Informing the Design of Mobile and Wearable Technology for Noise Sensitivity

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Research on understanding and supporting the experiences of people with noise sensitivity (PWNS) and their challenges is limited within HCI. Therefore, we build on prior work to understand the challenges they consider and what technological solutions they create to support them. Through eight participatory design workshops involving PWNS and their carers, we considered their needs and challenges and how technology can be designed to support their well-being. Results indicate that wearable and mobile technology can facilitate awareness of sensory triggers and impacts on their well-being. Further, enabling both self and collaborative regulation is also necessary, especially as end users seek independence or interdependence with those around them to manage their experiences. We identified three tensions for designing technology to support PWNS and their sensory experiences.

CCS Concepts: • **Human-centered computing → Ubiquitous and mobile computing design and evaluation methods**.

Additional Key Words and Phrases: Noise Sensitivity, Autism, ADHD, Assistive Technology, Participatory Design

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1 INTRODUCTION

Autistic[1] and ADHD people often face challenges with noise sensitivity [28, 52, 81]. Noise sensitivity can be described as one or a combination of the four conditions: hyperacusis (*e.g.*, the perception of everyday sounds as excessively loud and/or painful.), misophonia (*e.g.,* an aversion to specific sounds like mouth noises, repetitive sounds, etc.), tinnitus (*e.g.*, perception of sound in the absence of sound/ringing in the ear), and phonophobia (*e.g.,* the fear of sound). While highly prevalent within this population, its impacts extend to a broad demographic of people [18, 34, 48, 56], with some symptoms of noise sensitivity manifesting in early childhood [12, 30, 61].

Differences in sensory processing and regulation create substantial and sometimes debilitating distress [18, 40]. As reported in prior work, people with noise sensitivity (PWNS) may respond to sounds deemed annoying, painful, or intolerable by covering their ears, fleeing, self-injury, humming/vocalizing, avoiding, or adapting environments [19, 30, 56, 72]. Others may not be aware of how PWNS are impacted by sounds, thus sometimes inadvertently invalidating experiences and failing to accommodate as needed [18]. These accounts highlight the necessity of increasing awareness of noise sensitivity and having assistive tools to aid in supporting self-regulation. Current approaches for supporting PWNS typically include the use of ear protection devices or therapy (*e.g.,* exposure therapy, auditory integration, etc.). However, research cautions that ear protection devices may exacerbate noise sensitivity [31], and some intervention effects may not last [31, 33], indicating the need for a different approach.

Mobile and wearable technologies offer opportunities to alleviate distress and enhance sensory experiences for PWNS. For instance, technology-based interventions can support regulation and coping under duress. Alternatively, smart systems might automatically adjust the environment or alert the origin of the noise trigger with a request to change. For instance, work by Dotch *et al.* [19] includes a “Technological Wish List” which includes wearable devices, such as smartwatches, and mobile and intelligent systems to support awareness and self-regulation for noise sensitivity. Additionally, Park *et al.* [53] indicate that mobile technology can assist in sound masking methods. Further, prior work has explored noise regulation practices and the design of technological artifacts to manage auditory environments [7, 78], support sound awareness [32], and detect arousal during stressed states [3]. This research contributes to our scholarly understanding of the potential of technology to support PWNS. However, further work may be required to better understand the specific challenges faced by PWNS and to realize the potential of these technologies in addressing these challenges.

In this work, we collaborated closely with PWNS as design partners to understand what is essential to support and accommodate their needs on both personal and societal levels. We used participatory design to identify challenges PWNS face and design solutions to support their experiences, answering these questions:

(1) What challenges do people with noise sensitivity and those around them face regarding their own and others’ experiences with noise sensitivity?
(2) How do people with noise sensitivity envision the design of technology to support their shared challenges?

[1]The use of person-first or identity-first language has been a topic of discussion within the autism community [5, 37]. Here and throughout, we use identity-first language based on previous research for preferences in the U.S. [74] and personal experience (first author).

We conducted eight participatory design workshops, during which participants (n=20) designed paper prototypes of smartphone, tablet, and smartwatch applications to support noise sensitivity management and regulation. We conducted a thematic analysis of the design workshop transcripts and artifacts, including prototypes designed by workshop participants. The results of our analysis illustrate preferences for technologies that foster awareness of sensory triggers, capture context-sensitive information about experiences, and facilitate both self and collaborative regulation through coping strategies. From these results, we describe a set of tensions that arise when designing for noise sensitivity. Finally, we outline potential design directions that address therapeutic and societal approaches for supporting PWNS.

This paper makes both scholarly and design-oriented contributions. Our analysis reveals that while existing therapeutic approaches mainly target behavior change, PWNS require systems that integrate real-time physiological and environmental monitoring to support awareness and self-regulation. This finding suggests a more nuanced socio-technical approach, in which awareness and validation of the patterns of sensory triggers and overstimulation are central to managing experiences of noise sensitivity. Our work goes beyond current therapeutic approaches to begin to consider solutions that combine physiological and environmental sensing to support both individual and collaborative regulation. At the same time, our work contributes an understanding of the tensions around the interests of advocates to focus on society-facing techniques in light of design preferences of PWNS to focus on more therapeutic approaches, which we unpack in our discussion. We present notions of balancing self- and co-regulation as a potential path forward that respects the autonomy of end users while recognizing the responsibility for others to change so that our environments are less disabling. Finally, we discuss the need to increase awareness without distractions, which can potentially trigger other sensory challenges.

2 BACKGROUND AND RELATED WORK

In this section, we provide background on noise sensitivity, approaches for supporting PWNS, and the challenges associated with these approaches. We then summarize relevant work in Human-Computer Interaction (HCI) on the use of mobile and wearable devices to contextualize the appeal of such technology in supporting PWNS. Finally, we review relevant literature on participatory design to frame the use of this method as an approach to probe experiences that inform features of design and envision technological solutions with PWNS.

2.1 Background on Noise Sensitivity

Noise sensitivity is a sensory challenge experienced by a small portion of the world's population [60, 64] and is highly prevalent amongst neurodivergent populations [28, 81]. Individuals with noise sensitivity may experience a heightened physical and emotional response to sounds and struggle with loud and quiet sounds, managing their sensitivities, and sharing their experiences with others [15, 18, 30, 56, 58, 72]. For example, Rinaldi *et al.* [58] found that children with misophonia quickly respond to abrasive sounds with negative emotions and experience them intensely or for a long time. Similarly, through the exploration of noise sensitivity experiences described on online autism forums, Dotch *et al.* [18] revealed that noise sensitivity may lead to experiences of sensory overload and impact the person's work and school life. As a means of regulating, Stiegler and Davis [72] found that PWNS may respond to sounds deemed annoying, painful, or intolerable by covering their ears, crying, fleeing, self-injury, or humming/vocalizing. Some actions are considered self-stimulating and can help the person regulate and feel calmer; however, due to the stigmatizing nature and lack of understanding of some self-stimulating behaviors, PWNS may resort to masking, suppressing, or camouflaging [36].

