MaskSound: Exploring Sound Masking Approaches to Support People with Autism in Managing Noise Sensitivity

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Abstract

Noise sensitivity is a frequently reported characteristic in many autistic individuals. While strategies like sound isolation (e.g., noise-canceling headphones) and avoidance behaviors (e.g., leaving a crowded room) can help, they can reduce situational awareness and limit social engagement. In this paper, we examine an alternate approach to managing noise sensitivity: introducing ambient background sounds to reduce the perception of disruptive noises, i.e., sound masking. Through two studies (with ten and nine autistic individuals respectively), we investigated the autistic individuals' preferred sound masks (e.g., white noise, brown noise, calming water sounds) for different contexts (e.g., traffic, speech) and elicited reactions for a future interactive tool to deliver effective sound masks. Our findings have implications not just for the accessibility community, but also for designers and researchers working on sound augmentation technology.

CCS Concepts

• **Human-centered computing**; • **Accessibility**; • **Empirical studies in accessibility**;

Keywords

accessibility, autism, noise sensitivity, sound masking

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1 Introduction

Noise sensitivity is a common experience among autistic individuals [37]. For them, unwanted, disruptive sounds can often cause emotional distress and physical discomfort [22, 37]. To mitigate the effects, prior work has explored two approaches: sound isolation devices (*e.g.,* earmuffs, noise-canceling headphones) [7, 15] and intervention therapies (*e.g.,* Auditory Integration Therapy (AIT) [30], exposure therapy [8]). However, these approaches have several limitations. First, while sound isolation devices can effectively block noises, they tend to be non-selective and can decrease situational awareness by blocking out important sounds like car honks and speech. Second, therapies require the services of qualified behavioral health providers [13] and can be expensive. Moreover, intervention therapies such as AIT are not evidence-based and report mixed results regarding their effectiveness [23, 29].

The above limitations motivated us to explore an alternative approach for managing noise sensitivity: introducing additional sounds to reduce the perception of disruptive noises, *i.e.,* sound masking. Sound masking has been demonstrated to improve sleep quality [38], improve cognitive performance in the workplace [1], and help manage tinnitus and ADHD [21, 24]. For this study, we extended the research on sound masking by assessing its application in helping autistic individuals manage noise sensitivity. Specifically, we conducted two qualitative studies to gather the preferences of autistic individuals regarding sound masking technology.

Study 1 contained two parts. We first interviewed ten autistic individuals on their experiences with noise sensitivity, any challenges or coping strategies, and ideas for future technology. We then conducted a design probe where the 10 participants listened to 20 potential sound masks across three categories—colored noises (*e.g.,* white, brown noise), frequency sounds (*e.g.,* 125Hz, 1kHz), and nature sounds (*e.g.,* rain, ocean)—and provided feedback on their effectiveness across three everyday scenarios: while relaxing, while focusing, and a scenario of their choice.

Informed by the insights from Study 1, we designed a mobile app prototype that allows users to mix sound masks (*e.g.,* pink + white noise, rain + brown noise) and conducted a design intervention study (Study 2) where nine participants used the prototype to create and customize sound mixes for four common disruptive noises:

background speech, traffic sounds, electronic droning (*e.g.,* fridge), and mouth sounds (*e.g.,* chewing, smacking). Participants imagined potential real-life scenarios containing these disruptive noises and provided feedback on their experience creating complex sound mixes.

Together, our findings make two contributions. First, we provide insights into autistic individuals' desired sound masks (*e.g.,* brown noise, nature sounds) for common disruptive noises (*e.g.,* background speech, traffic sounds) and scenarios (*e.g.,* while working in the office). Second, we provide design considerations for future interactive sound masking technology to manage noise sensitivity in people with autism (*e.g.,* customization preferences and automatic mask generation).

2 Related Work

We provide background on and situate our work within (1) noise sensitivity among autistic individuals and management strategies, (2) sound masking and its applications in different domains, and (3) mobile sound management apps.

2.1 Autism, Noise Sensitivity, and Management Strategies

Numerous prior studies showed that autistic individuals tend to have non-typical auditory processing, including increased pitch sensitivity [2] and enhanced ability to recognize musical notes [12]. However, these auditory processing patterns can also lead to noise sensitivity, a common challenge experienced by autistic individuals [37]. Noise sensitivity can cause unpleasant physiological sensations, hyperventilation, difficulty working, or intensified emotional responses like fear and "meltdowns" [7, 33, 37]. These experiences can lead to reduced social involvement and difficulties with school and work [22, 33, 34]. Several studies have sought to understand noise sensitivity from clinical and neurophysiological standpoints [11], but the exact cause has not yet been fully understood [5].

Prior work has explored two types of strategies to manage noise sensitivity: sound isolation and intervention therapies. Sound isolation involves blocking environmental sounds using devices like earmuffs and noise-canceling headphones [7, 33]. While these devices could help manage the noise sensitivity [15], they have two limitations. First, excessive reliance on this technique can reduce noise tolerance, thereby increasing the sensitivity [9, 18, 33]. Second, as Morris *et al.* [26] stated, the sound isolating devices can also block potentially useful sounds (*e.g.,* car honks while crossing a street), thereby decreasing situational awareness.

Another management strategy concerns intervention therapies, such as auditory integration therapy (AIT) and exposure therapy. AIT exposes individuals to specifically filtered and modulated sounds across multiple training sessions [32, 33], but its effectiveness lacks empirical evidence [30]. In contrast, exposure therapy gradually introduces disruptive sounds to help individuals "desensitize" to sounds and has shown initial benefits in autistic children, but it can be expensive [20]. Overall, both these therapies often view autism as a medical condition, treating it as an individual deficit to be cured instead of embracing a user-driven, social-model approach for managing the effects of noise sensitivity. We acknowledge the inaccessibility of safe and accessible spaces for autistic individuals and design interactive technologies that help mitigate this issue.

