. For example, in an individual capacity, citizens can act on warnings to protect themselves and their loved ones, and they can contribute data by submitting images and other types of data and information. Citizens can also interact collectively in engaging with the warning chain as a community; for example, by interacting with each other to help disseminate, interpret, and reinforce warnings.

Citizen science contributions to the warning chain

The second theme highlighted by the workshop was that citizen science (research) could contribute to the different parts of the warning value chain and enhance the value chain for warnings, as illustrated in Figure 5. The public can participate in these citizen science projects in varying ways, ranging from passive contributions (e.g., sending images from an event) to more active roles (e.g., co-designing warning approaches).

The cyclical representation in Figure 5 shows that each part of the warning value chain affects the other parts. Consequently, contributions of a citizen science project on one part of the chain may influence other parts and the warning value chain as a whole. For example, a project involving community engagement activities (e.g., hazard observation with citizens) may help develop public awareness and build relationships between citizens, authorities, and the warnings; processes which can then help citizens with decision-making when warnings are issued. Citizen science can engage people to become interested, support science, and make *'warning ready citizens.'*

5 https://wow.metoffice.gov.uk/

6 https://www.wunderground.com/

7 https://www.citizenscience.gov/mping-weather-reports/

8 https://weathex.app/

9 https://www.warnwetterapp.de/

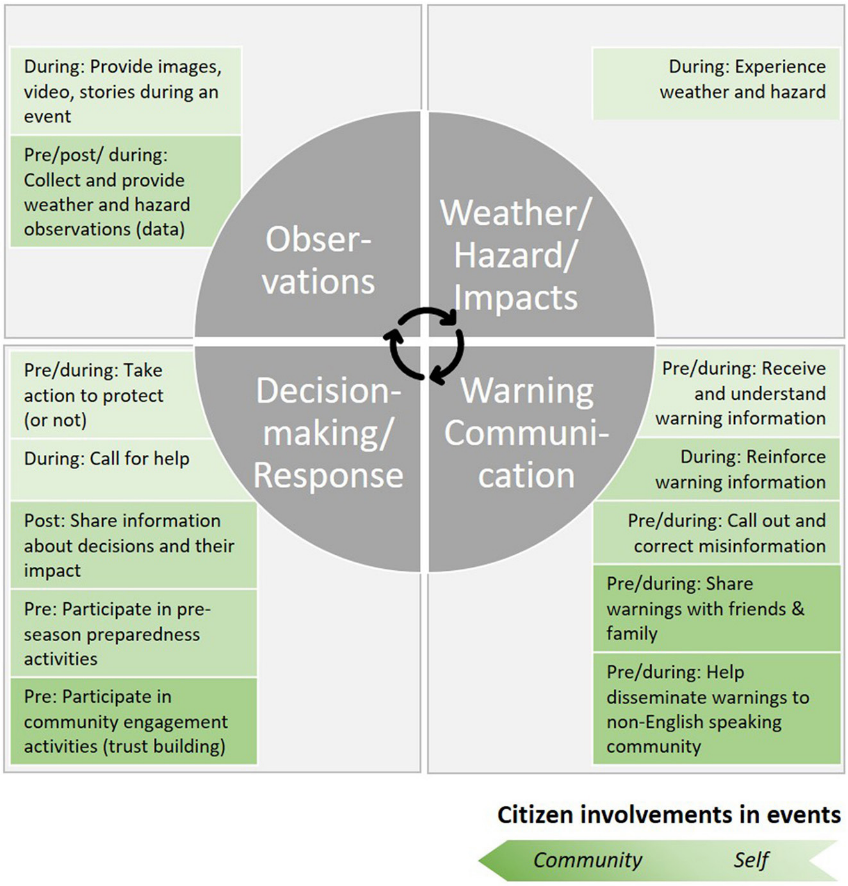

FIGURE 4
A visual summary of findings on citizens' involvement in the warning value chain.

Snippets from participants' sticky notes highlight some example outcomes of engaging in citizen science in the warning chain:

> *"School science projects" and "Involving younger people - raising awareness/understanding of weather [and hazard] topics (e.g. schools)."*
>
> *"collaborat[ion] with citizens to ensure warnings are delivered in a format that is easy to consume and take action quickly."*
>
> *"community groups, e.g. neighborhood flood action groups taking action to mitigate the risk (both longer- or shorter-term actions)."*