Some PWNS when identifying assistive tools to help self-regulate may prefer using devices that are more *"subtle"* [18]. Furthermore, research has shown how the visibility or invisibility of designed assistive tools can further amplify or conceal one's disability or health condition [23]. Considering the subjective and diverse manifestations of noise sensitivity experiences, PWNS may not always be aware of their triggers nor how to cope with them. In such cases, those around may need to be aware of how to support the PWNS by either providing them with regulatory tools or adapting the environment around them [19]. Thus, methods to support PWNS should facilitate joint awareness and self- or co-regulation [19]. Building on this work, we explore the experiences of PWNS and contribute findings on what challenges PWNS consider when they design assistive tools to manage their noise sensitivity for themselves and those around them.

2.2 Relevant HCI Work on Wearables and Mobile Technology

We build on HCI research that explores the use of wearables and mobile devices to collect personally relevant data and help people become more aware of their behaviors and make necessary changes [42, 43], to explore the suitability of such technology to support and improve the awareness and regulation practices of PWNS. Many studies have explored the use of wearable and mobile devices to aid in the management of health conditions [13, 55, 62, 68] as these devices can be discrete, enable multimodal feedback, and provide personalized data tracking for self-knowledge and reflection. For noise-sensitive people, technological tools can enhance awareness and aid in managing their condition. Below, we review literature on the use of wearable and mobile technology for self-regulation and awareness.

2.2.1 Supporting regulation. Therapeutic approaches have been applied to support noise sensitivity responses, such as fear, increased stress and anxiety, and emotion dysregulation. In this work, wearable devices to track personal health-related data include wrist-worn devices such as smartwatches, for collecting physiological data to provide personalized support [14, 75, 76] or providing technological interventions without collecting any physiological data [22, 35, 69, 84]. For instance, Costa *et al.* designed a smartwatch-based intervention device called BoostMeUp that detects fast-beating heart rates and simulates slow-pacing artificial heart rates through haptic feedback to help the user slow their heart rate, thus helping them in self-regulating their anxiety and improving their cognitive performance [14]. Simm *et al.* [69] also conducted workshops during which autistic participants used do-it-yourself (DIY) kits to create a digital stretch wristband called Snap that records the physical interactions to provide more personalized interventions later. After four weeks of an evaluation study tracking the participants' anxiety levels, they discovered that all the participants were highly engaged and had positive experiences with using Snap for anxiety regulations [69]. With the recent influx of interest in artificial intelligence, many scholars have paired these approaches with sensor technologies and automated emotion recognition.

2.2.2 Supporting Awareness. We build on sound awareness research, which has been conducted in the context of D/deaf and hard-of-hearing communities (DHH), to understand approaches for facilitating awareness and recognition of sounds using mobile and wearable technologies. Jain *et al.* [32] applied a deep-learning approach to sense, process, and provide feedback on real-time sounds via an Android-based smartwatch app. This work demonstrates the feasibility of wearable and ubiquitous technology to support sound awareness, which we believe can be leveraged for PWNS to identify sound triggers. This approach may serve as a first step in supporting PWNS, addressing a subset of sounds that may be triggering them, and facilitating awareness of these sounds; however, sounds that do not reach a certain decibel level or frequency may not be detected, which could be troublesome for some PWNS.

In this work, we contribute to prior research by demonstrating how PWNS envision the use of and interactions with wearable and mobile technology to facilitate awareness of physiological and environmental indicators of noise sensitivity distress and aid in regulatory behaviors through their designs of technological artifacts.

2.3 Supporting PWNS Beyond Wearable and Mobile Systems

Various environments are inaccessible for PWNS, requiring us to examine the societal and environmental factors that influence overall experiences. Similarly, we must also consider technologies that aim at adapting environmental triggers of noise sensitivity. Notable approaches that consider environmental and social aspects of noise sensitivity and foster awareness of noise for identification and/or regulation of noise in public spaces include the intentional design of neonatal intensive care units (NICUs). These spaces involve using sensor devices and applications to monitor sound levels in rooms, ear protection tools, and re-education of care teams to minimize noise levels around premature babies [6, 78]. Similarly, outside of hospitals, other efforts have attempted to monitor and regulate environmental sound in shared spaces, such as Tunee, an interactive speaker that helps housemates share their noise-level preferences to facilitate awareness of this social context and inform behavior change [38]. The use of Tunee in this research led to increases in behavior reflection and behavior change to accommodate the noise preferences of others. Research and tools outside of the disability context provide insight into how sharing social information can enhance coordinated behaviors in shared spaces and consider options beyond medical and therapeutic models of noise sensitivity. Experiences of noise sensitivity are frequently inherently social, and past research indicates that increasing awareness of noise in social spaces can lead to coordinated behavior changes that support improving noise regulation [18, 19].

2.4 Participatory Design

Participatory design (PD) has an extensive history of involving key people in the design of social and technological systems [51]. Researchers and designers have used PD to understand the values and interests of end users, gain a contextualized understanding of how systems may be used, provide an inclusive space for diverse users to inform technology design, and receive continuous feedback for refining end products. PD can empower end users of various backgrounds through the co-creation of technology and tools that are intrinsic to the population's interest [8, 71]. In their work, Frauenberger *et al.* [26] draw on agnostic PD [4] to describe moments of conflict and how they can serve as constructive opportunities for design. After sharing cases of conflict, the authors discuss how these conflicts became "features of design." This work indicates that constructive disagreements within PD can enhance design outcomes. Rapp *et al.* [57] investigated the spatial needs of autistic adults by engaging them in interviews and participatory design, which led to the development of a crowdsourced map featuring relevant points of interest and descriptions of sensory information, enabling end users to make informed decisions about "comfortable spaces" based on sensory preferences.

Wearable and mobile applications have been collaboratively designed (co-designed), deployed, and adapted to understand and support the end needs of neurodivergent populations [11, 65, 68]. For example, Stefanidi *et al.* [71] conducted co-design sessions with five children with ADHD and six without ADHD to design technology they would like to use to support their daily well-being. In their sessions, they used paper, crayons, icons, and emoticons to create an app for tracking things they liked or disliked, allowing reflection later. The collaborative approach enabled exploration of how technologies might be used as well as the values and goals of their end users.

Other studies have created applications with children with ADHD to understand and support the development of self-regulation in children and co-regulation between children and their caregivers using a token-based economy [16, 68]. This prior research indicates that developing effective technological systems necessitates a greater understanding of those using the devices regarding their personal needs, interests, and goals. Therefore, in our work, we use PD as an approach to gain a contextual understanding of why and how PWNS may use and interact with technology to support their noise sensitivity experiences (RQ1); as well as to inform the design of future technology to support PWNS (RQ2). We present design artifacts that reveal the technological values of PWNS and discuss the challenges and potential solutions for effective technological designs and interaction with mobile and wearable devices. This contributes to the scholarly understanding of designers and developers within MobileHCI and the broader HCI community.

3 METHODS

We conducted eight participatory design workshops with 16 noise-sensitive individuals and four caregivers, all in the United States. The authors' university Institutional Review Board (IRB) approved this study protocol.

3.1 Participants

Noise sensitivity can be experienced throughout life, and both children and adults are worthy of study [19, 58]. Furthermore, ideal tools can be adopted in childhood and transitioned through to adulthood. Thus, we recruited both children and adults for this work, though not in the same sessions. Participants were recruited through a clinical center for neurodivergence and a regional non-profit center contracted by the State of California to coordinate lifelong services. Given the sensitive nature of recruiting children, parents of all participating children were contacted to obtain consent for their child's involvement in the study. After consent was received, the parent and child were scheduled to attend a workshop session. On the day of their session, we reviewed the study procedures and purpose again with both parent and child and confirmed verbal consent/assent to participate in the study. Participants were reminded they could withdraw consent at any point during the study.