These limitations motivated us to explore an alternative approach: introducing additional background sounds to reduce the perception of disruptive noises, *i.e.,* sound masking. We review sound masking in more detail in the next section.

2.2 Sound Masking

As mentioned above, sound masking refers to introducing additional sounds to reduce the perception of disruptive, unwanted noises. In contrast to sound isolation, which aims to limit access to environmental noises, sound masking allows pass-through of outside sounds (*e.g.,* playing sounds via Apple AirPods Pro's transparency mode) and keeps users aware of their environment. Sound masking has been demonstrated to increase cognitive performance [1, 31], help manage tinnitus and ADHD [21, 24], and relieve stress induced by traffic and industrial noise post-hoc [3, 4]. For the current study, we extend this line of research by probing its effectiveness in helping autistic individuals manage noise sensitivity.

There are two widely used dimensions to describe sound masks: colored noises and natural sounds; our work investigates both. Colored noises (*e.g.,* white or pink noise) are characterized by different distributions of energy across audible frequency ranges. For example, white noise has equal energy across all audible frequencies. Pink noise, on the other hand, has more energy distributed at lower frequencies, producing a waterfall-like sound. Blue noise, focusing more energy on higher frequencies, resembles a hissing hose sound. Noises of different colors may serve different purposes. For example, white noise can improve the cognitive performance of individuals with ADHD [31], while pink noise has been demonstrated to improve sleep quality [38]. While these colored noises show promise, further investigating the role of frequency (*e.g.,* by delivering noises at distinct frequencies such as 500Hz and 1KHz) could provide valuable insights—a gap we address in our work. On the other hand, nature sounds like water and bird sounds have been associated with benefits for mitigating the effects of disruptive noises in urban and industrial settings [3, 4].

2.3 Sound Management Apps

While we are not aware of explicit sound masking applications, many commercial apps and artifacts explored in HCI literature involve sound management. These applications broadly fall into three categories: sound recognition and interpretation, sound augmentation, and sound transformation.

Sound recognition and interpretation. Sound recognition and interpretation applications receive audio and present users with knowledge regarding the sound. A classic example of a sound recognition app is music recognition (*e.g.,* Shazam [41]). Within accessibility research, SoundWatch [17] and HomeSound [16] sense the environmental sounds and use deep learning to recognize and report them as sound events. AudioBuddy [6], an app built for autistic individuals with noise sensitivity, notifies users of increased environmental noise levels and suggests coping strategies like relevant support groups, music, and meditation.

Sound augmentation. Sound augmentation applications introduce additional sounds to the environment, though not necessarily

Table 1: Demographics of participants in Study 1. Modes of management for noise sensitivity may include the use of noise-canceling or dampening devices ("NC"), use of music ("M"), and/or avoidance ("Av").

ID	Age	Gender	Occupation	Modes of Management		
P1	22	Man	Software Developer	-	M	Av
P2	33	Woman	Community Engagement Coordinator	-	M	Av
P3	22	Woman	Student	NC	M	Av
P4	44	Woman	Professor	NC	M	Av
P5	21	Woman	Student	NC	M	Av
P6	39	Woman	Quality Assurance for Manufacturing	NC	M	Av
P7	27	Woman	Clinical Researcher	NC	M	-
P8	38	Nonbinary	Testing Accommodations Center	NC	M	Av
P9	37	Other	Unemployed	NC	M	Av
P10	24	Woman	Student	NC	M	Av

to mask disruptive, unwanted sounds. This category includes mainstream music apps like Spotify [42] and wellness apps like Calm [43], BetterSleep [44], and MyNoise [28], which use ambient sounds to help focus or sleep.

Sound transformation. Sound transformation applications allow users to modify sounds through increasing volume and equalizations (*e.g.,* [39, 40]). While not explicitly built for sound transformations, short-form video production apps like TikTok [45] and CapCut [46] allow users to add voice effects or filters to their speech. Other work explored spatial and selective focus of sounds based on the semantics or user intentions, such as focusing on the conversation [35, 36].

These apps informed the design of (1) the 20 sound masks explored in Study 1 and (2) our sound masking mobile app prototype, which supports all three interactions described above: playing and creating sound masks (sound augmentation), modifying existing sound masks (sound transformation), and auto-suggestion of sound masks based on the current environmental noises (sound recognition and interpretation). Through studying this prototype with autistic individuals (Study 2), we uncovered insights for the design of future sound masking tools for managing noise sensitivity.

3 Positionality Statement

Our team consists of five researchers, three of whom have disabilities. One team member has autism and experiences severe noise sensitivity in daily life. The experiences of our autistic team member greatly shape our work, including the introduction of the idea, the initial design of our sound masks and our mobile app prototype, and the design of our study protocols.

4 Study 1: Formative Study

The goal of Study 1 was to understand the challenges and needs of autistic individuals who have experienced noise sensitivity and gauge their interest in utilizing sound masking as a management strategy.

4.1 Methods

Participants: We recruited 10 individuals with autism who experience noise sensitivity through social media, mailing lists, and snowball sampling (Table 1). The average age of the participants was 30.7 years (*SD*=8.5 years). Seven participants were women, one was a man, and two identified as non-binary. All participants were U.S. residents.

Procedure: Our IRB-approved study lasted for 90 minutes on average and was conducted online via Zoom. To facilitate communication, we recruited a real-time captioner for all sessions since people with autism may struggle with speech processing [27]. The sessions began with a questionnaire to collect demographic information and contained two parts. First, we conducted a semi-structured interview on participants' experience with sounds and noise sensitivity in daily life, any challenges faced, existing management strategies, and ideas for future technologies to manage noise sensitivity.