Citizen science projects can offer a way for communication and knowledge exchange between various parties (e.g., between weather agencies and the people). Citizen science projects can facilitate the exchange so that the communication could become two-way. For example, citizen science projects can be designed to help identify and correct misinformation in real-time to communicate warnings better. Citizen science projects are not just about citizens passively contributing data (with no reward for effort), but citizen projects can be a platform for agencies or authorities to acknowledge the value of the citizens' contributions and participation. Citizen science projects can also be designed to evaluate the effectiveness of warning communications and people's responses to warnings. Snippets from participants' sticky notes present some ideas on how projects can enable public participation and input in enhancing the warning value chain

> [citizen projects can help] in *"calling out and correcting misinformation."*
>
> *"citizens to see their contributed data being used for verification and ongoing improvement of forecasts & warnings."*
>
> *"a post-event [study] where citizens [share] about how they were warned, [...] how they were affected, or how they responded."*
>
> [agencies can] *"find out who is not receiving warnings and what communication medium would reach [the public]."*

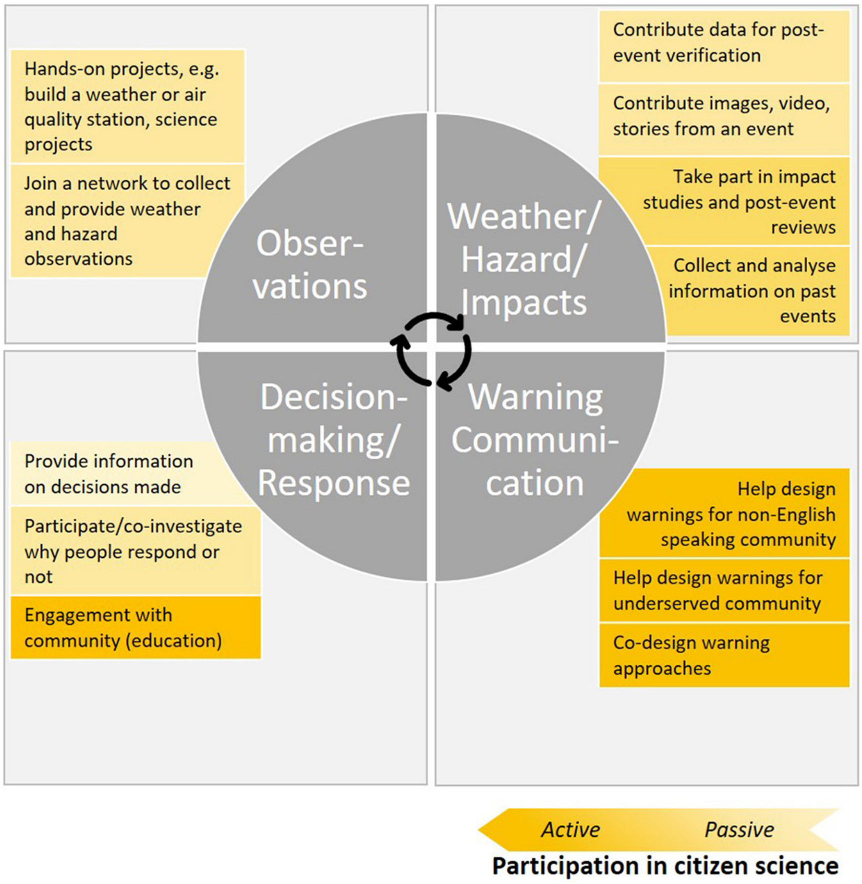

FIGURE 5
A visual summary of findings on citizen science contribution to the warning value chain.

The findings also pointed out opportunities for projects that engage with communities where current warning communication strategies are not as effective, e.g., minorities, differently-abled communities, and those with limited or no access to media. Citizen science research can help warning services become more accessible. Snippets from participants' sticky notes highlight the issue of accessibility of warnings and the potential for citizen science to enhance this space:

> *"warning communication that might differ according to their technology and information accessibility."*
>
> *"Help disseminating the warning to people who have no access to media."*
>
> *"include citizens from marginalized groups in warning product development and dissemination."*
>
> *"Helping with language interpretation."*

As identified in the findings, project opportunities include co-designing improvements in the warning system, such as translations for non-local languages and integrating assistive mechanisms for the hearing or sight impaired. Such projects can improve engagement, enhance people's understanding of warnings, and lead to specialized services that current warning systems may not yet capture. Citizen science projects can potentially improve the gap between warning communication by building engagement and trust between authorities and the people.

Discussion

As seen in the literature and the workshop findings, citizens are involved throughout the warning value chain. Given the citizens' presence throughout the chain, there is also potential to engage in citizen science projects and initiatives that enhance parts and subsequently the whole warning value chain, thus helping warnings achieve their goals to reduce impacts and improve safety.