All participants had the opportunity to join up to two co-design sessions (one session in Workshops 1-3 and one session in Workshops 4-6). Some participants did not participate in both sets of design workshops due to scheduling and recruitment challenges. Table 1 summarizes participant demographics and the workshops in which they participated. Participant ID "NS" indicates participants who are noise-sensitive, and "C" indicates caregivers. Caregiver/child dyads are indicated by a shared number (*e.g.,* 1A-NS and 1B-C).

In total, we recruited 20 participants (8 male-identifying, 11 female-identifying, and one non-binary/gender-fluid person) between the ages of 8 and 69 years old. Of our participants, 14 identified themselves as sensitive to noise, four were caregivers, and two were caregivers who also identified themselves as noise-sensitive.

3.2 Procedure

We developed our protocol to make the workshops inviting for younger participants, while also creating activities that were engaging for adults. Nearly all the participants with noise sensitivity either had a diagnosis of autism or ADHD or believed themselves to be undiagnosed neurodivergent. Thus, we designed our workshops following research about neurodiverse populations in PD [25, 67, 69].

3.2.1 Managing Dynamics: The first author developed a protocol focused on understanding and designing for experiences of noise sensitivity, which was then revised by the research team to determine how to best address our research aims and to consider both child and adult participants.

Table 1. Summary of Study Participants

ID	Age	Gender	Diagnosis	Ethnicity	Workshop
1A-NS	9	M	ASD	Latino, Asian	W1, W4
1B-C	45	M	-	Latino	W1, W4
2A-NS	33	NB/GF	ASD	Asian	W2, W5
3A-NS+C	60	F	-	Asian	W2, W5
3B-NS	25	M	ASD, OCD	Asian, White	W2, W5
4A-NS	41	F	ASD-PPD	White	W3, W6
4B-C	69	F	-	White	W3, W6
5A-NS	54	F	-	White	W3
6A-NS	27	M	ASD	White	W3
6B-C	65	F	-	White	W3
7A-NS	9	F	ASD	Asian, Hispanic	W4
7B-NS+C	37	F	Anxiety	Asian	W4
8A-NS	14	F	ASD, SPD	White, Asian, Hispanic	W4
8B-C	50	F	-	White	W4
9A-NS	53	M	Bipolar	White	W5
10A-NS	28	F	ASD	White	W6
11A-NS	10	M	ADHD	White	PW1, PW2
12A-NS	8	F	-	White	PW1, PW2
13A-NS	11	M	undiagnosed ND	White	PW1, PW2
14A-NS	9	M	-	White	PW1, PW2

Note: PW = Pilot Workshop (n=2), W = Main Workshop (n=6); ND = Neurodivergent

To limit power dynamics between children and adults and to focus activities appropriately, the groups were split by age. We leave open to future work dyad-focused design workshops that could provide other insight. Caregivers and parents of the children were also present for child-focused workshops. However, we engaged them in a separate discussion in another area to minimize interaction. During the workshops, two to four researchers were present to take notes and assist in managing activities.

3.2.2 Co-design Workshops: Before each session, we explained to participants that the aim of our study was to understand their experiences with noise sensitivity and how we could design technology to support their needs. Workshops 1-3 focused on designing for noise sensitivity and challenges experienced in various environments and contexts (*i.e.,* social model oriented), and Workshops 4-6, which occurred three weeks later, focused on supporting self-regulation and management preferences (*i.e.,* therapeutic/medical model oriented). A summary of each session is detailed in Table 2.

Table 2. Overview of the Design Sessions

Session	Objective
Pilots	Test co-design protocol and materials. Understand experiences and challenges of noise sensitivity current coping practices. Design potential solutions for supporting experiences and challenges with coping.
Co-Design 1	Understand experiences and challenges of noise sensitivity current coping practices. Design potential solutions for supporting experiences and challenges with coping.
Co-Design 2	Support self- and emotion regulation. Understand what emotions and actions are common during moments of noise sensitivity. Design for managing emotions and actions during noise sensitvity experiences.

Pilot Sessions: Before conducting our workshops, we tested our protocol with two sibling pairs (three boys and one girl, ages 8 to 11), including one child with ADHD and another who reports he is undiagnosed neurodivergent; two reported noise sensitivity. We encouraged the participants to express their needs and those of others sensitive to noise. In the initial pilot, the first author guided discussions on sensory experiences and instructed participants to brainstorm technological solutions through activities such as storytelling with Story Cubes[2], noting problematic sounds on sticky notes, and suggesting noise management solutions. After gathering feedback, including a lack of interest in certain activities, we revised our protocol. Changes included replacing Story Cubes with oral storytelling, card sorting, and using paper prototyping instead of sticky notes for idea generation. We also provided blank sheets and wireframes of smartwatches, tablets, and mobile devices, all of which participants were familiar with and appropriate for our age groups [1, 71], to facilitate design ideas. With these adjustments, we piloted the updated protocol with the same children, resulting in a more engaging and interactive experience.

Workshops 1-3: *Designing for noise sensitivity experiences and coping.* In Workshops 1-3, participants engaged in storytelling, card sorting, and paper prototyping. We began by sharing a narrative about Ashley, a persona, to inspire participants' own storytelling. Participants then shared their experiences in response to prompts about noise sensitivity. In the card sorting activity, they sorted sound cards into categories of liked and disliked sounds, based on a prior analysis of positive and negative sound reactions. They also created scenarios involving sounds, associated emotions, and actions. To develop solutions, we used a fictive narrative and *Bag of Stuff* method [79] to create solutions, using materials from a provided creative toolbox to make low-fidelity prototypes. The workshops concluded with a "Show and Tell" session, where participants discussed their inventions and shared insights.

Throughout the session, we informed participants that they could use the provided tools (*e.g.,* wireframes or blank sheets) or other methods to share their ideas; this way, we did not limit participants to a single way of sharing their ideas during the workshops. Additionally, to minimize

[2]https://www.storycubes.com/en/

dynamics between the researchers and participants, we did not engage in critique, only helping participants when asked. We probed participants to elaborate on comments and ideas to help us better understand their experiences and ideas.

Workshops 4-6: *Co-designing for self- and emotion regulation.* Discussion during Workshops 1-3 informed the focus on self- and emotion regulation for Workshops 4-6, which were held three weeks later. During the workshops, each session included circle time, design time, and discussion time, as seen in work by Woodward *et al.* [83]. Circle time discussions centered on self-regulation by asking questions like *"How do you get a handle on your big feelings? What motivates you to calm down when you feel big emotions? Tell me about a time when you lost control."* Following the discussion on emotion and self-regulation practices, we moved into design time during which we gave participants the following task: *"Design an app that helps you control your feelings when your feelings are getting big."* During design time, we separated the participants into smaller groups, where one group consisted of two to three participants with two workshop leaders (one moderator and one scribe), depending on group size, to collaboratively design tools to support self-regulation. Each group was given a creative toolbox with materials (*e.g.*, markers, popsicle sticks, glue sticks, emojis, and technological wireframes) and easel pads (*i.e.,* Big Sheets [83]) to create low-fidelity prototypes to support self-regulation. Following design time, we came back together as a group and discussed the different design ideas created by each group using the "Rose, Bud, Thorn" method to evaluate ideas generated [29, 82]. "Rose" indicated ideas or concepts that the participants loved; "Bud" indicated new ideas or concepts that came out of hearing other's ideas; "Thorn" indicated ideas or concepts that were challenging or hard to do.