Second, we introduced participants to the concept of sound masking and organized a design probe to explore their preferences regarding different sound masks. We curated 20 individual sound masks in three categories: colored noise (*e.g.,* pink, white), frequencies (*e.g.,* 60Hz, 125Hz), and nature/ambient (*e.g.,* rain, wind); see Table 2. The selection of these categories was based on our reviews of current sound masking techniques (Section 2.2). We presented these sound mask items on the Figma board each with an attached audio clip that played the sound when clicked. The order of presentation of the sound categories and of the individual sounds within these categories were randomized.

During the activity, we presented two potential usage scenarios for sound masking (based on a discussion with our autistic team member)–(1) "relaxing" and (2) "focusing"–and asked participants to imagine a third problematic scenario of their choice (*e.g.,* socializing, playing sports). Then, we played the 20 sound clips individually and instructed participants to rate them on a scale of 1 (extremely unfavorable) to 5 (extremely favorable) for their ability to mask sounds across the three potential usage scenarios (see Figure 1). For all ratings, we asked participants to provide reasoning for their choice. The session ended with gathering open-ended thoughts on a potential idea of a mobile app that allows participants to play and customize these sound masks. For more details, we attach our study protocol as supplementary material.

Analysis: Our Study 1 data included the transcripts of the 10 interview sessions obtained from real-time captioners and 10 copies of Figma files containing the participants' sorted sound masks. We employed an iterative thematic coding approach to analyze the

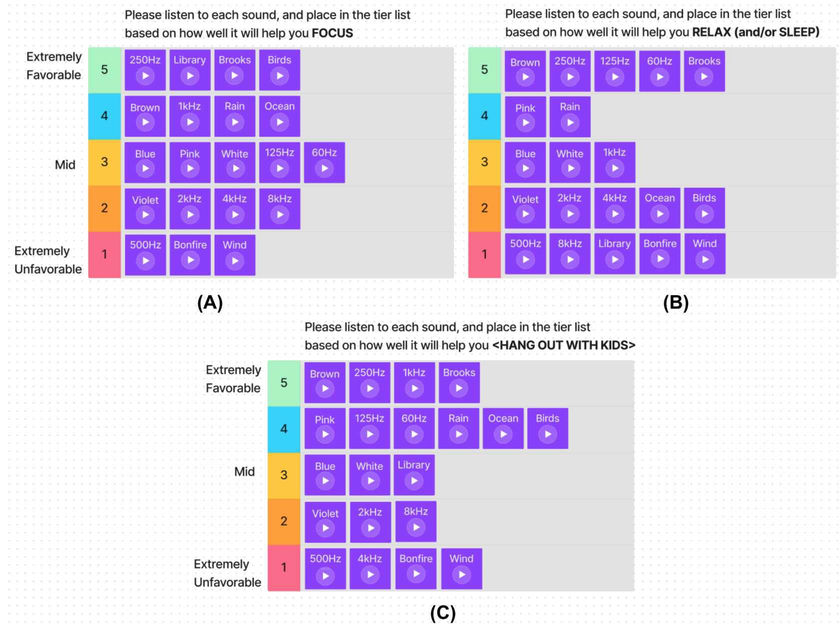

Figure 1: Study 1 Figma activity board that displays sound mask preferences of P7 for the following use cases: (a) Focus, (b) Relax and/or Sleep, and (c) Hang out with kids (P7's scenario of choice)

Table 2: The 20 sound masks presented to participants categorized by the type of noise ('Colored Noise', 'Frequencies', 'Nature/Ambient'). The final row represents other sound masks desired by participants in Study 1 and 2.

Category	Sound Masks
Colored Noise	White, Brown, Pink, Blue, Purple
Frequencies	60Hz, 125Hz, 250Hz, 500Hz, 1kHz, 2kHz, 4kHz, 8kHz
Nature / Ambient	Rain, Waves, Wind, Brooks, Birds, Bonfire, Library
Other Desired Masks	Cat purrs, train, birds (*e.g.,* songbird, seagull), wild animals (*e.g.,* owl, cricket)

data, by treating the interview transcripts and Figma files for each participant as a unit. Specifically, we used Guest *et al.*'s applied thematic analysis approach [10]. Two coders randomly selected three of the 10 participants, scanned the data (step 1), met, and developed an initial codebook (step 2). They then refined the codebook through discussion with the entire research team (step 3). The final codebook organized the codes in a 3-level hierarchy: 4 first-level, 22 second-level, and 163 third-level codes. The two coders then independently applied the final codebook to the remaining seven participants' data (step 4). For this last step, the interrater reliability, calculated using Krippendorff's alpha, was 0.85 (>0.80 is considered a good agreement) and the percentage raw agreement was 97.1%. Conflicting code assignments were then resolved through mutual consensus between the two coders. We then used the final code assignments to generate themes (step 5) and write our narrative (step 6). For reproducibility, the final codebook is attached as supplementary material.

4.2 Findings

We describe participants' challenges and management strategies for noise sensitivity, thoughts about future technology, and preferences for specific sound masks. Quotes were drawn from the real-time captioners' transcripts and were lightly edited for grammar.

4.2.1 Triggering Sounds and Challenges Brought by Noise Sensitivity. Participants reported a wide range of sounds that are unfriendly to their noise sensitivity, including electronic sounds (*e.g.,* printer, computer fans, and beeping sounds from low-battery fire alarms; N=6), traffic sounds (*e.g.,* car engine and honks; N=4), mouth sounds (*e.g.,* chewing and smacking; N=3), other disruptive man-made sounds (*e.g.,* speaking, crying, screaming, yelling; N=3), and scratching sounds (*e.g.,* scratching fabrics, chalkboards; N=3).

