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Research Paper

Community-engaged heat resilience planning: Lessons from a youth smart city STEM program

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HIGHLIGHTS

- Heat resilience planning, STEM education, and spatial cartographic mapping.
- Youth planning and STEM program, including sensors, interviews, and mapping.
- Shift understanding of heat from individual to collective landscape-based issue.
- Technology a helpful hook for initial engagement for some students.

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ABSTRACT

While recognition of the dangers of extreme heat in cities continues to grow, heat resilience remains a relatively new area of urban planning. One barrier to the creation and successful implementation of neighborhood-scale heat resilience plans has been a lack of reliable strategies for resident engagement. In this research, the authors designed a two-week summer STEM module for youth ages 12 to 14 in Roanoke, Virginia in the Southeastern United States. Participants collected and analyzed temperature and thermal comfort data of varying types, including from infrared thermal cameras and point sensors, handheld weather sensors, drones, and satellites, vehicle traverses, and student peer interviews. Based on primary data gathered during the program, we offer insights that may assist planners seeking to engage residents in neighborhood-scale heat resilience planning efforts. These lessons include recognizing: (1) the problem of heat in neighborhoods and the social justice aspects of heat distribution may not be immediately apparent to residents; (2) a need to shift perceived responsibility of heat exposure from the personal and home-based to include the social and landscape-based; (3) the inextricability of solutions for thermal comfort from general issues of safety and comfort in neighborhoods; and (4) that smart city technologies and high resolution data are helpful "hooks" to engagement, but may be insufficient for shifting perception of heat as something that can be mitigated through decisions about the built environment.

1. Introduction

Extreme heat events pose a growing threat to human health (Ebi, Balbus, Luber, Bole, Crimmins, Glass, Saha, Shimamoto, Trtanj, & White-Newsome, 2018; Habeeb, Vargo, & Stone, 2015; Russell et al., 2020) and urban infrastructure (Clark, Chester, Seager, & Eisenberg, 2019) and are a major consequence of climate change. Extreme heat is exacerbated in cities, where temperatures can range from 1 °C to 4 °C hotter than in rural areas (US EPA, 2008). In the US, the historical effects of residential segregation and disinvestment in Black and other people of color neighborhoods persist today and are reflected in higher temperatures in these neighborhoods (Hoffman, Shandas, & Pendleton, 2020; Saaroni, Ben-Dor, Bitan, & Potchter, 2000; Wilson, 2020; Dialesandro, Brazil, Wheeler, & Abunnasr, 2021). In addition, fatalities and hospitalizations due to heat exposure disproportionately impact low-income communities of color (Klinenberg, 2003), and social vulnerability in select areas within cities is increasing due to increasing temperatures in these areas (Weber, Sadoff, Zell, & de Sherbinin, 2015).

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Despite a growing awareness of health and mortality effects of heat waves, planning for extreme heat by local governments is far from a universal practice (Keith, Meerow, & Wagner, 2019). The majority of surveyed urban planners are concerned about heat, however they perceive the lack of human and capital resources to be major barriers in heat resilience planning (Meerow & Keith, 2021). There is also a disconnect between the availability of scientific data that may be useful for planning for heat, and how such information can be usefully incorporated to respond to heat threats in more tailored and equitable ways in communities (Wilson, 2020). Knowledge gaps are particularly apparent in determining what interventions are most salient to the communities that disproportionately bear the brunt of extreme heat exposure in cities and in understanding the role of temperature data of different types and spatial and temporal resolutions in enhancing planning processes. These gaps prevent planners and residents from translating scientific knowledge of urban extreme heat into community action to reduce the disproportionate impacts of heat in marginalized neighborhoods. Because heat exposure and the ability to cope with its consequences vary widely within cities, appropriate interventions must be designed and implemented at scales smaller than the entire city and should respond to the experiences and priorities of those most acutely affected (Keith, Meerow, Hondula, Turner, & Arnott, 2021).

In this study, we use the concept of increasing “community resilience” to refer to “the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.” (Meerow, Newell, & Stults, 2016). Resilience is therefore related to the idea of adaptation, and both concepts are often included in climate resilience plans, climate action plans, and specific strategic plans dealing with the consequences of climate change. With respect to extreme heat, threats include both discrete events that have been identified as heat waves, as well as routine increased temperatures as a result of global climate change (Li & Bou-Zeid, 2013; Keith & Meerow, 2022).

Youth are an important focus of efforts to increase community resilience to the effects of climate change, both as potential agents of change themselves, and as partners in community-engaged planning processes (Bey, 2020; Frank, 2006; Lawson, 2019; Trott, 2021). In this research study, we address gaps in understanding effective pathways for increasing community heat resilience through an engagement activity with youth, ages 12–14, enrolled in a two-week summer smart city STEM program, led by the authors. Drawing upon our engagement with youth, this study elucidates the ways that residents interpret their experiences with heat, explores how different methods of measuring heat exposure (e.g. air temperatures, thermal comfort) and spatial resolution affect understanding of heat exposure, and identifies strategies for better engaging residents in heat resilience initiatives. Specifically, this research seeks to address two related questions: (1) How do youth conceptualize the impact of heat in their lives and how does this change over the course of a smart city heat resilience planning program? And (2) What impacts do different kinds of data and data collection activities, especially higher resolution data associated with smart cities sensing technologies, have on youth understanding of heat in cities?

We analyze transcripts of 48 interviews with the youth and our ethnographic-style notes taken during the two-week engagement period to identify strategies for how urban planners can better engage residents around issues of heat exposure and mitigation. We found working with youth to be particularly elucidating because they tended to be very forthcoming with what they did and did not understand about the topic, what activities and types of data and data collection activities were helpful to them, and what they believed to be reasonable measures for individuals and local governments to take in order to deal with heat.

In the following section, we situate our research within relevant existing strands of literature and highlight how this article extends prior studies.

2. Related literature

2.1. *Heat and urban planning*

Land use planning can advance climate adaptation through strategies ranging from building-level policies such as albedo enhancement and green roofs to city-scale efforts to increase tree canopy and reduce impervious surfaces (Heris, Middel, & Muller, 2020; Larsen, 2015; Stone, Vargo, & Habeeb, 2012; Vargo, Stone, Habeeb, Liu, & Russell, 2016). Prior studies have demonstrated that these strategies are effective in reducing air temperatures (Middel, Chhetri, & Quay, 2015), and that combining strategies amplifies the heat mitigation impact (Stone, Lanza, Mallen, Vargo, & Russell, 2019).