3.3 Data Collection and Analysis

During the design workshops, we collected observation notes and recorded the audio and video for all workshops. Immediately following each session, the authors met as a group to discuss the workshops and add to the memos and notes collected by the research team. These materials became central to our analysis alongside the audio recordings and observation notes. The audio recordings were later transcribed for analysis. Additionally, in instances in which the audio was unclear, we relied on observations and notes taken by the scribes during the workshops.

Data from the design workshops were analyzed using deductive and inductive coding [63]. Following the pilot participatory design workshops, we analyzed the audio recordings and observation notes from the participatory design workshops by creating affinity diagrams using Miro[3]. We extracted quotes and observations from the workshops onto sticky notes and created clusters of similar topics. In particular, we placed notes that shared similar intent, phrasing, or concepts and grouped them into clusters (*i.e., affinities*). This preliminary analysis resulted in three key insights [17]. The findings from the pilot data analysis provided a perspective into what may arise from our main workshop sessions once conducted. Therefore, after conducting the remaining six workshops, we then analyzed all memos, design artifacts, and transcripts. Each member of the team took a subset of our data and analyzed it both deductively and inductively, organizing the data into affinity clusters on Miro. We met weekly to discuss our insights. Through this iterative process of grouping and regrouping data into affinity clusters, insights about our data emerged. Our affinity clusters identified insights related to challenges experienced with noise sensitivity and features of design for mobile and wearable technology to support PWNS.

[3]https://miro.com/

3.4 Positionality Statement

Five of the authors come from backgrounds experiencing noise sensitivity and/or encountering people in their family who have noise sensitivity. Two authors have noise sensitivities themselves; one is the parent of a child with noise sensitivities, and one is the sibling of an autistic, noise-sensitive adolescent. Having this first-hand experience of the impacts of noise sensitivity on either themselves and/or members of their social circles, the authors took precautions to ensure that noises were mitigated. Workshops were conducted in an on-campus conference room with minimal foot traffic, allowing participants to be in a low-stimulus environment. Additionally, during the workshops, participants could take breaks to ensure their well-being. To address potential biases before, during, and after the data analysis process, the authors met following each interview and during the data analysis process. This reflexive process enabled the researchers to understand how their own experiences, biases, values, and vulnerabilities impact the study and shape the contributions expressed in this paper.

4 FINDINGS

In this section, we describe how participants in our co-design sessions designed technological systems to support their noise sensitivity experiences. Our analysis reveals opportunities for mobile and wearable technologies to facilitate awareness of sensory triggers and heightened emotions that contribute to challenges of sensory overload and dysregulated states. Additionally, from the applications designed by participants, current technologies should be responsive to environmental and physiological indicators of potential stress and facilitate self-regulation and opportunities for co-regulation with others. Despite specific prompting to think about social and structural challenges and solutions, participant designs predominantly aligned with therapeutic approaches, showing their need for individual support and suggesting a view of their needs that leans towards addressing immediate concerns and relief of their own symptoms.

4.1 Facilitating Awareness

Participants discussed various environments and sounds that impacted their noise sensitivity. For example, school and social settings (*e.g.,* parks, restaurants, family gatherings/vacations) were mostly discussed as being too loud, or places where triggering sounds were likely to occur. In such places, PWNS or those around them may not be able to control the auditory environment, or those around the PWNS may not be aware that the sounds or sound levels may be problematic. For example, 13A-NS shared a story about being in art class at school, and as someone was running their hands on the chalkboard, it made him tense, tighten up his shoulders, and *"want to run away forever."* In such cases, the student in the classroom was unaware of how their actions might trigger 13A-NS's noise sensitivity. Others shared similar experiences, including how unexpected fireworks at a baseball stadium (6A-NS), their baby sister crying (1A-NS), and conversations at the dinner table becoming louder (5A-NS) were problematic for them. Still, others who are not noise sensitive in the same environment may not view these sounds as triggering. Therefore, two challenges participants considered related to their noise sensitivity informed how and what they designed during the workshops: 1) their experiences of sensory overload and 2) their own and others' awareness of sensory triggers. Participants shared feelings of being overwhelmed and experiencing "sensory overload" until they reached a state of emotional distress, such as "meltdowns" or a sense of "burnout" from overstimulating work and school settings or crowded public spaces (*e.g.*, public transportation, restaurants, hospitals). This experience aligns with prior work that explores the impacts and experiences of people with noise sensitivity [18, 41].

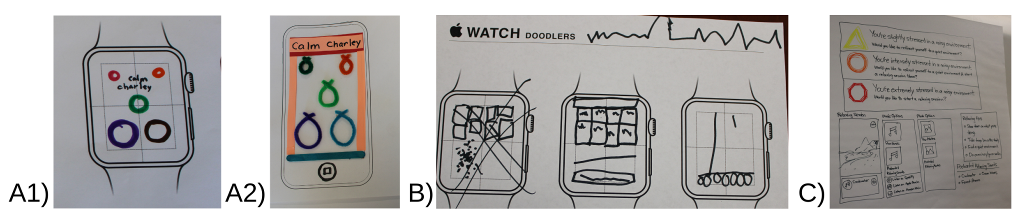

Fig. 1. Low-fidelity prototypes with sensing and tracking abilities: A1) and A2) a mobile and smartwatch application with an interactive user interface (3A-NS, Workshop 4). B) An application that depicts the noise level in the surrounding area while engaging with playful games (1A-NS, Workshop 3). C) A mobile application that senses decibel levels and notifies users of increased noise levels (2A-NS, Workshop 4)

Participants suggested technologies that sense and track physiological data, such as heart rate and blood pressure, and environmental data, such as noise levels, to address these experiences. Designed applications also indicate the potential to help increase awareness of how noise may impact one's well-being. For instance, 3A-NS designed an app that would sense her heart rate and blood pressure to detect when either is increasing, notifying her to engage with her app she named Calm Charlie (Figure 1). In 3A-NS's designed app, tracking her heart rate and pressure enables her to determine when she is becoming stressed due to her surrounding environment. Other sensing data participants suggested included tracking body temperature, activity level, blood pressure, and location *"to give a well-rounded idea of [their] state of being"* (9A-NS). While these are standard health-related indicators with which most participants were already familiar, the notion of combining them into a more holistic view of welfare indicates interest in drawing attention to larger impacts.