Value of citizen science for bridging communication gaps

Examination of the warning value chain has identified communication gaps between expertise areas, such as between warning providers, decision-makers and responders (Golding et al., 2019). Findings from the workshops have shown that citizens are involved in various parts of the warning value chain, which opens a clear opportunity for citizens and citizen science research to help bridge gaps and design systems to meet the needs of all concerned. A study on coastal residents' decision-making during a typhoon identified that "during impending severe weather, residents may receive information about the storm from various resources including state and local government officials, news media, and their community contacts, including neighbors and civic organization." (Pan, 2020, p. 6). Different factors and contexts are involved in the official messaging and people's decision-making, which could create communication gaps in translating warnings into an appropriate response. Trusting the official information source is an essential criterion for making decisions (Pan, 2020).

A potential opportunity for citizen science is to aid the handling of misinformation during events. Multiple channels may improve people's decision-making when communicating risks (Pan, 2020). However, the diversity of information can also cause confusion, especially in the era of social media, where misinformation can proliferate. Individuals, after all, are influenced by their social networks, both online and offline, during decision-making when risks are communicated during extreme weather events (Sadri et al., 2021). Unlike traditional hierarchical communication through weather services and emergency management agencies, decentralized communication may be prone to misinformation and bad-mouthing. Weather and emergency services and some avid citizens might call out and correct misinformation. Still, quality control for warning information shared *via* social media and word-of-mouth remains a challenging task. Citizen science projects can have some mechanisms or processes to get citizen scientists to help in quality checking and verification to help identify and correct misinformation in real-time during events.

Citizens may often be considered the endpoint of warnings, where they interpret and act on information and warnings provided by authorities (Kox et al., 2018; Taylor et al., 2019). However, actively involving citizens in collecting, verifying, and sharing information before, during, and after an event can lead to better outcomes for the community (Kaewkitipong et al., 2016). Citizens' ground observations can be used to see whether forecasts match actual events. For example, during or after events, people can share (e.g., images, videos, and stories) and verify with their experiences whether the weather, hazard and impacts were more or less extreme than predicted and whether or not they received warnings. Citizen science can facilitate two-way communication between citizens and authorities and improve public awareness of hazards (Ferri et al., 2020).

Research on warnings also has tended to treat the general public as homogenous, but the push toward people-centered warning systems has emphasized the need to recognize diverse groups and how differently they may respond to warnings (Tan et al., 2020). The findings point to the need to collaborate with underrepresented communities, e.g., minorities, elderly, differently-abled communities, and those with limited or no access to media. Citizen science has an important role in co-designing more diverse and accessible warning services.

As technology advances, so does the digital divide (Schulze et al., 2015; Lorini et al., 2019). The digital divide is a product of many factors, including social and economic status and accessibility to the internet, and it has introduced problems in engagement and information dissemination (Harrison and Johnson, 2019). Authorities and researchers, including those involved in citizen science, must ensure that those underrepresented in the digital world are included and do not miss opportunities to receive life-saving information (Anderson et al., 2016; Tan et al., 2020).

Similarly, citizen science in the warning chain can bring a risk of increasing the digital divide or isolating communities, but it also provides an opportunity to bridge gaps. The WMO (2021) guidance note on high impact weather citizen science encourages project leaders to consider such ethical issues. This includes asking questions such as: "are there steps in place to ensure equal and meaningful opportunities for different groups (e.g., gender and marginalized groups)" WMO, 2021, p. 8)?

Enriching warnings with citizen science data

The World Meteorological Organization encourages citizen science to enhance the global weather enterprise (WMO, 2021). National weather services have started to recognize the role of citizen science as a source of weather intelligence to better observe, predict, and understand the environment by harnessing the power of the crowd (NOAA., 2021). Citizen science can add value by enabling citizens to collect data that may be difficult or expensive to collect using traditional science methods (e.g., observations from remote locations or perishable impact data). New citizen science projects could set up observation stations with communities in remote places and could also enable the rapid collection of impact information.

Citizen science can employ crowdsourcing, where members of the public act as sensors, and it can provide information by using readily accessible instruments (Kankanamge et al., 2019). Citizens can record information on the impacts of hazards through sharing locations, messages, images, and videos of damaged properties, data that is often difficult to obtain and access using other means (Kankanamge et al., 2019). The benefits of citizen science for collecting data could outweigh the cost of preparation, post-processing and quality control (Lee et al., 2020). If conducted successfully, scientists receive significant contributions of crucial data and knowledge for their studies (Lee et al., 2020). There is also an opportunity to advance citizen science in managing data quality by tying in with social sensing—the science of extracting crowdsourced information for routine warning and analysis (Arthur et al., 2018; Spruce et al., 2021; Weaver et al., 2021). Social sensing is an emerging field that explores new data collection paradigms and reliability problems from data collected from humans and their devices (Wang et al., 2015).