Although evidence that land use planning can mitigate extreme temperatures is increasing, the majority of cities tend to recommend generic city-wide actions (i.e., to increase surface albedo and plant more vegetation) that are untethered to either implementation strategies or to specific problem areas (Dare, 2019). This is despite much research that shows that neighborhood-specific solutions are necessary. For example, within an urban area, there are wide temperature variations (as much as 7 °C land surface temperature) that spatially correlate with different land uses, land surface covers, materials, and morphologies (Hoffman et al., 2020; Oke, 1982; Stone & Rodgers, 2001). In Seoul, South Korea, recent research has shown that even small green spaces can exert a significant cooling effect at the neighborhood scale (Park, Kim, Sohn, & Lee, 2021). And, the way heat mitigation interventions are designed or configured can also influence their effectiveness (Bartesaghi-Koc et al., 2021).

Because of highly variable exposure to the risks of extreme heat within cities, approaches that involve resident participation at scales smaller than the entire city are especially important for heat resilience planning. Neighborhoods with higher proportions of minority and lower income residents, and those that were previously targeted for disinvestment through the state-sanctioned practice of redlining continue to have higher mean land surface temperatures than non-redlined neighborhoods (Hoffman et al., 2020; Wilson, 2020; Dialesandro et al., 2021). Exposure and risks of extreme heat are not completely represented by land surface temperatures however. Other factors that affect exposure to heat risk include: poorly insulated/weatherized buildings, access to air conditioning and the costs of cooling, and the resilience of the electrical grid during periods of high demand. For each of these factors, neighborhoods with higher proportions of people of color and poor residents experience more vulnerability than neighborhoods with higher proportions of wealthier or White residents (Stone et al., 2021).

In addition, disparities in the way urban residents experience heat extends beyond fatalities and hospitalizations, which are often the indicators used to assess vulnerability. Extreme heat contributes to higher energy bills, which are especially burdensome for low income families (Sailor, Baniassadi, O’Lenick, & Wilhelmi, 2019; Thomson, Simcock, Bouzarovski, & Petrova, 2019), as well as missed work days or decreased productivity (Lundgren, Kuklane, Gao, & Holmér, 2013), significant physical discomfort/inconvenience (Guardaro et al., 2020), and mental stress (Hansen et al., 2008). However, experiential outcomes beyond fatalities or hospital visits are rarely documented or used as the evidence base for heat mitigation initiatives of resilience planning processes.

2.2. *Citizen Participation, and the smart city*

The proliferation of “big data” from information communications technologies and from environmental sensing technologies, as well as increased computational power to store, process, analyze, and visualize this data, underlies the idea of managing and designing smarter cities. Increased deployment of real-time sensors in urban environments for example, could be used to optimize garbage collection routes (Perera, Zaslavsky, Christen, & Georgakopoulos, 2014), and automate air/noise quality warning systems, traffic congestion management, and smart parking or lighting systems (Zanella, Bui, Castellani, Vangelista, & Zorzi, 2014). In each of these cases, the high spatial and temporal resolutions of data collected from the urban environment enable opportunities to tailor responses to the high spatial and temporal heterogeneity of conditions within cities. Aside from real-time urban management, some have suggested that policy and planning processes, which usually operate on longer timeframes, could similarly benefit from insights derived from higher resolution data and the "digital exhaust" produced and collected within urban areas (Batty 2013; 2018; Westraadt & Calitz, 2020).

Criticism of the smart city paradigm however, includes that it promotes top-down, technocratic, and even anti-democratic tendencies latent in the planning profession (Cowley & Caprotti, 2019; Evans et al., 2019) and "cybernetic," corporation-led, and neoliberal views of wicked social problems (Goodspeed, 2015; Grossi & Pianezzi, 2017; Kitchin, 2014). Supporting more effective and responsive governance is often a stated aim of smart city technologies, but a recent study argues that the technologies themselves and the mode of governance that constitute the smart city have contributed to a more transactional and less meaningful form of interaction between citizens and government (D'Ignazio, Gordon, & Christoforetti, 2019; Johnson, Robinson, & Philpot, 2020).

In response to these criticisms, others have suggested additional criteria by which the use of big data and algorithms in cities should be evaluated, such as whether their use increases the governance capacity or the livability of the members of the community (Allam & Dhunny, 2019; Yigitcanlar et al., 2018). In planning for smart cities it is therefore very important that higher resolution data and urban sensing programs have a clear connection with community capacity building, rather than merely serving technocratic urban management ends. This is especially true for urban planning for resilience, in which residents often remain excluded from meaningful engagement in planning processes (Meerow & Mitchell, 2017).

2.3. *Place-Based urban sensing and youth STEM education*

2.3.1. *Youth and STEM specific skills with maps and environmental literacy*

One area in which the use of technology may present promising avenues for increasing community resilience while also advancing bottom-up visions for smart cities is through youth environmental literacy and education (Bey, 2020). Microcontrollers and sensors have become so small and affordable that they are common staples as part of STEM education outreach with youth. Technologies which once had to be learned about through books, videos, field trips, or classroom demonstrations can now also be put directly in the hands of each student. Youth engaging with programmable sensing and controls devices can be beneficial in a variety of ways such as: the development of specific STEM skills (e.g., Chou, 2018); sparking situational STEM interest which can be further scaffolded such as in a community of practice to enable more individualized interest development over time (e.g., Gomoll, Hmelo-Silver, Šabanović, & Francisco, 2016); helping demonstrate the everyday and everywhere relevance and applicability of these technologies and career pathways such as targeting "engineering is in every community and makes a difference in people's lives" (Grohs et al., 2020, p. 8); expanding traditional limited views of STEM by integrating explicitly with other subjects such as the arts (e.g., Peppler, 2013); and the development of key lifelong professional competencies such as 21st century skills learned in team-based robotics (e.g., Eguchi, 2016).

Children can be an invaluable source of insight and expertise in urban planning processes (Frank, 2006; Halseth & Doddridge, 2000), but their still-developing map and environmental literacy skills can pose unique challenges. Even preschool children have an ability to interpret aerial photographs as maps to an extent (Blades et al., 1998; Blaut, 1997; Plester, Richards, Blades, & Spencer, 2002), although confusion between symbols and their referents and scale can interfere with learning (Liben & Downs, 1997; Liben & Myers, 2007). The use of satellite or air photo interpretation in the K-12 classroom has become much more common with the advent of platforms such as Google Earth (Naumann et al., 2007; Patterson, 2007) and new virtual reality immersion projects using similar technology offer even more advantages (Hagge, 2021).

The use of more sophisticated remote sensing products in the classroom, such as land cover and land use maps that are often used to engage with adults is less common with youth (Dziob, Krupiński, Woźniak, & Gabryszewski, 2020; Shepardson, 2019). Outside the classroom, video games that include maps or map-like views can help children develop limited map-reading skills, although these tend to focus on navigation and goal-direction rather than analysis (Khan & Rahman, 2018). Terrain maps provide an interesting exception to this, where color, shading, and contour lines indicate elevation changes; however, such maps can also be confusing to children and inexperienced map users alike, where symbol-referent confusion (e.g., low-lying areas expressed as green are believed to be vegetated because of their color) is relatively common (Patterson & Jenny, 2013).