Co-designers also explored the need for awareness of noise levels in environments participants frequented, particularly before arriving or entering. This information can aid in decision-making and planning, validate perceptions of those experiencing noise sensitivity, and help them understand patterns in the spaces they frequent. Multiple participants designed technologies that could sense the ambient sound in the environment and notify them when the sound around them increases or exceeds tolerable levels. For example, in the app 1A-NS designed, he included a *"sound graph showing sound levels"* continuously on the watch's face to monitor the sound around him while also playing the game he designed (Figure 1). These designs indicate that technological artifacts should include sensing environmental noise levels and giving feedback about the environment to the user to create awareness of the environments that are of interest. Notably, the participants also make clear that while they understand their responses to particular environments, they cannot always predict them, making it more challenging for them to have the kind of autonomy and control they wish to have. Such design features were common among the adults who participated in our study, whereas the children, with the exception of 1A-NS, were more interested in wearable and mobile tools that would help them regulate once they were aware of a sound. This suggests that while children may not always be aware of a triggering sound or environment, they do not fully engage with or understand the physiological or environmental cues associated with it. Thus, mobile and wearable technologies that support self-regulation behaviors may be of greater value for children with noise sensitivity. We discuss this in more detail in Section 4.2.

Gathering information and displaying it may not be enough. Participants expressed interest in greater support for reflection, including check-in notifications and other mechanisms to increase their awareness. For instance, 5A-NS designed an app to send reminders to check in with herself throughout the day, stating, *"Sometimes we don't check in with ourselves until we're overwhelmed. [I designed] an app that reminds me to check in with myself."* In this case, *"check in with ourselves"* alludes to individuals evaluating their physical, emotional, or mental state at a given time. However, they also suggested not sending too many notifications because they may become *"stressed out when there are constant notifications"* (9A-NS).

Furthermore, many participants preferred the app to operate in the background without occupying space on their device interface. Despite wanting to track their data, they did not want these functions visible. For example, as demonstrated by Prototype A1-2 and Prototype C (see Figure 1), participants did not include visible tracking elements on their interfaces.

These tensions between visibility and hidden support, between proactive and reactive engagement on the part of the system and possibly even the user, and the role of overload should be examined carefully. In our workshops, co-designers often brought a personalized view to these design choices, noting how specifically *they* would want to engage with tracked data, sometimes without a sense of how other users might do so. Overall, these findings suggest that designs should enhance and utilize tracking and sensing related to auditory input and noise more broadly, while allowing sufficient flexibility to cater to each individual's sensory needs.

4.2 Enhancing Self-Regulation Through Interactive Systems

Another challenge participants considered was self-regulating during unexpected or prolonged noise exposure. Therefore, the artifacts they designed suggest an interest in technologies to aid in self-regulation. In particular, child participants preferred applications that helped distract them as a means to regulate their emotions in noisy environments. Thus, they primarily designed games that included elements of storytelling, adventure, and mindfulness to facilitate self-regulation behaviors. For example, 8A-NS expressed her aversion to typical mindfulness activities stating, *"Everyone says that meditation and deep breathing is good for you, but it should be outlawed in [State]."* Instead, during our design activity, she designed a farming game where the intent is to *"virtually get your anger out,"* because in moments of anger from noises, *"you think more about ruining stuff, and you can do it in the game instead."* Other youth designed similar interactive games that would help them feel better or distract them when they were overwhelmed by noise. 12A designed a dancing ice cream game that generates a physical force field around her as she engages with it, blocking out the surrounding sound. These designs suggest that youth associate what brings them joy with ways of helping them self-regulate, rather than traditional mindfulness activities such as meditation and deep breathing.

In comparison, adult participants designed applications that helped them recognize their emotional state, apply appropriate coping strategies, and guide them through this process. For example, 10A-NS, 4A-NS, and 4B-C worked together during Workshop 6 to design an app that guides users through identifying their mood and its intensity, offers coping activities, and prompts them to reassess their mood upon completing a coping activity. Similarly, 6A-NS and his mother (6B-C) developed a simplified app that reveals the next step only after the current one is completed. She said, "*One button doesn't come up until the previous one is pressed...Too many options make him feel overwhelmed and stressed about what to do. When [he is] in panic mode, he needs simple steps*" (6B-C). They sought a step-by-step process for self-regulation to provide structure when feeling overwhelmed by noise triggers. In these sessions, we observed distinct preferences in how children and adults perceive technology as a means to support their self-regulation needs. Specifically, children did not design systems that facilitated guided, step-by-step regulation support as adults did, but were more interested in self-regulation through play that was less structured. Such differences may relate to the developmental stage of children compared to adults, as children might not be developmentally ready for the cognitive engagement necessary for the guided regulation systems

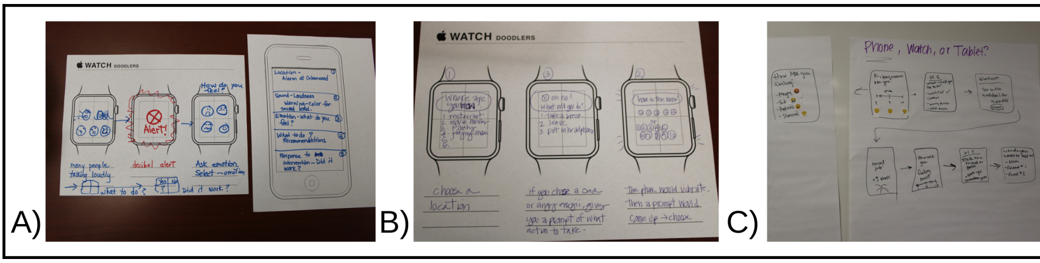

Fig. 2. Prototypes with emotion tracking: A) a mobile and smartwatch application that detects decibel levels and uses emojis to express user emotions B) A smartwatch app for people to check in with themselves using emojis. C) A mobile app that tracks emotions and provides tools to help the person feel better

proposed by adults in our study. Thus, when designing for noise sensitivity, we must consider the trade-offs of both approaches for supporting the diverse needs and preferences of people with noise sensitivity, especially as we account for designing across ages.

Beyond creating strategies to support self-regulation, technologies might also integrate methods for assessing the effectiveness of such strategies. Participants created concepts for new technologies that would inform decision-making across various contexts and apply effective practices for coping. For example, 5A-NS shared that *"collecting data and keeping track of patterns and what [she] did in a location and if it worked"* would help her determine what to try next time she faces noise sensitivity challenges. Moreover, in cases where interventions proved ineffective, 5A-NS suggested an adaptive system capable of recommending alternative approaches for future use – *"if the suggested item was not helpful, [the app would] suggest something else next time"* (5A-NS). Furthermore, participants wanted follow-up prompts to assess the relative success of the methods they used, such as *"Did this exercise work?"* or *"How are you feeling now?"* This type of adaptation can assist individuals as they age or as other life changes affect their ability to manage their noise sensitivity as they once did.

Participants described the benefits of and interest in tracking emotional states during and after noise sensitivity incidents. For example, four of nineteen prototypes featured emotion tracking, in which users identify emotions and/or intensity (see Figure 2). Additionally, 4B-C revealed that her daughter, 4A-NS, has used emotional arousal scales with her care staff to communicate levels of emotional distress, which helps to connect her to existing systems of support. While regulating their emotions was of interest to the children in our study and during group discussions, they were aware of the impacts of their noise sensitivity on their well-being, such as feelings of discomfort or being overwhelmed; yet, they did not share the adults' interest in tracking their emotional states. Instead, the interactive systems they designed were geared more toward expressing and relieving their intense emotions as a means of emotion regulation.