The triggering sounds mentioned above led to numerous negative impacts on participants' mental health. All participants reported varying degrees of anxiety (*N*=10), irritation (*N*=7), and exhaustion (*N*=4). In more severe circumstances, participants experienced physical pain such as migraines (*N*=3) and *"panic attacks"* (*N*=2). As a result, daily tasks like "grocery store runs" and "doctor's visits"

(P9) can lead to significant stress. To make matters worse, these situations could take long to recover:

> "If I fail to address the oversensitivity, the noise exposure goes over my limit. It can take me a day or two to recover. . . And I could not get away from it. I have been driven to tears before." (P9)

Participants' sensitivity to noises also limited participants' ability to engage socially (*N*=7). For example, P2 stated:

> "... If I walk into [a restaurant] that is too loud, I cannot do this. I cannot talk myself into being here for this period of time. So again, there's this feeling of stress and overwhelm and just wanting to leave." (P2)

P6 also expressed frustrations on this limitation:

> "When the sounds are overwhelming to me in the evenings, instead of spending time with family, I don't like that I need to sometimes leave the room and go lay down. But I haven't found a better method." (P6)

4.2.2 Strategies for Managing Noise Sensitivity by Autistic Individuals. In addition to disclosing the daily challenges of noise sensitivity, participants shared the strategies and tools they used to mitigate them. These strategies generally fall into the below three categories:

Avoidance. Nine participants reported avoiding or exiting the current situation when encountering noise sensitivity. While this approach helped mitigate discomfort, avoiding the situation limited participants' social, academic, or professional engagements (*N*=7). For example, P10 described that, *"how [my professor] enunciates or pronounces words drives me insane. Like [I'm not] able to go to that class anymore."*

Sound isolation devices. Participants also mentioned sound isolation technologies such as noise-canceling headphones and earplugs (N=9). While sound isolation devices are effective in reducing sensory input, these devices can limit participants' abilities to "know what is happening" and block wanted sounds, including important conversations (N=7). For example, P6 stated:

> "If I am spending time with my kids, I can't [use noise-canceling headphones] unless I am really having a hard time. . . I don't want to do any sort of noise-canceling because then I am not interacting with my kids." (P6)

Participants also reported that sound isolation devices like noise-canceling headphones could cause "headaches" (P9) and general discomfort (N=2).

Introducing additional sounds. Notably, all participants reported listening to additional sounds to cope with noise sensitivity. These sounds included music (*N*=10), white noises (*N*=5), podcasts (*N*=3), and audiobooks (*N*=3). Within the types of sounds, preferences varied considerably across participants. For example, while all participants listened to music to mask disruptive sounds, some preferred lyrics in their music (*N*=2) while others opted for lyricless genres (*e.g.,* instrumental, Lo-Fi beats) (*N*=8). For podcasts and audiobooks, some participants (*N*=2) preferred listening to content they had consumed before, while others preferred new content. These findings point to a need for a customizable sound masking tool that can support multiple sound types.

4.2.3 Thoughts on Technology to Mask Noise Sensitivity. We asked participants about potential future technology designs to manage noise sensitivity. Owing to the drawbacks of noise-canceling technologies, five participants wanted a tool that reduced the perception of disruptive sounds while still maintaining the ability to hear important sounds (*e.g.,* conversations). For example, P10 described her ideal technology:

> "[An] ear plug that [can] perceive the environment around me so it's not like I completely canceled out all the noise [...] so block out people chewing or people humming [...] and then maybe also could be aware of my surroundings. So, it would tell me, oh, this is like a bus noise, or this is a car alarm that you should be hearing."

Notably, seven participants reported technology designs that introduce additional sounds to the current environment (*e.g.,* configurable sound mixes on earphones, or music playing on a speaker). When specifically asked about the desired functionalities of a future sound masking technology, most responses indicated the need to experiment with and customize sound masks (*N*=7). For example,

> "Just having a lot of different sounds and being able to [combine and] adjust their. . .volume, pitch, regularity or irregularity of sounds. Being able to play with all of those different settings." (P7)

Similarly, P6 explained, "The more customization possible, I would think, the better. Again, I want different sounds at different times, right?"

When presented with the potential idea of a mobile app for sound masking, the response was generally positive. Most participants (*N*=8) expressed interest in using such an app in the future, with three being particularly enthusiastic. For example, P5 stated,

> "I could see this being extremely useful for me, personally. . . If I go on vacation and I need noise to make me relax, I can see this being extremely helpful. I can see myself pulling that out and mixing the pink and the brown noise together that I really liked [...] I could easily see it for my work environment. I could see it when I'm just walking down the street and I need [some sound] in my ears to [mask the traffic sounds]."

The remaining two participants (P2, P6) expressed less interest in the mobile app idea. P2 stated that added sounds to the environment could be stressful and, in some situations, would prefer "*silence over any noise*." P6 preferred using music like "*lo-fi beats.*"

4.2.4 Sound Mask Preferences. To probe further in-depth into participants' sound preferences for managing noise sensitivity, we invited participants to listen to 20 sounds listed in Table 2 and evaluate their effectiveness across three everyday scenarios: relaxing, focusing, and a scenario of their choice.

For relaxing, participants preferred low-frequency sounds (250Hz, 125Hz, and 60 Hz; *N*=6) and nature sounds (*N*=6). Participants explained that low-frequency sounds made them feel calm (*N*=6) and *"gave a sense of relaxation"* (P1). Among nature sounds, participants favored "rain" (*N*=6), "birds" (*N*=6), and "waves" (*N*=5).