Showing thermal photographs and images to children as a way to visualize and learn about the urban heat island effect increases interest in both the problem and in remote sensing technology (Adaktylou, 2020), but thermal maps and images use a wide variety of non-intuitive colormaps for their expression that may limit map users' ability to deeply understand quantitative relationships. Even so, evidence suggests that activities like these are an important part of the holistic process of building map skills outside their current primary classroom use to support geography and geography-adjacent studies (Davies & Uttal, 2007; Wu, Liu, & Peng, 2014).

2.3.2. *Place-based sensing as culturally relevant pedagogy*

Engaging with youth as students requires an understanding of culturally relevant pedagogy. Ladson-Billings (1995) first introduced culturally relevant pedagogy as pedagogy that "not only addresses student achievement but also helps students to accept and affirm their cultural identity while developing critical perspectives that challenge inequities that schools (and other institutions) perpetuate" (p. 469). In the decades since, educators, researchers, and activists have continued to draw upon this foundational work as essential to prioritizing the thriving of marginalized youth, especially racially marginalized youth, within education. For example, "STEM courses are often taught in a culturally irrelevant or unresponsive way for Students of Color" which, along with other factors such as how practices in STEM often center "White ways of knowing, doing, and being" are all critical pieces of how STEM disciplines can marginalize, exclude, and other. (Henderson, Rangel, Holly, Greer, & Manuel, 2021, p. 3). In discussing operationalizing culturally relevant pedagogical strategies within engineering outreach, Gillen et al. highlight the importance of strategies such as making direct connections within activities to youth culture, incorporating hands-on, and inquiry-based activities, and emphasizing student self-direction and agency (Gillen, Carrico, Grohs, & Matusovich, 2018). However, in practice, even these strong strategies articulated at a general level can tend to miss the aspirations of culturally relevant pedagogy as Ladson-Billings laments in her 2014 retrospective because "many practitioners… seem stuck in very limited and superficial notions of culture" and "few have taken up the sociopolitical dimensions of the work, instead dulling its critical edge or omitting it altogether" (Ladson-Billings, 2014, p. 77).

In a general sense, the use of thermal sensors in this project is aligned with the myriad potential benefits of technology-focused STEM education outreach. However, our approach further focuses these potential benefits through connecting them with ways to increase community resilience to extreme heat.

3. Methods

In order to explore our research questions, we designed and carried out a two-week intensive smart city urban sensing program for middle school students, described below.

3.1. Roanoke public schools summer enrichment program context

Roanoke, Virginia is a mid-sized city (population: 100,000) in the Southeast United States, nestled in a valley of the Blue RIdge province of the Appalachian Mountain range. Growth of the city occurred in the late 19th and early 20th centuries, associated with the functioning as a tobacco, and later, coal transportation hub of the region (Dotson, 2008). In the early 20th century, Boston landscape architect John Nolan produced Roanoke's first city plan, which has subsequently been recognized as a National Historic Planning Landmark. Although never fully adopted, the spirit of Nolan's vision for Roanoke can be seen in many neighborhoods, with tree-lined, walkable streets, and nearby shops and businesses.

Historically the city was divided into four quadrants, which still remain today. Of the four quadrants, Northwest Roanoke (hereafter referred to as "Northwest") was the subject of renowned sociomedical scientist Mindy Fullilove, MD's work *Root Shock*, which detailed the psychosocial effects of urban renewal-led destruction of Black neighborhoods in American cities (Fullilove, 2001). In the four decades starting in the mid-1950 s, many of the vibrant Black neighborhoods of Northwest were razed in order to make room for highways, the civic center, and businesses (Bishop, 1995). Today, the city is about 57% White, 27% Black, 6% Hispanic, and 2% Asian (**U.S.** Census Bureau, 2020).

In the summer of 2020, Roanoke City Government's sustainability director was awarded funding from the US National Oceanic and Atmospheric Association NIHHIS (National Integrated Heat Health Information System) Heat Mapping Campaign (https://nihhis.cpo.noaa.gov/Urban-Heat-Islands/Mapping-Campaigns/Campaign-Cities) to produce maps of air temperature in the city. The maps are produced using a combination of vehicle-collected air temperatures and satellite-collected land surface imagery data (Shandas, Voelkel, Williams, & Hoffman, 2019). The purpose of the maps was to generate high resolution urban heat island data that could be used to develop vulnerability maps and approaches to dealing with heat. By summer 2021, the city did not have concrete plans to use the data products developed, but were interested in partnering with others to extend the work to engage more substantively with community members, especially in areas that were shown to be much hotter than the mean temperature in the city. Northwest, the borders of which are shown overlain on one of the air temperature maps produced by the urban heat mapping campaign in Fig. 1, was identified as particularly vulnerable to extreme heat.

In the summer of 2021, students of James R Breckinridge Middle School (of the Roanoke Public School-RCPS- system), located in Northwest, were chosen to enroll in a summer program run by the school district, called RCPS +. The researchers worked specifically with the RCPS Director of STEM education and one Breckinridge science teacher to develop a 2-week curriculum to deliver to students participating in RCPS+. Students in the program were divided into four, 45-minute class periods, each of which had 19–20 students enrolled. Since students were not required to attend RCPS+ however, daily attendance fluctuated greatly. While all students present were allowed to participate in the designed curriculum, researchers were only able to collect data for research purposes from students who returned consent/assent to participate in research forms. Since students were under 18 years of age, they signed assent forms to participate in the research. Consent was obtained by adult guardians of the student. The research protocol was approved by the Virginia Tech Institutional Review Board (#21-513). Of particular note was that the program was delivered in summer 2021, after many children spent a full school year online.