Sensory-friendly spaces can help escape overstimulating environments, whether in the physical or virtual world. Virtual games, such as Minecraft, have been shown to provide a space for people with autism to self-regulate and have sensory breaks [59]. Similarly, in our design sessions, participants designed interactive and open-world exploration games as spaces to escape for self-regulation. To create these kinds of escapes, they sketched ideas for games meant to distract them from the sounds around them. These games indicate the potential of mobile devices, such as smartphones and tablets, to allow people to remain in problematic physical environments by providing a distraction from the stimuli. When co-creating a game with 7A-NS during one of the children's co-design workshops, 1A-NS shared, *"Games make me focus, games that need extreme focus, help me. The game distracts you from the feeling."* Similarly, 3B-NS designed a smartphone and smartwatch app called SoundWave, which allows him to explore a virtual world with sounds that are calming and relaxing to him.

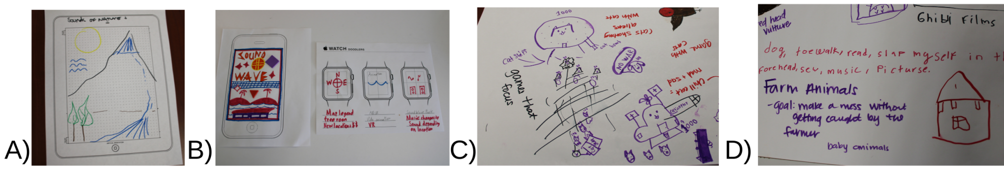

Fig. 3. Game Prototypes: A) An immersive tablet-based game to listen to music and sounds based on the landscape pictured in the game. B) An immersive game in which avatars can explore different auditory landscapes and unlock new terrains. C) A game called "Cat-icopter" to help with feeling big emotions. D) Farm Animal interactive game to help with releasing emotions by destroying the farm.

Depending on the location of his avatar in the virtual world, calming noises are generated. These designs suggest that sometimes people cannot or do not want to leave or avoid an environment, and tools for momentary escapes could help.

Participant designs also incorporated elements that appealed to gamification. Gamification elements, such as levels, challenges, and a point or token system, are familiar motivation approaches for many children, which were prominent in their game designs and discussions. For instance, 1A-NS and 7A-NS mentioned their game included a boss level, which indicates another level of difficulty in gameplay (see Figure 3 Game Prototypes C and D). Similarly, 8A-NS and 11A-NS mentioned getting tokens and Robux[4] in their games when using them. Notably, similar elements of gamification appeared in adult participant designs (see Figure 3 Game Prototypes A and B), suggesting interactions with gaming elements, such as levels, challenges, and a point or token system, may encourage both children and adults to manage their reactions and potentially motivate continued use of the system.

Finally, participants expressed interest in the personalization of their tools and supports. During the workshops, 17 participants proposed features related to personalization and customization of activities tailored to individual emotional arousal levels and contexts. For instance, children in the workshops discussed adding to their apps personalized coping strategies, such as playing video games, playing with their dog, or eating their favorite snack. Adults in the workshops discussed more advanced features of personalization, such as interventions that offer recommendations based on past tracking of emotional states and coping strategies, or by anticipating optimal times to encourage regulatory activities.

> *"Based on the score I select when I check in, it will either end there and remind me later, or it'll go to a coping screen."* - 5A-NS
>
> *"You use the emojis to check in, and based on the emoji, specific tools are suggested to cope."* - 4A-NS

These design suggestions indicate the potential of using machine learning techniques to support self-regulation behaviors for people with noise sensitivity.

4.3 Engaging Others in the Regulation Process

PWNS might not always realize a sound or environment's impact or potential impact. In these cases, those close to them, such as family members, teachers, or partners, play essential roles as allies in social engagements and co-regulators [19, 68]. For example, 3A-NS and 9A-NS developed

[4]Robux is a reference to Roblox and a form of currency for the game.

a "Phone My Friend" feature that automatically notifies secondary supporters when the person indicates a heightened stress level.

> *"The app will send an automated text to your support people that says*, 'Hey. X is having some problems right now. Text them'. *The app will send the geolocation to your support network in case they need to find you, [like]* 'Find My Friend.' *"* - 9A-NS

Although 9A-NS, an adult, was interested in this concept for themselves, this kind of support is even more frequent when the person is a child. For example, a group of parents from Workshop 6 designed their app to be shared between parents and their children.

> *"The parents' side should be more functional, and the kids' [is] more playful, but the app shouldn't confuse them. [It] needs to be simple for the children's interface."* - 7B-NS+C

In their app, parents share coping strategies with their children. For example, one parent (1B-C) wanted to suggest to his child that he should *"step away and engage in science stuff to help calm down."* Following the coping activity, the child could receive an award for engaging in the coping exercise. Similarly, 7B-NS+C suggested awarding points for completing calming activities, which can be *"cashed in"* for real-life prizes.

Child participants discussed integrating co-regulation methods by involving others, such as their parents or pets. Although the artifacts they designed did not incorporate features for notifying others, during group discussions, participants discussed how they went to their parents to help co-regulate or adapt an environment for them. On the other hand, caregivers in the workshops designed systems that enabled their children to reach out for support when they needed it. One method involved enabling the child to send notifications to a trusted person or their care network during stressful situations, but only if they wish, thus indicating the need for their assistive tool to empower agency and autonomy. This flexibility allows control of disclosure and can limit attention to a specific situation. Another approach permitted data sharing after the incident, allowing a trusted adult to support the child in reflecting on the situation and better preparing for the future without risking real-time disruption.

Taken together, our analysis of the approaches to designing and the tools themselves indicates that games, apps, and other technologies for noise sensitivity support should be capable of sensing and tracking relevant data to help facilitate awareness for the PWNS and those around them. Such tools could assist PWNS in recognizing patterns related to their sensitivity, including triggers, management strategies, effectiveness, and contextual factors. This enhanced awareness could empower them to better self-regulate their responses, as well as raise awareness with others, request accommodations they may need, and gain support from allies in their lives. Additionally, incorporating modes for self- and co-regulation and elements of gamification provides approaches to inform the design and development of interactive systems to support noise sensitivity and emotion regulation for both children and adults. Overall, through these design workshops, we have described potential avenues for mobile and smartwatch applications to support the experiences and challenges of people with noise sensitivity (PWNS).

5 DISCUSSION

Our analysis indicates that technology can address issues around awareness of noise sensitivity challenges, triggers, and difficulties in regulating that lead to sensory overload and burnout. Potential technological solutions can integrate sensors and tracking technology to increase awareness of both physiological, psychological, and environmental indicators of sensory overload and support regulation with evaluation to monitor outcomes. Additionally, collaboration and automation of technology together can manage noise sensitivity and the surrounding contexts. This work aligns with prior literature highlighting opportunities for sensing technology to support awareness and regulation [10, 54, 76] and the role of technology in enhancing collaboration and interdependence within communities [2, 77]. Despite this potential, tensions emerged in our analysis that designers must consider when creating technology to support people with sensory differences, such as noise sensitivity (see Table 3).