(A) Sound Palette View (B) Sound Library View (C) Recommendations View

Figure 2: Three views of the customizable sound masking prototype in the form of a mobile app (*MaskSound*): (A) Sound Palette, (B) Sound Library, (C) Recommendations View

For focusing (*e.g.,* when they are working), participants favored a similar set of sounds: "rain" (*N*=6), "birds" (*N*=5), and low-frequency sounds (250Hz, 125Hz, 60Hz; *N*=6). However, these sounds were not universally preferred for focusing, further indicating the need for end-user personalization. For example, P4 and P10 considered nature sounds as distracting for focusing because it would make them *"want to go outside"* (P4). Moreover, P2 enjoyed the deep and rumbly sound of the low frequencies (60Hz, 125Hz, 250Hz), but would not use them due to the insufficient variation required for them to maintain focus (as opposed to nature sounds such as *"bonfire crackling"* which provided a mix of highs and lows).

For social settings, a common problematic scenario, low-frequency sounds (250Hz, 125Hz, 60Hz; *N*=5) were the most preferred. P4, for example, rated 250Hz highly, stating that at parties where she did not want to fully leave, she would temporarily move to a quieter area, use the low-pitch sound to *"rest in [...], and then come back to socializing."* The nature sounds, in contrast, were not rated highly because, as explained by P8, they contain too much variation, so *"when it ebbs and becomes quiet, it can break my concentration on [conversation]."*

Besides individual sound masks, participants also indicated that an amalgamation of sound masks, particularly of colored noises (*e.g.,* pink + brown noise), may more effectively conceal disruptive noises. For example, P5 envisioned that a mix generated by combining pink and brown noise could be *"extremely helpful [for sleeping] at night."*

5 Study 2: Design Intervention Study

While Study 1 mainly studied individual sound masks, we conducted Study 2 to gain further insights into the design of compound sound mask mixes (*e.g.,* by mixing individual sound masks such as brown noise and nature sounds). We implemented a mobile app prototype that allows users to mix sound masks and conducted a design intervention study with nine autistic individuals.

5.1 The MaskSound Mobile App Prototype

Based on the Study 1 insight and prior work in the sound management apps [6, 28, 42–44], we implemented a mobile application prototype, *MaskSound*, that allows users to play, customize, and create sound mask mixes. It contains three views (Figure 2): a sound palette for creating custom mixes, a sound library for exploring and saving mixes, and a recommendation feature to suggest sound mixes based on the current soundscape.

5.1.1 Sound Palette View. The sound palette view (Figure 2A) allows users to explore the 20 built-in "sound items" (*i.e.,* sound masks with only one element; see Table 1) and layer these sounds to create "sound mixes" (*i.e.,* sound masks with multiple elements). Each sound item is represented by the name of the sound (*e.g.,* pink, "rain") inside of a colorful bubble. Users can select multiple sound items (by clicking the requisite bubbles) and adjust their individual volumes (by holding and dragging individual bubbles up or down) to create layered sound mixes. These custom sound mixes can be saved to the sound library by clicking the "create custom sound with selected" button located below the sound palette (see Figure 2A). Additionally, as suggested by participants in Study 1, the app allows users to import sounds from external music libraries (*e.g.,* Apple Music). Once imported, these sounds appear in the sound palette with other sound items.

5.1.2 Sound Library View. The sound library view contains two tabs: "preset sounds" and "favorite sounds" (see top of Figure 2B). The presets tab initially contains various built-in sound mixes (*e.g.,* sleep, focus) based on participants' preferences from Study 1. Each sound mix is represented as an expandable tile with a "play/pause"

Table 3: Demographics of Participants in Study 2. Modes of management included the use of noise-canceling devices ("NC"), use of music ("M"), and/or avoidance ("Av"). Given the scarcity of the autistic population, six individuals from Study 1 participated again.

ID	Age	Gender	Occupation	Modes of Management		
R1 (P6)	39	Woman	Quality Assurance for Manufacturing	NC	M	Av
R2 (P2)	33	Woman	Community Engagement Coordinator	-	M	Av
R3	38	Nonbinary	Assistant Director of Student Learning	NC	M	Av
R4 (P8)	38	Nonbinary	Testing Accommodations Center	NC	M	Av
R5 (P5)	21	Woman	Student	NC	M	Av
R6	33	Man	Software Developer	-	-	-
R7 (P10)	24	Woman	Student	NC	M	Av
R8 (P7)	27	Woman	Clinical Researcher	NC	M	-
R9	37	Nonbinary	Professor	-	M	-

button and a "favorite" button. When the user creates a custom sound mix using the sound palette view, it gets saved in the preset tab as another tile. A tile shows the individual sound items, with their specified volume (see Figure 2B). Users can further modify the created sound mixes by adding or removing sound items and adjusting their volumes. They can also favorite a sound mix to move it to the favorite tab.

5.1.3 Recommendations View. The recommendations view (Figure 2C) suggests sound mixes based on users' environment. Users click the "listen" button to record a short audio clip. MaskSound then recommends sound mixes that the system determines will best mask the recorded soundscape. Our implementation is inspired by previous work in speech privacy [15]. This work demonstrates that speech-like audio engineered to overlap with frequencies in the human vocal range is most optimal for masking the intelligibility of speech. Similarly, we recommend a combination of sounds with dominant frequencies that most closely align with the environmental sound clip. To do so, we first extract the three most dominant frequencies in the recorded clip. Then, we look at the users' library to find sound mixes with dominant frequencies that most closely match the users' clips. We prioritize the users' existing mixes since they likely suit their preferences, and the users may find them enjoyable. If none of the existing sound mixes shares at least two dominant frequencies with the recorded clip, we automatically generate a new mix covering all three dominant frequencies. To create a pleasant mix, we prioritize nature sounds, the most preferred Study 1 mask, followed by colored and frequency sounds.

MaskSound was implemented as a fully functional iOS application using Swift. The source code of the application is posted on GitHub: <link withheld for review>.