3.2. "Smart City" heat resilience planning activity Descriptions

Table 1 below summarizes the activities conducted on each day of the two-week program. During the first week of the program, students were introduced to various data sources and sensing technologies, and engaged in data collection in their schoolyard. During the second week of the program, researchers also presented examples of dealing with heat in other cities. These examples included: public infrastructures such as

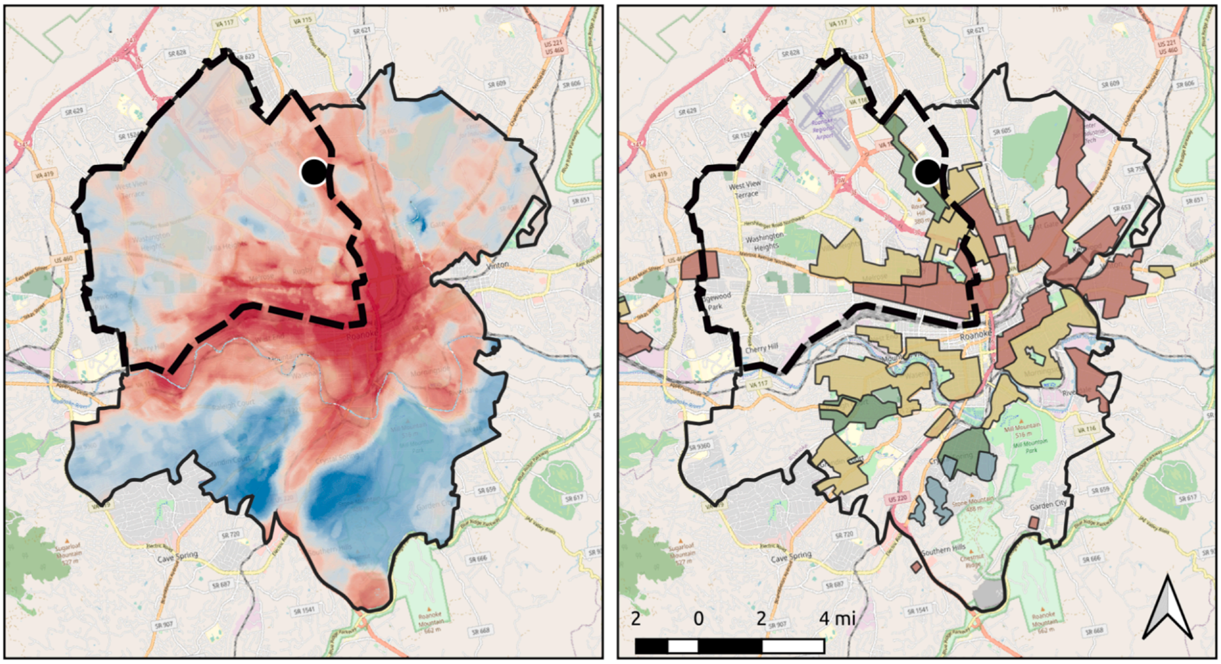

Fig. 1. Left: air temperature estimates made for the City of Roanoke from Summer 2021 Urban Heat Campaign data. Air temperature estimates range from 80°F (deep blue) to 90°F (deep red). Right: historical boundaries of the 1937 Home Owners Loan Corporation (HOLC) classes for the City of Roanoke (source: https://dsl.richmond.edu/panorama/redlining/#loc=5/39.1/-94.58). Red indicates Class D (riskiest class), Yellow indicates Class C, Green indicates Class B, and Blue indicates Class A (least risky class). In both figures, dashed line shows the approximate extent of Northwest Roanoke and the Black Dot shows the location of Breckinridge Middle School.

Table 1
Descriptions of activities during the two-week program.

Day	Description	Data Generated	Used to elicit responses in reserchers' one-on-one interviews	Trasncribed and directly analyzed for themes
1	Researchers present an overview of urban planning and urban heat islands; Demonstration of thermal drone flight	Thermal drone images collected at different times during the day (stitched thermal imagery used on Day 3 in GIS touchscreen activity); photographs	●	
2	Students use Google Street View and tabletop GIS touchscreen to make correlations between landscape elements and air and surface temperatures in the City of Roanoke	Worksheet; photographs	●	
3	Students use Google Maps and tabletop GIS touchscreen to make hypotheses about temperatures in their schoolyard	Worksheet; photographs)	●	
4	Students measure temperatures and thermal comfort at six outdoor locations in their schoolyard	Worksheet with instrument measurements and thermal comfort ratings	●	
5	Students review data from schoolyard measurement activities, complete worksheet	Worksheet; photographs	●	
6	**Students interview each other using an interview guide to better understand the impacts of heat in their community**	Audio files; photographs taken		●
7	Researchers present examples of approaches to dealing with extreme heat in other cities; students brainstorm what kinds of places such approaches would "fit well" into	Worksheet; photographs	●	
8	Students identify places that are important to them and make sketches of how the thermal comfort of those places might be improved	Sketches	●	●
9	Students work in groups to create a "heat resilience network" using green streets, splashpads, and other techniques to connect several parks in Northwest Roanoke	Sketches and plans	●	●
10	Researchers conduct one-on-one interviews with students	Audio files		●

public cooling centers, water fountains/bottle refilling stations, splash pads/fountains, public pools; home improvement social services programs including air conditioning giveaway programs, energy subsidies, home weatherization, building resurfacing programs, and community-owned solar programs; public awareness campaigns, such as fairs and print and media advertisements; urban greening projects including tree planting, vacant lot clean-up and community gardens; and street improvements, such as adding bike lanes, and street trees. Students also interviewed each other to understand the impacts of heat in their lives, and conducted planning activities, such as sketching solutions to make places they care about more comfortable in the summer and sketching a "heat resilience network" (connecting several parks together with green street improvements) on a map. On the final day of the program, members of the research team interviewed students who returned signed assent and consent forms to participate in research.

3.3. Primary data collection and analysis

Both the recordings of the peer-interviews (Day 6) and the researcher interviews (Day 10) were transcribed and analyzed.

Although our interview questions and planning of all smart city engagement activities were motivated by the theories and related research presented in the above sections, we did not attempt to assign codes directly from *a priori* themes. Instead, after the interviews were transcribed, we analyzed them, alongside the ethnographic-style notes we took during the two-week program and the worksheets, sketches, and plans the students produced, using a two-stage coding process (Charmaz, 2014). In the first stage, open themes were free-coded to allow for the emergence of new ideas, with the intention to better understand how youth conceptualized the problems and potential solutions to heat in their neighborhoods, and what role different kinds of technology and data played in the evolution of these conceptualizations. In order to maximize understanding of context in our codes, we attempted to code longer segments that represented a complete thought with multiple codes, rather than splitting up thoughts into shorter segments with fewer codes.

In the second stage, axial codes were used to group ideas into larger categories. Coding was performed using Dedoose qualitative data analysis software. Analyses included counting frequencies of occurrences of codes as a proxy for the importance of that coded concept to the participants. We also examined correlations and co-occurrences between codes to better understand which ideas were most related in our participants' minds.

In addition to the two-stage coding procedure, some answers to interview questions were treated as characteristics specific to the participants. For example, during the peer interviews the students conducted, the interviewee was asked questions about whether they had ever experienced discomfort due to heat in their own home, whether they had ever thought about going to another place or changed their plans due to heat. The interviewees' answers to these questions were recorded as binary (0/1) codes that were associated with each student. During the interviews with the researchers, students were asked to give a rating, between 1 and 10 for the 2-week program overall. This rating was also associated with the student. These data were entered into Dedoose as "Descriptor" characteristics, which would later be associated with the codes appearing in the media linked to each participant.