Table 3. Overview of the Design Tensions

Tension	Description of tension
Balancing Regulation with Autonomy	Balancing personal autonomy with necessary intervention across diverse demographics, managing disclosure control, determining appropriate support escalation thresholds, and providing intelligent feedback support when human assistance is unavailable.
Balancing Therapeutic with Sociatel Approaches	Reconciling PWNS preference for personal therapeutic approaches versus addressing environmental causes, managing information sharing considerations, and supporting both individual coping and environmental advocacy.
Technical, Ethical, and Design Tensions	Challenges involving accessibility barriers, data literacy limitations, design complexity for subjective experiences, privacy concerns with sensitive data collection, and potential negative psychological impacts of continuous monitoring.

5.1 Role of Technology in Facilitating Awareness

Limited awareness of triggers and experiences of sensory overload and heightened stress states, especially as they are building, can challenge people to manage their noise sensitivity experiences and regulate them. Our work suggests that smartwatches and mobile systems that employ sensing technology can aid in boosting awareness of noise sensitivity and initiate self-regulation and reflection behaviors. The aggregation of such data can help individuals gain a deeper understanding of themselves and make necessary adjustments, similar to practices in the Quantified Self community [9, 73] and typical Personal Informatics systems [42]. Our findings revealed that PWNS and their caregivers are interested in mobile and wearable tools that track features, such as heart rate and emotional states, to recognize when a sound or environment may be too overwhelming for them. Ubiquitous biofeedback systems have been used to support emotion regulation while minimizing distractions [13, 14], including through gamified approaches [66]. Additionally, smartwatch tracking capabilities can help people identify and manage triggers as observed in children with ADHD [1], regardless of age. Such technology can raise awareness of bodily changes that may be indicators of stress resulting from noise sensitivity and sensory overload.

Future designs can build on these insights by applying gamified biofeedback systems to increase awareness of noise sensitivity symptoms (*e.g.*, increases in emotional arousal, heart rate, or changes in breathing phases) while delivering personalized interventions. Personalization is particularly important in the context of noise sensitivity due to its broad impact across ages and how the condition manifests. Thus, personalization and gamification can better accommodate different attentional and regulatory needs of both children and adults. Based on our findings and prior work [45, 50], we suggest incorporating gamified elements into systems for children to support their different attention levels compared to adults. However, tensions may arise when designing for children and adults within the same platforms; what may be compelling to one group may be boring or silly to another. Additionally, a system that is helpful in one situation can become distracting in other environments or contexts. For instance, gaming at home may be acceptable, but it would not be appropriate as a solution at school or work.

Notification systems can leverage biofeedback to prompt self-checkins in real-time, supporting bodily awareness and attention to reduce stress from sensory overload. While such systems have been used to improve well-being [24] and support self-regulation in neurodiverse populations [27, 35], tensions remain around balancing awareness and distractions of notifications. Future work may explore how to dynamically adapt notification frequency based on PWNS preferences and contextual cues, as too many notifications can cause disengagement [46] or contribute to overstimulation, while too few limit awareness. We must consider the different thresholds for both physiological data and noise sensitivity when aiming to facilitate awareness.

5.2 Balancing Self- and Co-Regulation With User Autonomy

Participants tended to design applications that included features for self-regulation as individuals and co-regulation with support from others in the moment (see section 4.3), likely in response to the immense challenge of self-regulating while in intense stress. Integrated models for both self-regulation and co-regulation can support self-sufficiency within a support structure. Still, tensions arise in balancing each person's autonomy with decisions by others to intervene to co-regulate. Future work should explore these issues with a wider range of people than we were able to recruit in this work. Autonomy may look different for a PWNS who lives independently than one who requires more care and support. For children, implementing self- and co-regulation modes could allow children who want independence and autonomy to take it, while allowing for more supportive modes for those who need or want such approaches. One might allow a child to send notifications or otherwise communicate with a trusted person or network during stressful situations, but not automatically send such alerts. This flexibility allows the child to choose their disclosure levels and how much awareness and attention they want to bring to a particular situation. Another approach could allow for data sharing after the incident, thereby allowing a trusted adult to support the child in reflecting on the situation and better preparing for the future without risking disruption in real time. These realities and experiences must be teased apart and considered critically as we think about balancing modalities of regulation with user autonomy.

Future technologies should provide levels of regulation support based on the stressed state of the individual. For instance, low stress levels may indicate a potential opportunity for self-regulation, while extremely high stress levels may indicate that others are needed to support co-regulation. Depending on user preference and abilities, they may choose to directly and explicitly inform the system of a preference for self-regulation. They may also choose modes that automatically sense when greater support from either the system — an autonomous and intelligent systems approach — or other people — a collaborative technology approach — is most appropriate. Even if a preference for human support is indicated, intelligent systems aware of who is in proximity and able to help could default to an automated support approach when there are limited human resources available to help. For example, when the PWNS is not co-located with someone from their emergency contacts, the system may deliver co-regulation support, such as boxed breathing therapy via haptic feedback or a guided meditation session. Taken together, this approach empowers the PWNS to have the autonomy and agency to make decisions that best support their sensory and regulation needs while also allowing others or the application system to intervene when appropriate.

5.3 Designing Beyond a Therapeutic Approach

Participants were encouraged to think about challenges they experienced with noise sensitivity and potential solutions. Despite a combination of societal and intrapersonal challenges recounted during the sessions, most of the solutions designed centered on therapeutic interventions. This suggests that participants may be more interested in tools that support their individual needs rather than addressing the societal sources that are provoking their experiences. Caregivers already take actions to avoid and adjust the environment to help the person in their care [19], but these actions often limit the autonomy and opportunity of PWNS.

Various researchers and advocates have called for a move beyond therapeutic strategies for various experiences of disability [47, 70, 80], an interest we share. While PWNS, when pushed, were interested in these kinds of solutions, even their social solutions tended towards an individualistic model. For example, they indicated the need for technology to show visible indicators of contextual information relevant to their sensory experiences, such as their heart rate, environmental noise levels, and blood pressure; this information was solely for their personal consumption and reflection, suggesting that seeing this information may validate what they are experiencing (see section 4.1). With whom and how we might share such information implicates questions of privacy and trust, stigma and identity, and even larger cultural concerns, like mutual aid.

While PWNS understand that the environment is provoking their experience, their first interest tends to be their own personal well-being and not larger environmental or social change. Thus, designers must reconcile this first-order challenge of helping people who live in a disabling world while not masking or hiding the ways in which the environment is, in fact, disabling. We must be careful as we shift and expand our interests to these kinds of social and policy concerns not to invalidate the noise-sensitive person's experiences and directly expressed needs and interests.

Technologies that both aid in self-regulation and adapt the surrounding environment are needed to balance these tensions between therapeutic approaches and societal triggers. Constraints that environments place on PWNS are real and disabling. At the same time, PWNS want to build their own awareness and self-regulation abilities. As participants demonstrated, assistive technology may serve as a tool that provides both awareness to others and coping methods for self to support the regulation and management of experiences (see section 4.2) while encouraging self-advocacy to change and challenge the societal actors around them by bringing awareness to others (see section 4.3).

