Article

SoundFields: A Virtual Reality Home-Based Intervention for Auditory Hypersensitivity Experienced by Autistic Children

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Abstract: Previous studies have shown that autistic people often display atypical responses when processing sensory information, with particular prevalence within the auditory domain. Often provoked by common everyday sounds, auditory hypersensitivity can result in self-regulatory fear responses. This can be potentially harmful to autistic individuals and the people around them and is associated with greater occurrence of anxiety, depression, and poorer overall quality of life in the autistic population. Rather than a physiological causation, the literature suggests that hypersensitivity to sound is likely to be caused by how auditory stimuli are processed in the brain. This paper reports a home-based digital intervention aimed to address auditory hypersensitivity in autistic children. Developed as an interactive virtual reality game, the system integrates exposure-based therapy techniques into game mechanics and delivers target auditory stimuli to the player rendered via binaural-based spatial audio. The performance of the platform was evaluated in a 10-week feasibility study, during which children (n = 7) engaged weekly with the game during a 30 min session. Following this period, a comparison of pre- and post-study measurements showed a decrease in sensitivity for five participants, with qualitative feedback highlighting an increase in tolerance towards real-world stimuli and challenging environments. These results provide initial support for SoundFields as a home-based intervention targeting auditory hypersensitivity experienced by autistic children.

Keywords: autism; neurodivergence; auditory; hypersensitivity; children and young people; virtual reality; serious games; digital intervention

1. Introduction

Autism is a form of neurodivergence, characterised by differences to the neurotypical population in several domains, including social and communication style, repetitive behaviours, and sensory processing [1]. Research has demonstrated that many members of the autistic community prefer the use of ‘autistic person’ or ‘person on the autism spectrum’ as these terms signify their individual identity and diversity, whereas the term ‘person with autism’, typically used by professionals, is felt to have negative connotations that suggest autism to be a fixable problem [2]. In this paper, we use the term ‘autistic person’ based on such research along with the views described by our own patient and public involvement.

The way in which autistic people process sensory information may prelude some of the behaviour patterns that differ to those of the neurotypical population [3]. Experience of sensory stimuli varies from person to person and ranges from hypersensitivity (stimuli are experienced in the extreme [4]) to hyposensitivity (stimuli are under-experienced [5]) and everything in between. This paper focuses on hypersensitivity relating to auditory stimuli, a behavioural response that has been reported frequently in the literature as being potentially...
harmful to autistic individuals and the people around them. Specifically, hypersensitivity to sound has been found to be associated with greater occurrence of anxiety, depression, and poorer overall quality of life in the autistic population [6,7], providing a clear requirement to investigate potential solutions.

Hypersensitivity to sound (including hyperacuity, misophonia, phonophobia, and recruitment) is thought to be experienced by 50 to 70% of the autistic population throughout the course of their life [8]. For individuals experiencing hypersensitivity to sound, everyday occurrences may feel painful and/or unbearable [9,10]. Birkett et al. [9] found young autistic people in mainstream secondary school reported their sensory experience of school to be chaotic, invasive, overwhelming, and confusing.

Around 70% of diagnosed autistic children attend mainstream schools in the UK [11]. Schools have a duty to promote inclusion for neurodiverse children and young people (among other diversities, e.g., Every Child Matters, 2005). However, research has suggested that autistic children and young people experience high levels of social isolation and feelings of loneliness at school [12,13]. This may be linked to the experience of sensory hypersensitivity and behaviours associated with it, such as avoidance.

1.1. Potential Cause of Sound Hypersensitivity for Autistic People

Autistic individuals experiencing hypersensitivity to sound have exhibited loudness discomfort levels that are lower than those displayed in neurotypical individuals [14,15]. To date, evidence surrounding the cause of this is limited. There appears to be no distinct differences in the auditory canal of autistic individuals compared to neurotypical individuals, which suggests that the pain and/or discomfort experienced is unlikely to be caused by physical features of ear anatomy [16–18]. This suggests that the hypersensitivity to sound experienced is likely to be due to the way in which the auditory stimuli are processed in the brain.

Lucker and Doman [19] suggested that one neural mechanism that may lead to hypersensitivity to sound is a differing auditory pathway in autistic individuals compared to neurotypical individuals. The authors describe a ‘non-classical pathway’, in which auditory sensory input is connected to the emotional centres of the brain along with additional brainstem levels of awareness, raising attention to the sensory input. This may explain the additional emotional responses experienced by autistic individuals in relation to such sensory information.