4. Results

We received assent/consent to use activity and interview data for research purposes from 32 out of a total of 52 students that attended the RCPS + program at least one day in the two-week period. Of the 32 students, 27 participated in peer interviews and 25 participated in an interview with a member of the research team, and 31 participated in at least one interview. Of the 25 students who participated in research team interviews, 14 were entering 7th grade, 8 were entering 8th grade, and 2 were entering 9th grade. Ages ranged from 12 to 14. All students interviewed by the research team reported overall positive experiences in the two-week program, with an average rating of 8.7/10 and ranging from 7 to 10.

4.1. Eliciting experiences of how heat affects and is a part of daily life

Students reported their personal experiences with heat in the peer interviews. For example:

- 75% reported having felt uncomfortable in their own homes because of heat
- 62.5% reported going to another location in order to cool down or access air conditioning
- 58.3% reported impacts on their own or family members' moods or energy levels
- 58.3% reported having to change plans because of heat

The most striking account of how heat directly affected life was made by a 12 -year old incoming 7th grade student, who recalled how because of a broken air conditioner, their[1] grandfather suffered a heat stroke in their home. They were the one who recognized that something was wrong, and called 9-1-1. After the incident, the entire family went to live in a hotel room for a period of time. Other students reported impacts including: feeling as if they "would pass out inside because the AC wasn't working"; putting ice packs on their heads in order to be able to sleep at night; putting bottles of water in the freezer to sleep with at night; pets overheating in the house; feeling stressed or tired because of the heat; taking frequent cold showers; sleeping on the floor in the living room or a sibling's room to deal with the heat; and fighting with siblings over electric fans. The code that most frequently co-occurred with students feeling uncomfortable in their own homes was "air conditioning problems." Students most frequently reported air conditioning systems being broken or "not working."

When the students reported having to change plans because of the heat, it most frequently was related to outdoor activities, for example, not visiting the park or getting outdoor exercise because of the heat.

> *"I usually go for a run in the morning, but lately I haven't been able to go because it's too hot"*
> *"I have little siblings that like to go to the park and older siblings who run and exercise there. But sometimes if it is too hot, they don't want to go there to run or play, because the swings and other things in the park get too hot."*

For youth, parks, streets, and other outdoor spaces are important places for socialization. In response to a question to sketch a place they cared about that they would like to improve the thermal comfort of, one student said:

> *"This is my neighborhood. I have a lot of friends there. We always like to walk around the neighborhood and stuff. That's why it's very important for me."*

For several students, the issue of safety and comfort in their neighborhoods due to heat was inseparable from other safety and comfort concerns related to neighborhood streets. And they would quickly shift from solutions that mitigated heat to other improvements they believed were needed to make their neighborhoods safer.

> *"We need a lot more trees. There's only like one tree in every lane, and they're not really trees. Definitely less road and more bike lanes, sidewalks, stuff like that."*
> *"I think we need more trees in my area. I live on [Redacted] Road, right next to the [Redacted] store, and I think we need more trees in that area… [and] I usually hear cars crashing, because they need to put [traffic] lights because [they] are really far [apart], which… [makes] the cars keep crashing."*

During the activity in which students were prompted to pick a place that mattered to them, and sketch how the thermal comfort of that place might be improved, several students drew crosswalks and stop signs (some in addition to urban greening, and others exclusively focused on traffic calming infrastructure) (Fig. 2). When asked about the rationale for drawing stop signs, traffic lights, and crosswalks in order to deal with thermal comfort, one student explained they wanted to improve the area near their house so they could walk to the park, which they expected to be cooler. They mentioned needing speed bumps on the roads to slow cars and make it safer to walk outside. Another student sitting nearby however made a comment about the area near the park being "not a good area," questioning whether it would be a realistic place to hang out if it were too hot at home for safety reasons.

Several students directly mentioned or alluded to other problems relating to safety. For example, two students who sketched the walk from their neighborhood to a nearby gas station mentioned that more trees and shade along the walk were needed to make it more comfortable on hot days. However, in their sketches, when talking through their solutions, they also mentioned having to walk past an unpredictable "crack addict." Another student, who in previous, more science-oriented activities, had been very engaged, became very disengaged during the activity in which students had to pick a place that mattered to them and sketch their ideas for how to improve it. Observing this, one of the researcher's notes included:

> *"[student's name] specifically made an impression on me today. They seemed very sad at the beginning of the exercise, and kept repeating that they weren't any good at drawing, and that they didn't go anywhere outdoors……. During the mapping activity, they showed us where their house was as an example of a street that needed improvements. Several houses from Google Street View appeared to be condemned/boarded up. Today, this student said [unlike others' neighborhoods] there was nowhere to go outside and nothing to do."*

Another student had similar issues, repeatedly saying that they never went anywhere and that they did not have any memories of being anywhere in their neighborhood except their own house. For these students, heat was not an explicit problem since both had access to air conditioning. Rather, access to safe outdoor environments for exercise or play was the peripherally related need, that caused them to not be able to engage with coming up with solutions for how to make outdoor spaces more comfortable thermally. In addition to neighborhood-level issues, the experiences of the students were also probably greatly impacted by the COVID-19 pandemic, since many children spent a full school year online and were allowed fewer activities with friends and unsupervised outside.

4.2. Shifts in understanding of the problem of heat

There was a noticeable shift in conceptualization of the problem of and solutions to heat between the peer interviews (conducted on Day 6 of the program) and the researcher-led interviews (conducted on Day 10 of the program). During the peer interviews, the code "feeling uncomfortable" most frequently co-occurred with the code "air conditioning problem." Solutions mentioned during the peer interviews also tended to focus on making sure everyone has a working air conditioner (mentioned as a solution 14 times), and even back-up air conditioning, with students suggesting the following:

> *"Tell shop owners to share their ACs, and water, and if there is no rain, save water for future summers"*
> *"More cooling systems and air conditioners in more houses if they don't have it or if their air conditioning is broken"*
> *"There should also be a [backup] AC in your house just in case the other one breaks"*

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[1] "They," "their," and "them" are used as gender-neutral pronouns throughout this article in order to protect the identities of minors participating in research.

Fig. 2. Examples of street improvements students sketched in response to a prompt to choose a place that mattered to them, and ideas for how the thermal comfort of that place could be improved. Sketches included greening and trees, but also traffic calming and pedestrian infrastructure.