5.3.1 Broadening Implications for Design. With these considerations in mind, designers and the broader HCI community must consider how to accommodate people with various sensory sensitivities at the same time as we improve the design of spaces and interactive artifacts in general. Diverse sensory processing and experiences create another level of vulnerability that must be considered when assessing the accessibility of environments. This may include the implementation of interactive systems to support sensory needs while also addressing other barriers that contribute to the inaccessibility of spaces frequented by people with sensory sensitivities or the redefining of what it means for a space to be accessible beyond logistics and acts for diversity and inclusion [49]. Individual experiences of sensory sensitivities are widely misunderstood in some spaces; therefore, future work would be beneficial in exploring sensory needs and designing more sensory-accessible environments for people with sensory sensitivities, especially regarding auditory sensitivities, and we can first start by integrating them into the design process of the various artifacts we engage with daily.

5.4 Technical, Design, and Ethical Challenges

The approaches proposed in this work to support and facilitate awareness and regulation present technical, design, and ethical challenges that must be considered. From a technical standpoint, adequately supporting the sensing capabilities discussed by PWNS would require access to technology with robust sensor capabilities, which can be costly. This can be a barrier for PWNS from non-WEIRD[5] communities [44], as well as younger end users who may, due to restrictions set by caregivers or institutions, have limited access to such technology. Additionally, simply being able to access the data does not necessarily mean they are informative or understandable. Children, who are still learning numeracy and graph literacy, may have radically different experiences reflecting on such data than their adult counterparts. Similarly, personal informatics literature has long described challenges in the ways in which different people take in different information [1, 21, 42, 43]. The relevance of specific data reflection practices may depend on general data literacy, preferences for narrative or visual information, or even just the context of the specific day or experience. These complications may lead to a need for more customization or personalization, or may be a broader set of barriers for real-world and long-term implementation of the solutions we propose here. We intentionally did not ask co-designers to be practical. So, the artifacts they designed do not generally consider all of the challenges of such interventions, nor do they provide a detailed context for daily use.

Designing systems that perform as PWNS from our workshops expect becomes increasingly complex when accounting for the diverse characteristics of PWNS. Their challenges with noises are not restricted to only loud sounds, but repetitive (*e.g.,* tapping, clicking pens), perceptibly quiet, or only occurring in certain contexts [18]. Additionally, some sounds that are triggering depend on the context. For example, a sound that is triggering in one environment may be tolerable or even enjoyable in another, and aids for regulation may not be needed. Simply put, experiences of noise sensitivity are highly varied; thus, designing a system that supports all experiences of PWNS is challenging and even costly. The diversity of experiences also extends to how PWNS describe and choose to manage their sensitivities [19]. As our findings and prior work have shown, physiological and psychological reactions to triggering sounds can range from covering ears and leaving to meltdowns and sensory overload. Consequently, systems must be adaptive on multiple levels, which increases the technical complexity and potential costs.

Finally, from an ethical perspective, we must account for the data privacy and security concerns that arise when handling sensitive data, such as people's physiological data as well as data from the surrounding environment (*e.g.,* sound, location). For instance, wearable and mobile devices are equipped with "always-on" sensors that continuously collect personal information, often without the user's full awareness or informed consent [39]. Gaining informed consent is further muddled when accounting for the use of these devices by children as opposed to adults and their differing mental models of privacy risks these devices pose, as well as differences in laws around and regarding to the capability of consenting. Limited understanding and awareness of the sensing capabilities of these devices can lead to uncertainty about how their data is protected or the inability for users to make the best decisions to protect themselves [20]. Environmental data collection, specifically sound, raises another layer of ethical concerns as we think about end users and bystanders who may not be aware of or consent to ongoing surveillance to collect audio data, even if only to collect decibel levels as PWNS are interested in. With this in mind, system designers must also contend with the fact that the collection of sound data is legally complicated and varies depending on the state, country, and people's awareness in which such technology would be deployed. Therefore,

[5]WEIRD - **W**estern, **E**ducated, **I**ndustrialized, **R**ich, and **D**emocratic

ensuring that systems designed to support PWNS needs comply with the various recording laws is complex, yet necessary.

6 LIMITATIONS AND FUTURE WORK

In this work, we aimed to incorporate the perspectives of both neurodivergent people and their neurotypical allies across a range of ages, racial and ethnic backgrounds, and gender identities. This diversity, across 20 participants, necessarily limits our ability to generalize to any one population but enables our goal of expansive and creative thinking about design. We recruited participants through organizations with therapeutic aims, which may have shaped the participants' perspectives. Further, our participants were from more affluent areas in a U.S. community. While we were able to include Asian and Hispanic participants in our study, Black/African American and other ethnic minority participants were not represented in our sample. Therefore, our results may not reflect the perspectives of PWNS from non-affluent communities or minority ethnic groups, and they do not attempt to expand beyond a US context at this time. To extend the findings we propose here, we will expand our participant set further to represent a greater set of backgrounds. However, we will likely remain limited in translating these findings globally or nationally. Thus, we will also share our prototypes and materials open source with the hope of engaging noise-sensitive people, those with sensory sensitivities, and those with disabilities more broadly, further in this research globally.

Not all participants in our study took part in both series of workshops. We prioritized exploring the breadth of noise sensitivity as a phenomenon rather than tracking individual participants across both workshop series. This approach allowed us to capture diverse experiences, creating a rich understanding of the phenomenon itself. Future work should take these findings into more depth with the same or other participants, building on our existing findings and collecting additional empirical data from sensing systems, research observations, feasibility and usability studies, and self-reports to develop algorithmic approaches and new computational models of behavior around noise sensitivity. Using these models and collaboratively developed tools, researchers can then determine more concretely the effectiveness of our proposed approach.

7 CONCLUSION

This paper presents insights aimed at understanding how people with noise sensitivity design technology to support their challenges and sensory experiences. We conducted eight participatory design workshops involving people with noise sensitivity and caregivers, generating 27 prototypes and designs. We find that individuals with noise sensitivity experience difficulties recognizing triggers and sometimes require support to self-regulate. These experiences led them to develop technological solutions for awareness and collaborative noise sensitivity management. These findings indicate a vast space and several opportunities for technology to facilitate the management of and self-regulation of noise sensitivity. By engaging directly with people who are noise sensitive, eight of whom also identify as autistic, as well as their allies and caregivers, we were able to bring to light not only the challenges they face around noise sensitivity but also the creativity and problem-solving they bring to bear on these experiences. From this work, we make three contributions and present the perspectives and design considerations for technological systems to support noise sensitivity and sensory sensitivities more broadly, based on prototypes designed by people with noise sensitivity.

8 AUTHOR CONTRIBUTIONS

CRediT[6]: **Emani Hicks**: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; **Sohyeon Park**: Formal Analysis, Investigation, Writing – review & editing; **Avery Mavrovounioti**: Formal Analysis, Investigation, Writing – review & editing; **Weijie Du**: Formal Analysis, Investigation, Writing – review & editing; **Jialuo Hu**: Formal Analysis, Investigation, Writing – review & editing; **Kade Joshua Na**: Formal Analysis, Investigation, Writing – review & editing; **Nathan Serrano**: Formal Analysis, Investigation, Writing – review & editing; **Rafael Carrillo Muñoz**: Formal Analysis, Investigation, Writing – review & editing; **Elizabeth A Ankrah**: Investigation, Writing – review & editing; **Aehong Min**: Investigation, Writing – original draft, Writing – review & editing; **Jazette Johnson**: Investigation, Writing – review & editing; **Gillian R Hayes**: Conceptualization, Funding acquisition, Supervision, Writing – review & editing

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