5.2 Methods

Participants: We recruited nine autistic individuals (five women, one man, and three non-binary individuals) who had experienced heightened sensitivity to noise through email lists and snowball sampling (Table 3). As the autistic population is limited, we did not exclude repeat participants. Consequently, six of these nine individuals also participated in Study 1. The average age of the participants was 32.2 years (*SD*=6.6). Eight participants listened to music for sound management, six used noise-canceling or dampening devices, and six preferred avoiding or leaving situations with disruptive noises. All participants were U.S. residents.

Procedure: We opted for an online interaction study protocol for two key reasons. Firstly, the limited size of the local autistic community posed challenges in recruiting participants within our vicinity. Secondly, considering the impact of noise sensitivity, limited situational awareness, and other factors [47], some individuals with autism may prefer to participate from their homes and avoid commuting. As a result, we conducted our interaction study via Zoom and utilized Xcode, a mobile app simulator, to emulate the app on a virtual iOS device. Our setup allowed participants to remotely control the app by mapping mouse keys to mobile touch input (*e.g.,* by using the left pointer to "tap" or mouse scroll to "swipe").

The study contained three parts: (1) introducing the MaskSound app, (2) assessing the potential effectiveness of the sound mixes created through our app, and (3) soliciting overall feedback on the experience with the app. We proceeded after receiving an electronically signed IRB-approved consent form. Similar to Study 1, we enlisted a real-time captioner. Participants took part in the studies individually.

Before the sessions, we instructed participants to situate themselves in a quiet space. The sessions began with an online background survey to collect participants' demographic information. We then introduced the concept of sound masking and demonstrated the MaskSound app workflow using the Xcode simulator. Participants were then granted remote access to the simulator and asked to complete the following interactions: (1) exploring built-in sound mix presets in the sound library, (2) modifying the presets according to their preferences, (3) marking their preferred sound mixes as "favorites," and (4) creating a custom sound mix from scratch and saving it to the library. After each task, we took participants' feedback.

After evaluating the individual app features, participants created custom sound mixes targeted to mask four common disruptive noises: background speech, traffic sounds, electronic droning (*e.g.,* fridge, computer), and mouth sounds (*e.g.,* chewing, smacking). These noises were chosen based on Study 1 findings and provided a good diversity in terms of their technicality (spanning varying

Table 4: Sound Recommendations. The four disruptive noises used in Study 2, and the corresponding recommended sound mix by our algorithm to mask the noise.

Disruptive Noise	Recommended Sound Mix by our App
background speech	brown noise
traffic sounds	brown noise + "waves"
electronic droning	1kHz + 2kHz
mouth sounds	"birds" + "waves"

frequency ranges and cadences) and real-life situations where they occurred (covering indoors, outdoors, and urban environments). We played the disruptive noises over Zoom and asked participants to simultaneously create a sound mix to mask it. Participants could adjust the volume of the sound mask via the app to a level they desired to effectively mask the disruptive noise. While the participants were creating the masks, the researcher noted the sound items (*e.g.,* brown noise, nature sounds) included in each sound mix. Then, participants listened to the sound mixes generated by our recommendation algorithm (Table 4). We collected feedback on the effectiveness of the mixes that participants created (or listened to) and asked for potential real-life scenarios where they would use the mix (*e.g.,* at work when there is distracting background speech).

Finally, we asked overall questions on their experience with MaskSound, the current user interface design, and any future improvement suggestions. Similar to Study 1, our Study 2 protocol is available as supplementary material.

Analysis: Our Study 2 data consisted of transcripts of nine interview sessions obtained from real-time captioners. We used iterative thematic coding to analyze the interview transcripts by adapting Guest *et al.*'s applied thematic analysis approach [10]. One researcher randomly selected and skimmed through three transcripts (step 1) and discussed with the research team to establish an initial codebook (step 2). The researcher then assigned the codes to all nine transcripts, while iteratively refining the codebook (step 3). The final codebook contained 5 first-level codes, 14 second-level codes, and 88 third-level codes. Another researcher then used the final codebook to independently code all transcripts (step 4). The interrater reliability between the two coders, calculated using Krippendorff's alpha, was 0.82 and the raw agreement was 97.0%. The two coders then met and resolved the disagreements. Finally, we organized the codes into themes (step 5) and wrote our narrative (step 6). The final codebook is uploaded in supplementary materials.

5.3 Findings

We detail the participants' overall sentiments on our MaskSound prototype, specific feedback on the app's features, and their preferred sound mixes across the four disruptive noises. Quotes were drawn from the captioners' transcripts and lightly edited for grammar.

5.3.1 Overall Feedback. Most participants (*N*=8) saw the potential value of sound masking (*i.e.,* using individual sound items as well as mixes) to manage noise sensitivity and envisioned using MaskSound in at least one scenario in their daily life. For example,

> "It just made me think [of] all the different scenarios where I wish I had something like this, because other tracks I was trying to play [on] my phone weren't really helping even if I would increase the volume. [. . .] Like when I was out [at] certain places or at a cafe trying to study, it's so easy to become overwhelmed." (R8)

The remaining participant (R2) appreciated the app's functionality but would prefer not to change their daily routine of listening to podcasts or relying on noise-blocking strategies (*e.g.,* noise-canceling headphones).