In situations where air conditioning was not mentioned during the peer interviews, solutions tended to be very focused on individual activities or changes in individual behavior:

> *"Put an icepack on [your] head"*
> *"Take three showers and turn on the AC"*
> *"Get… a glass of ice water, or take a shower"*

Students suggested larger personal lifestyle changes as well, with one saying, "get a job, so you can get some air conditioning" in response to the peer interviewer questioning whether everyone could afford air conditioning. Another suggested that people should move to another state, or another country if it was too hot for them. In response to a suggestion about putting in public drinking water fountains in areas where children would like to play, one student responded, if kids "can't carry their own [water bottles] then they don't deserve to drink," and in response to the idea of "cooling centers," that they were not necessary since their family could just go in their basement to cool down, and that people should just be responsible for their own family. The above sentiments were representative of the students' responses and a conceptualization of the problem of heat as one to be addressed as an individual (or individual family) dealing with a (usually temporary) state of discomfort, rather as a problem that disproportionately affects neighborhoods such as theirs.

Table 2
Frequency of original open codes included in three axial code categories related to science engagement activities.

Technologies codes	learning codes	Engagement codes
- Drone (58)	- General learning (38)	- Fun (24)
Specificity (55)	Visual comprehension (37)	Planning on map 15
Infrared gun (40)	Confusion (15)	Going outside (11)
Handheld weather sensor (27)	Temporal comprehension (13)	Interviews (9)
GIS touchscreen (24)	Exploring new places (5)	Drawing/sketching (5)
Google maps and Street View (20)		Trust (2)
Satellite imagery (17)		
Thermal camera (16)		
Thermal comfort measurements (13)		
Ease of understanding (10)		
General technology (8)		

However, by Day 10 of the program during the researcher-led interviews, the most frequently mentioned solution to heat was “trees” (mentioned 23 times). For example,

> *“On my street, we barely have any trees… So I was saying that we should put some trees near the sidewalk so if people need to stop, they can stop underneath the tree to get some shade.”*
> *“[pointing to a building in her sketch], there isn’t much trees surrounding it, so you can plant trees around it to make it cooler.”*

One researcher’s notes included that in order for students to grasp the premise of Day 9′s activity, where students were prompted to create a “Heat Resilience Network” on a map of their neighborhood, they had to first understand the following concepts: public/private spaces and individual/neighborhood-scale responses to heat; that the environment *is* changeable by humans, that there are different locations in Roanoke that look similar or different from each other; and concepts for proximity and boundaries of a “neighborhood,” such as how long it would take to drive or walk to a place.

Notably, although the connections between temperatures and urban materials and vegetation were well-covered in the technology demonstrations and activities in the first week of the program, it was not until students engaged in mapping solutions in their neighborhood that they began to grasp that solutions to heat could extend beyond individual homes’ AC units and individual behaviors. One researcher’s notes for Day 8 – the activity where students selected places in Northwest Roanoke that were important to them– indicated “a few students seemed to finally understand that the locations that they chose were consistently warmer than the median Roanoke air/surface temperatures, and question why that is the case.”.

These concepts were not understood by all students by the end of the program, however. On Day 9 of the program for example, during the “Heat Resilience Network” mapping activity, one researcher’s notes mentioned one student who challenged the idea that outdoor temperature is changeable by humans, saying “we can’t change the outdoor temperature– if you want to make it cooler, you got to go inside and turn on your AC.”.

In addition, even among students who eventually did recognize that changes to the built environment could have impacts on thermal comfort of their neighborhood, there was hesitance toward the idea that this was “unfair.” After comparing observational notes about the students’ comments during informal peer conversations and speaking with their teacher about his interpretation of the reasons why, the researchers later ascribed this hesitance to several factors: (1) students wary of admitting vulnerability or being labeled as someone asking for a handout or not having access to the same resources as others; (2) students unsure of who should be responsible for differences in tree canopy cover and lack of vegetation in their neighborhoods. In both cases, understanding the problem of heat as an issue of individual action (either not having air conditioning at home, or not having enough trees in one’s yard), would cause the students not to recognize the situation as inequitable.

In one of the class periods, the students’ science teacher, who had also grown up in Northwest Roanoke, and whom the students trusted, told a story of how his neighborhood previously had very full tree canopy cover, but then the city came through and chopped off the middle of the trees in order get branches out of the way of the power lines. Shortly after that, the street trees died and had to be completely removed, and he noticed an obvious increase in his monthly energy bill because suddenly his house was no longer shaded by the canopy of the street trees. He said that he thought that if he had lived in a wealthier neighborhood, the city might have considered moving the electric utilities underground, rather than haphazardly chopping off major tree branches from such old trees. After the teacher told this story, the students seemed more open to discussing whether the lack of trees in their neighborhoods was “fair,” since their teacher had both destigmatized why there might be fewer trees there, and also called attention to the responsibility of the city. His story helped illustrate that disproportionate heat exposure was not an issue of personal lack or poor decisions on their families’ part, but perhaps the result of decisions their community was excluded from.

4.3. *“Smart City” technology activities and community-based learning*

Our initial open codes relating to the technology activities we engaged the students in were grouped into three main axial codes: (1) Technologies, (2) Learning, and (3) Engagement activities. Table 2 below shows the initial open codes subsequently grouped under the three axial code categories and their frequencies.

Of the technologies codes, the most frequently mentioned was “Drone” (58). Students were only present for one short drone flight demonstration (conducted once for each of the four class periods). But, the students frequently mentioned the land surface temperature images produced from those flights as important for understanding how different surfaces and materials had different temperatures.“Specificity,” which was a code used to refer to when students mentioned the level of detail and variation captured by various data sets, frequently co-occurred with mentions of the “drone” (11 co-occurrences), as did the code for “visual comprehension” in the “Learning” category. “Visual comprehension” was used as a code whenever a student mentioned seeing differences between different surfaces spatially (referring to colors or visual patterns). For example, one student said:

> *“You could see the different colors and it shows you the highs or whatever – where it’s hotter and cooler. And that was the easiest to understand, because you got to fly the drone in the air and you don’t gotta move. [refering to be able to see the temperatures of a wider area]”*

While another said:

> *“You could see it fly up and see how hot all the asphalt and everything is. And you could see the thermal version of everything, [alongside] the landscapes and stuff”*