More robust engagement in citizen science projects inevitably creates intangible and social benefits for citizens (Haywood, 2014), such as increased awareness and understanding of the citizens in topics such as weather, hazards, and warnings. The value will be realized for citizen science projects related to hazards when the benefits (e.g., minimizing impacts and protecting life and property) manifest during hazardous events. Ferri et al. (2020) showed through a cost-benefit analysis of a citizen observatory in a catchment that citizen science coupled with citizen observatories with hydrological modeling can reduce damage by 45% for different flood scenarios. Liu et al. (2020) also describe the role of citizen weather spotters in enhancing public safety in Nashville, Tennessee. Citizen weather spotters supply ground information from vital locations, providing quick severe weather information that can be acted upon, thereby saving life and property (Liu et al., 2020). Sharpened perspectives, attitudes, and behaviors about weather, hazards and warnings would significantly increase community resilience (Ferri et al., 2020) and, as such, a merit consideration to continue the discourse on how citizen science can contribute to the warning value chain.

Limitations of this study

To the best of the authors' knowledge, the joint workshop described in this paper is the first to collectively explore citizen science and warning value chain together in the context of high impact weather. Through this workshop, we were able to bring together 29 experts from around the globe to explore the topic. However, as purposive recruitment was conducted with a focus on experts, the participants came from research institutions which would have provided perspectives from a scientist or researcher perspective. Future research on the intersection of citizen science in the warning value chain should include perspectives from citizens.

In this exploratory study, thematic mapping (see Figures 4, 5) was conducted, reflecting the participants' knowledge, highlighting where citizens interact with the warning chain and identifying areas where citizen science can potentially contribute. Although the participants provided many citizen science examples, this study was not intended to document an exhaustive list of citizen science projects in the high impact weather space. It would be worthwhile for future studies to survey citizen science projects to investigate and create a representative mapping of citizen science projects in the warning value chain.

This paper is of exploratory nature and does not detail how all communication gaps between expertise areas will be addressed by citizen science. However, the paper has illustrated instances of how gaps can be filled. For example, the gap between official warnings and the public's decision-making can be partly bridged by engagement through citizen science projects. Future research can investigate in detail the gaps in the warning value chain. Furthermore, prospective citizen science projects in the high impact weather space can use the warning value chain as a guiding tool to identify where the project's contributions lie in improving data and communication through the chain.

Conclusion

At the beginning of this paper, we raised the research question: How can citizen science contribute to the warning value chain? This study has shown that citizens, at individual or collective capacity, interact throughout the chain, and there are many prospects for citizen science projects that can be conducted throughout the chain. Both the literature and the findings highlight the potential usefulness of citizen science for data collection. Best practices from other areas, such as social sensing, can help with advancing citizen science, especially in managing data quality for use in warnings research. Organizations such as WMO and NOAA have recognized the crowd's potential "power" in enhancing the weather enterprise. The call for more people-centered early warning systems in the Sendai Framework (UNDRR., 2015) implies an important role for citizen science in their design, operation and improvement. Citizen science can be used as an engagement tool to bridge gaps and enhance communication between authorities and the public. It can be a platform for awareness and inclusivity for disadvantaged groups in the warnings space. The levels of engagement in citizen science projects create social benefits for citizens, such as increasing awareness and creating a sense of community that eventually translates to warning-ready citizens.

The beauty of citizen science is that anyone can do it, regardless of location, qualification or expertise. As highlighted in this paper, citizen science projects have potential value for enhancing the warning value chain. However, as there are benefits, there are also costs and considerations involved in conducting citizen science projects. The WMO guidance note 2021 is designed as a starting reference for groups and agencies considering citizen science; the guide raises key questions for project leaders to consider for citizen science projects. The joint workshop from this study is just the beginning of exploring the intersection of citizen science in enhancing warnings. Researchers and institutions are encouraged to explore further how citizen science projects can be used to bridge communication gaps in the warning value chain.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The project, however, received peer-reviewed approval under the Massey University code of ethical conduct for low risk research involving human participants (Application ID 400024723). Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

Conceptualization, methodology, investigation, and writing—review and editing: MT, DH, EE, DJ, and AC. Formal analysis: DH, MT, EE, and AC. Writing—original draft preparation: MT, DH, and EE. Visualization: DH. Project administration: MT, AC, DH, and EE. Funding acquisition: DJ, EE, MT, and DH. All authors have read the manuscript and agreed to be accountable for the content of the work.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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