5.3.2 Presets and Customization Features. Participants described the preset mixes as a valuable starting point when initially engaging with the app or when they don't know what they want to listen to (*N*=6). However, all participants expressed that they would like to adjust the presets to suit their own unique preferences, and appreciated the app's customization features:

> "It's great to have presets to start with and then just as people desire or, you know, need to, being able to adjust them is really helpful." (R4)

Some participants (*N*=4) were initially worried that offering too much customizability could make them feel *"overwhelmed"* (R3, R7, R9), causing them to *"just give up"* (R1). However, after exploring the recommendation feature, participants felt positive that it would help them narrow down the list of options. Two participants pointed out another strategy to reduce the possible options: restricting the mixing of certain sounds that are unlikely to occur together. For example,

> "Birds won't be chirping when it's raining. So, like, I feel like I wouldn't be able to relax or focus or whatever if these didn't match up. Like they would in nature." (R1)

R2 shared this sentiment, highlighting that the combination of a bonfire sound with birds chirping felt *"incongruous."* She suggested that a bonfire sound, which she associated with nighttime, should only be allowed to pair with other *"nighttime"* sounds, such as *"owl hoots," "a very soft cricket sound,"* or *"a soft, occasional frog sound."*

Besides sound mixes, participants (*N*=5) also found the option to play individual sound items valuable since they are less complex and could be more relatable and understandable. R9 explained:

> "Yesterday I was at a friend's funeral, and I was fine until the power went out and so everything started beeping, and it was just like. . . when you get in that overwhelmed space. But I knew that the blue [noise]

> was the one I was looking for, so I could just click that."

5.3.3 Recommendation Feature. As stated above, participants appreciated the recommendation feature for its ability to suggest potential sound masks. Indeed, most participants (*N*=7) found that at least one of the recommended masks that they tried for the four disruptive noises (*i.e.,* background speech, traffic sounds, electronic droning, and mouth sounds, Table 4) was *more effective* than what they had managed to create for the same disruptive noise. Two participants also appreciated the ability to further customize the recommended mask. For example, R8 said:

> "I like being able to add things in if I want to or I could just keep the recommendation as is. I like [having the recommendations] as a quick press of something to help. . . and then if you need to, you can add in other sounds."

5.3.4 Sound Mask Preferences. We summarize the participants' preferred sound masks for each disruptive noise below.

Background Speech: To mask speech, the most popular sound items included in sound mixes created by participants were brown noise (*N*=5), low frequencies (60Hz-250Hz) (*N*=4) and "rain" (*N*=4). Participants' feedback indicated that brown noise may work well alone (*N*=1), but it is intended to act as a "base layer" to pair with other sounds with greater variability (*N*=5), such as "rain" (*N*=4), "brooks" (*N*=3) and "library" (*N*=3), to successfully cover speech.

Participants detailed specific real-life scenarios with background speech and believed that the sound masks they created (or variations of it) would be useful (*N*=7). For example, R4 described *"probably [listening to it] at work"* where there are *"people talking and I can't leave,"* as well as school events where *"there is lots of talking"* and *"kid"* sounds. R9 would *"use it if I was grading somewhere [(e.g., a coffee shop)] and people were talking, and I just needed to tune them out."* These specific use cases reinforce our findings from Study 1 where the most popular masks for "focusing" were low frequencies (*N*=6) and "rain" (*N*=6), while brown noise alone was only somewhat popular (*N*=3).

Traffic Sounds: "Waves" was the most popular sound item found in participants' sound mixes to mask traffic sounds (*N*=7), followed by brown noise (*N*=5). Participants particularly liked the combination of "waves" and brown noise because the former *"effectively counters traffic noise"* and the latter *"provides support and consistency"* (R8). Similar to speech, some participants felt that variability was key to successfully masking traffic sounds. For example, R7 explained that adding sounds such as "brooks," "waves," and other variable sounds on top of constant sounds like brown noise caused him to *"actually not [hear] the traffic [and hear] a pleasant soundscape instead."*

Electronic Droning: To mask electronic droning (*e.g.,* fridge, computer), participants chose "waves" (*N*=4) and low frequencies (*N*=4) most commonly, followed by mid frequencies (*N*=3) and brown noise (*N*=3). In addition, seven participants mentioned that the high- to mid-range frequencies (*i.e.,* 8kHz, 4kHz, 2kHz, 1kHz) *alone* could also mask the electronic droning sound effectively, but they were unpleasant to listen to.

Mouth Sounds: For mouth sounds (*e.g.,* chewing, smacking), the most popular sounds included in participants' sound mixes were "birds" (*N*=7) and "waves" (*N*=6), followed by "brooks" (*N*=3). While *"waves blended smoothly"* (R7) with the mouth sounds, three participants found that "brooks" also worked as an alternative. R4 stated that *"[brooks] works perfectly because it's more like a bubbly wet sound,"* a quality shared with mouth sounds. Another approach employed by R6 involved adding pink noise as a *"background that has a similar frequency to the mouth sounds"* and "bonfire" to add the necessary variance to successfully mask the mouth sounds. R5 shared a similar idea by creating a mix with pink noise and "bonfire," while also adding brown and 125Hz noises for a robust sound mask.

Participants were excited about this application of sound masking, as mouth sounds were a regular problem in their lives (*N*=5). R3 described this use case as *"one of the most practical applications of the app"* as *"lots of [autistic] people need to mask out mouth sounds [. . .] while eating [with others]."* R8 added,

> "I definitely would use my mix that I had tested out for different meal scenarios I would be out engaging in. [...] Especially at home, because I always have at least one meal at home with other people, and then when I'm out with coworkers or with friends, sometimes I really need some more support, so having not like large headphones, but even an ear bud in one ear with something like this [playing] would be a lot of help."

While R8 envisioned listening to her sound mix through an earbud, R5 saw potential in "playing it on a speaker [...] while eating with family and conversing with family members."

6 Discussion

Noise sensitivity in autism is an underexplored research area. Prior work focused largely on tracing the clinical and neurobiological basis for noise sensitivity [11, 19, 22] and developing intervention therapies [20, 32], with little implications for understanding social aspects and designing user-centered technology. Recent work like Dotch *et al.* [7] revealed the challenges (*e.g.,* emotional distress) and management strategies (*e.g.,* ear protection devices) surrounding noise sensitivity by analyzing online reports of autistic people. Our work reaffirmed these findings, but also investigated the potential of sound masking to manage noise sensitivity in daily life.