Others emphasized the ease of deployability in helping them

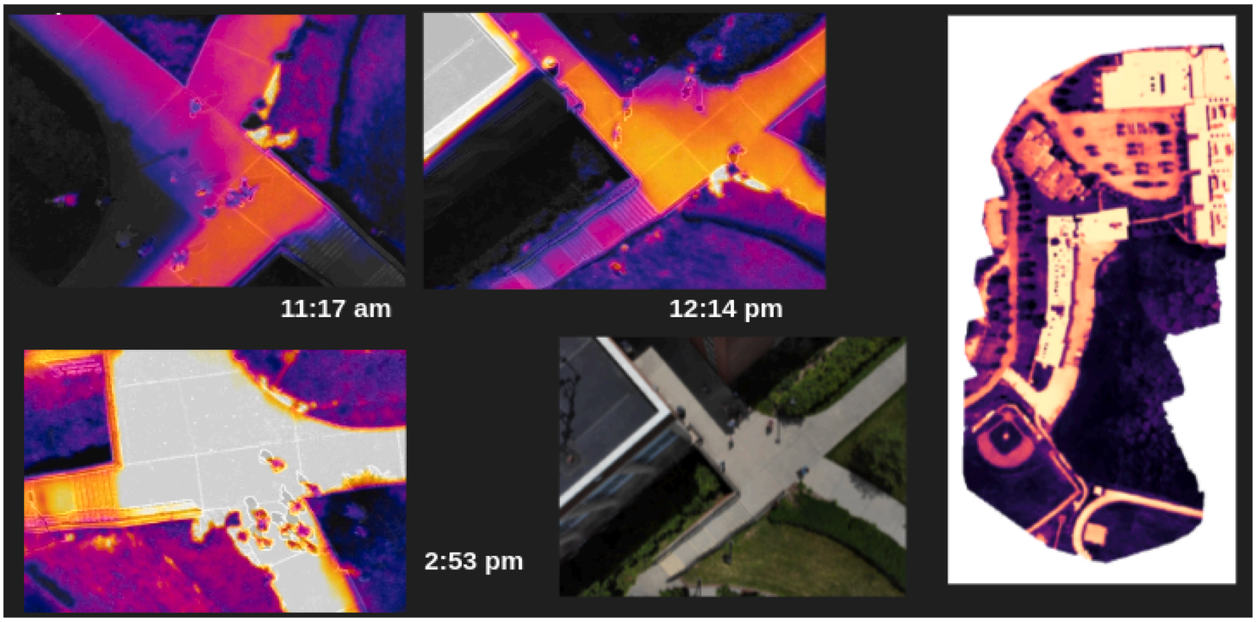

Fig. 3. Examples of data produced using the infrared thermal camera mounted on the drone, produced at different times of the day.

understand how heat can build up in different materials over the course of a day. Two students talked about seeing the thermal images taken by the drone at the schoolyard at different times of day (Fig. 3):

> *"When we looked at [the data] from the different hours, from 11o'clock it was hot on the [sidewalk] surface, and at 12 it was a little hotter, but at 2:53, it was very hot, and it showed just how hot it can get throughout the day"*
>
> *"That really showed us the different times of how the asphalt absorbs the heat from the sun"*

Compared to the Kestrel weather sensors, most students believed the handheld infrared thermal sensors to be both "more accurate" or "more precise" and therefore easier to understand. The Kestrels were used to measure air temperature, while the IR guns were used to measure surface temperatures. However, air temperatures on the Kestrel often oscillated around a particular temperature, and sometimes continued to increase as the student held the instrument in their hand, whereas the IR gun immediately returned a single number for every press of its "trigger." Air temperature exhibited less variability across the conditions of the schoolyard than the temperatures of various surfaces measured by the IR gun. Standing in a single location therefore, a student using an IR gun could make and test several hypotheses with the IR gun (for example, "is the grass cooler than this black rubberized asphalt track?" or "is this concrete cooler than my body temperature?"), whereas that was not possible with the Kestrels:

Fig. 4. Example of greenstreet connectivity plan produced by the students. Students selected streets to connect existing green spaces based on Google Street View images, and their knowledge of the neighborhood. The dashed line indicates the neighborhoods the students thought would directly benefit from the greenstreet connectivity.

> *"The drone and the IR Gun [were the most useful] because the drone could show [changes] throughout the day that it gets hotter, and the IR Gun would give them a direct temperature."*
> *"[with] the IR gun… you could tell the different temperatures at every place"*
> *"With the windmill thingy [Kestrel weather sensor], I couldn't…really tell and read what was going on with it. The IR Gun was better to use"*

Compared to the measurements of thermal comfort, which the research team summarized for the class from the students' worksheets, students continued to believe that the instruments were more scientific and exact, while their ratings of thermal comfort were considered inexact and not scientific. However, several students did note the importance of linking personal perceptions of heat and discomfort to the scientific measurements:

> *"All of them [the data sources] were useful, especially the drones and the satellite [data], [and] the graphs you showed to us of how many people preferred or what they feel"*
> *"If you use your own body to determine the heat, that's the thing that has the most accurateof all [for you]."*

Most frequently mentioned among the Activity Engagement codes was "fun" (24 times), which most often co-occurred with "going outside." This referred Day 4, where students were given various instruments (Infrared temperature sensors ("guns"), Kestrel weather sensors, a cell-phone mounted thermal camera) and walked six locations on their schoolyard to take measurements of the environment, as well as record their own personal levels of thermal comfort on Day 4 of the two-week program. Going outside and walking to the different locations was a welcome departure from their typical classroom setting, and several students mentioned the change of scenery and opportunity to get more physical exercise, while exploring the schoolyard with the equipment. Handling the equipment also engendered trust between the students and the researchers and helped students build interpersonal relationships with each other. In response to an interview question asking students to reflect on what was successful about the whole two-week experience, one student said:

> *"We earned your trust and you earned our trust, for every day that we spent together. You definitely trusted us by going outside, using the equipment, stuff like that."*

"Planning on the map", referring to the activity on Day 9 of the program, in which students tried to make a Heat Resilience Network in Northwest Roanoke by identifying where green streets and splashpads could be located, was mentioned 15 times. Figure 4 shows an example of what students produced to plan a heat resilience network connecting green spaces. "Planning on the map" was most frequently co-occurred with codes "help community," "solution," and "important issue."

From the above analysis, a complementarity between the activities emerged. First, use of a variety of different technologies and exposure to new places and experiences helped students grasp the variability of temperature and thermal comfort and its spatial distribution both in their schoolyard and across the city. And second, placing elements on a map of their neighborhood was much more linked to their sense of importance of the issue, thinking of solutions, and helping their own community.

5. Discussion

5.1. Lessons learned from youth for community heat resilience planning

From the above results, engagement with youth in a smart city heat resilience planning summer camp showed us the importance of planning with youth, both because they are frequent users of outdoor spaces for recreation and socialization, and because they are sources of knowledge about their own communities, and were generally very forthcoming with their opinions of different places, the needs of their neighborhoods, and their perceptions about what is wrong and how to fix it.

We learned concrete lessons from engaging with youth that could be transferred to further engagement with adult residents. First, because heat is pervasive and affects entire neighborhoods disproportionately, recognizing heat as a problem is not straightforward. For middle school-aged students, we attempted to have them "experience" differences in temperatures in different Roanoke neighborhoods by having them make observations about landscape elements in Google Street View in various neighborhoods in Roanoke, and then to use a tabletop GIS touchscreen to query air and land surface temperatures in those areas. With adults, this would likely be an easier connection to make, but adults still might be surprised by how large the differences in temperatures could be. Activities where adults are explicitly asked to hypothesize the relationships between various landscape elements and air or land surface temperatures could be beneficial in establishing the role of the built environment on thermal comfort, and associating elements of the built environment with distinct neighborhoods.

Second, we found that experiences of heat were varied and extend beyond often focused-on heat-related fatalities, including taking frequent showers, difficulty sleeping, irritability, and loss of recreation space. Once attention is drawn to these kinds of impacts, adults could be more likely than youth to recognize costs and inconveniences of excessive heat in their neighborhoods such as higher water/electric bills, and disrupted schedules, in addition to public health threats, since they might be more likely to be responsible for family bills and healthcare. Once such impacts are recognized it would also be important to clarify that the problem of heat is a systemic, wicked problem, and not merely an individual one. For adults, providing more context on the historical background of redlining and housing segregation in US cities and historical segregation maps' relationships with current day air and land surface temperatures could help emphasize the point that exposure to heat is not the result of personal actions or inactions, but rather, related to systematic public decisions about the built environment and infrastructure of cities. This might help to destigmatize heat as a personal problem and to recognize it instead as a social problem with origins in the history of how cities developed.

Third, when engaging with the youth around generating solutions to the issue of thermal comfort, their attention often quickly turned to solutions for other kinds of problems related to comfort and safety in their neighborhoods, including speeding traffic, street safety, and crime. For adults, it is likely that these issues are perhaps even higher priority than dealing with thermal comfort in their neighborhoods. Attempts to engage adult residents should therefore emphasize the interrelations between these important issues, rather than attempt to define heat mitigation as a unidimensional problem to be solved. Failing to acknowledge related community priorities could result in friction between government and residents of marginalized communities, where neighborhood greening is sometimes viewed with suspicions of gentrification or ulterior motives (Anguelovski, 2016).

Lastly, while higher resolution thermal images and data collection activities did help students identify landscape elements associated with cooler temperatures, seeing these relationships were not enough to shift their perception that humans could change the outdoor air temperature to be more comfortable. Instead, it took several *planning* exercises such as identifying candidate streets for street trees, and sketching solutions for specific places that allowed them to shift how they understood both the problem of heat and potential approaches to mitigating it. It is therefore important to acknowledge that the value of high resolution data may be different in stakeholder engagement than in scientific research. For example, air temperature and relative humidity have been shown to be better indicators of human thermal comfort (e.g. Salata et al., 2017), yet students found these the most confusing to understand of the sensor equipment. Also, many studies have found that meteorological data actually does *not* require a very high spatial resolution in order to be highly predictive of heat-related mortality, since heat waves typically cover large regions when they occur (e.g.: Wu, Zaitchik, Swarup, & Gohlke, 2019). Yet, in our study high resolution data played an important role in helping students understand the anthropogenic causes of elevated temperature in their neighborhoods.

Providing multiple entry-points to engage with these concepts was key: some students were attracted by the application of new technologies and the urban sensing activities; others were more interested in hearing their classmates' stories about experiences with heat; others liked drawing/sketching solutions and working with maps. This diversity of approaches to the problem's definition and development of community solutions is likely to also be helpful when working with adults. It also suggests that smart city sensing technology demonstrations with youth (and adults) may act as an effective "hook" for getting resident attention on issues like heat, which are pervasive yet often invisible.

5.2. *Empowering youth as family and community change agents*

Considering the context of culturally relevant pedagogy, the place-based sensing that was used in this project has significant potential to be strongly aligned with key tenets of assets-based pedagogies like culturally relevant teaching. The urban sensing and heat resilience project is primarily hands-on, inquiry-based, and scaffolds student self-directed defining of challenges and designing of potential solutions. Further, because sensing generates data about the immediate environment, it enables students to learn first-hand about critical infrastructure and public health issues and their inequitable geographic variation within their home community. Though issues of spatial justice were not embedded as comprehensively as future iterations of the curriculum could, we still intentionally and carefully engaged youth in learning about and problematizing heat resilience infrastructure issues.

We consider heat resilience in communities to be a critical public health and civic issue which requires community investment and collective change efforts. Youth education directly relates to a portion of the definition for urban resilience through its "ability… to transform systems that limit current or future adaptive capacity" (Meerow et al., 2016). Our case showcases youth engagement as a means to community adaptation by directly increasing their awareness, and as an initial step to broader change strategies. First, empowering youth to learn about and become change agents in their communities is regularly cited as essential to resilience, vitality, and long-term community change (e.g., Appalachian Regional Commission, 2019; Bey, 2020). Additionally, we also hypothesize that regular, quality engagement with youth can foster discussion and future participation with their families around issues of community heat resilience. Though this claim remains to be tested, it is rooted in literature expansions and adaptations of family systems theory and interest development. Specifically, Pattinson and colleagues define the family interest development system as "parents' and children's interrelated predispositions (stated and enacted) to reengage with a focus of interest over time, as well as the connected set of beliefs, values, knowledge, and skills that influence and are influenced by this reengagement and are distributed across family members" (Pattison et al., 2020, p. 5). The dynamic and reciprocal influences of systems-level theory in this context could be particularly beneficial as youth learning or community engagement around heat resilience issues can result in caregiver learning or direct civic action. Beyond the specific issue of heat resilience infrastructure, this family engagement is also vital to furthering youth STEM interest development since connecting the relevance of STEM content to one's own life and community is an essential aspect of culturally relevant pedagogy.

In this first iteration of the project curriculum, we did not explicitly engage families or seek to measure if our engagement with youth resulted in family learning or participation. However, this is an implicit goal within our approach and future activities and research can focus on it more intentionally, including developing research protocols grounded in the family interest development system. Development of empirical evidence demonstrating how data collection efforts, such as the original NOAA NIHHIS Heat Watch Campaign, can be translated into increased community resilience is an important next step for research.

6. Conclusions

In this research, we designed and executed a summer "smart city" STEM module with middle school students to begin to engage community members in heat resilience planning. Through participant observation and interviews, we distilled several lessons that can be applied to working with communities more broadly to identify, prioritize, and implement changes to built urban landscapes to improve thermal comfort and community resilience to extreme heat. These lessons included recognizing: (1) the problem of heat in neighborhoods and the social justice aspects of heat distribution may not be immediately apparent to residents; (2) a need to shift perceived responsibility of heat exposure from the personal and home-based to the social and landscape-based; (3) the inextricability of solutions for thermal comfort from general issues of safety and comfort in neighborhoods; and (4) that "smart city" technologies and high resolution data are helpful "hooks" to engagement, but may be insufficient for shifting perception of heat as something that can be mitigated through decisions about the built environment. Lastly, we demonstrate how the combination of youth STEM education, smart cities initiatives, and spatial planning and cartographic activities can be used as a next step for data collection efforts that successfully engage community members in thinking about urban landscape change and collective action.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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