Sound masking has shown benefits in other demographics, such as neurotypical young adults [1] and children with ADHD [31]. We extend this line of research by exploring its potential for helping autistic individuals manage noise sensitivity. To address this gap, we conducted two studies. In Study 1, we engaged 10 participants in semi-structured interviews and design probes to understand the challenges autistic individuals face in managing noise sensitivity and their preferences regarding sound masking. Based on the findings, we designed *MaskSound*, a mobile application that enables users to create and customize sound mask mixes. In Study 2, we invited nine participants to interact with MaskSound online and provide feedback. Below, we discuss and contextualize our findings, provide design recommendations for future sound masking tools, and state study limitations.

6.1 Sound Mask Preferences

Study 2 findings summarize participants' preferred sound masks for different kinds of disruptive noises. We found that several sounds tend to be suitable for multiple disruptive noises. For example, brown noise was commonly preferred for masking speech, traffic sounds, and electronic droning. Other sounds with multiple mentions included low frequencies (for speech and electronic droning) and "waves" (for traffic sounds and electronic droning). While more in-depth and long-term probes of sound mask preferences are needed, future sound masking technologies should leverage these insights and prioritize and recommend certain sound masks based on users' context. Importantly, the effectiveness in masking disruptive noises should not be the only criteria for suggesting sound masks. For example, while many participants claimed mid-range frequencies could mask the electronic droning sound, these sounds were unpleasant to listen to.

6.2 Providing Guidance for Using Sound Masking Tools

Participants responded positively to the MaskSound prototype and appreciated its customizability. While this reaction provided an initial promise for our approach, we learned that an excessively high degree of customizability (*e.g.,* too many sound masks to choose from) could decrease the usability of the sound masking tool and lead to feelings of being overwhelmed to the point where autistic individuals might give up using it. This insight matches prior findings that autistic individuals often find challenges in decision-making and may tend to avoid them [25].

To mitigate this paradox of choices, designers of sound masking tools should balance customizability with sufficient guidance for using the tool. For example, in MaskSound, we provided built-in sound mixes for different purposes (*e.g.,* sleep, focus) so that users can use and build on these presets without spending too much time experimenting. Additionally, we implemented a simple algorithm that recommends sound masks based on users' auditory environments.

We encourage designers to explore other ways to provide scaffolding on sound masking tools. For example, during the design intervention study (Study 2), participants suggested that some sounds do not work well together (*e.g.,* bonfire and birds chirping). Future work can explore establishing constraints when making custom sound masks. For example, the system can gently nudge users to reconsider adding a bonfire sound when a bird chirping sound exists in the mix.

6.3 Context-Aware Sound Masking

Inspired by previous work that demonstrates that speech-like audio (*i.e.* noise that is engineered to only overlap with frequencies in the human-speech frequency range) is optimal for masking the intelligibility of speech [14], our recommendation feature provided the combination of sound masks that most closely align with the environmental sound clip provided by the user, by comparing their dominant frequencies.

Our initial exploration of context-aware sound masks opened possibilities for developing a broader, more comprehensive, and more precise AI model to provide personalized sound masks based on user contexts. For example, our algorithm considered the dominant frequencies as the only factor for predicting sound mask effectiveness. Future work can extend the current algorithm by (1) considering more dimensions of auditory scenes, such as intensity, timbre, and patterns within the sound samples, and (2) leveraging other contextual information (*e.g.,* time of the day, user-defined routines) to deliver timely recommendations. Another promising alternative is an incremental reinforcement learning approach that learns from user feedback and past behaviors to improve on its recommendation.

6.4 Limitations and Future Work

Our study has several limitations. First, our study has a small sample size, with a total of 13 unique participants across both studies. While we uncovered meaningful insights, future work should draw from more perspectives and across more usage scenarios to corroborate our results and provide further insights. Second, while we considered the possibility of in-person evaluations, most participants preferred to participate in the study from their homes and did not prefer to travel. Therefore, our evaluation study was conducted remotely. As a result, the MaskSound prototype was not studied in a real-world context. As a potential workaround, future work should consider deploying a sound masking tool like MaskSound to users' phones and conducting a field evaluation to extend our findings with more ecologically valid insights. Third, as we mentioned in the above section, the recommendation algorithm we evaluated, though promising, should be further developed to consider more variables like sound characteristics (*e.g.,* intensity, timbre, sound sample patterns), individual preferences, users' physiological states, and social dynamics. Fourth, our findings are more valid for autistic individuals who may often function more independently and require relatively less support than those with higher severities, as most participants reported that they were social, held occupations, and/or were college students. Future work should extend our exploration and application of the sound masking approach to a broader autism spectrum.

We propose several additional directions for future work. First, researchers should explore whether the effectiveness of sound masks can be influenced by the relative loudness compared to their situated environments. For example, different settings, such as a library vs. a crowded restaurant, may require different contrasts of loudness between environmental noise and sound masks. Second, future work should explore sound masking for other relevant populations, including individuals with attention-deficit/hyperactivity disorder (ADHD) and those with intersectional identities (*e.g.,* ADHD and autism).

7 Conclusion

Noise sensitivity is a frequent challenge reported by people with autism. While prior solutions include noise-blocking techniques and intervention therapies, they can reduce social awareness and limit social engagement. Through two qualitative studies (with ten and nine autistic individuals), we investigate the potential of sound masking in helping autistic individuals manage noise sensitivity. While Study 1 elicited initial reactions on the preferences for sound masking technology and helped design individual sound masks (*e.g.,* white noise, specific nature sounds, low or mid frequency sounds), Study 2 further reaffirmed these findings and contributed preferences for complex sound mixes (*e.g.,* brown noise + nature sounds) to effectively mask environmental noises. Our findings have implications not just for accessibility researchers, but also, more broadly, for designers and practitioners working on sound augmentation technology.

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