Furthermore, individuals have described how the feelings associated with certain sounds may be different across situations, and that a build-up of sensory stimuli (auditory and other) make the feeling and experience worse. One study by Kirby and colleagues [20] looked specifically at the association between different sensory response patterns and contextual features of the home environment. The researchers found that hypersensitivity behaviours were more closely associated with family-initiated stimuli and activities of daily living compared to activities involving their own intense sensory interests, repetitions, child-initiated stimuli, and free play activities. This suggests that, when a child is enjoying an activity or feels in control of the stimuli, they have an improved ability to manage the stimuli. In light of the above, the high prevalence of auditory hypersensitivity among autistic individuals is likely to be a result of neurological processing and may be the presentation of a fear response.

1.2. Treatment

Previous research has suggested that acute stress can decrease tolerance to sound in some individuals [21]; therefore, reducing phobic anxiety could feasibly improve both the emotional reaction to the feared sound and its perceived loudness. Current recommendations pertaining to the treatment of phobia call upon cognitive behavioural therapy (CBT) techniques, such as systematic desensitisation (a procedure that reduces pathological fear and its related emotions by exposing the patient to the feared stimulus in the presence of relaxation or play activity) to target the emotional responses surrounding phobia.
These techniques do not alter existing pathological structures; rather, they form new and competing structures that aim to remove pathological associations [22].

There is extensive literature that supports the use of CBT as an effective intervention to reduce anxiety in autistic individuals. However, there are arguments based on the delivery of these traditional CBT techniques that suggest that they may not be appropriate for this neurotype. Firstly, CBT sessions often involve face-to-face verbal exchanges, which autistic individuals frequently report finding uncomfortable and anxiety-provoking [23]. Secondly, they typically use imagined exposure, which is, therefore, not contextualised and may not fully characterise the specific way in which the individual experiences their anxiety [24].

Another important consideration of current CBT is a lack of accessibility. A recent systematic review by Ince et al. [25] has noted that the rates of implementation for cognitive behavioural therapy are below the recommended levels for the United Kingdom. This gap in delivering successful mental health interventions has stemmed from a number of influences, including lack of resources, limited dedicated therapy time, and a lack of specialist training [26]. Therefore, to address these challenges for providing behavioural interventions, new and accessible approaches are needed. One possible solution is to exploit consumer gaming technology to deliver low-cost digital interventions at home; this will allow for flexible usage with minimal training required [27].

There is evidence to suggest higher involvement in video games among the autistic population compared to their neurotypical peers [28]. These systems are capable of incorporating CBT protocols into the core game mechanics and gameplay loops, thus delivering a safe, controllable, and engaging environment in which players can achieve meaningful therapeutic outcomes. Furthermore, the use of game-based digital interventions can provide a cost-effective and accessible method of remediation for autistic children. An example of one such game that targets auditory hypersensitivity is Sinbad and the Magic Cure [29], which motivates players to voluntarily expose themselves to problematic sounds in order to progress through the gameplay narrative.

With the development of low-cost consumer virtual reality (VR) devices over recent years, the development of digital interventions deployed to this platform has become more popular. The technology is capable of rendering realistic and immersive three-dimensional audio and visual environments whilst simultaneously providing novel and engaging methods for serious game interactions. VR environments have played a key role in reducing specific phobias in autistic children in a study conducted by Maskey et al. [30,31]. Participants were exposed to hierarchical levels of virtual representations of their feared stimuli, such as animals and open spaces. Following multiple sessions, one-third of the participants displayed improvements in their response to real-world phobias.

In order to simulate realistic auditory environments, VR applications often utilise binaural-based spatial audio [32]. This audio reproduction technology is capable of moving virtual sound sources that rotate and transform depending upon the dynamic movement and rotation of the listener’s head within the virtual environment. Simulations are achieved via the use of filters named head-related transfer functions (HRTFs), which simulate the free-field acoustic path of a sound source to the ear canal [33]. Each HRTF contains the directional-dependent data for each ear, including the interaural differences in time and intensity in addition to the spectral shaping of the sound caused by the pinnae, head, and torso [33]. From here, a monaural anechoic signal can be filtered with an HRTF to simulate a sound source localised at a specific point across a 360-degree sphere over headphones [34,35].

Current VR head-mounted displays (HMDs) contain accelerometers and video tracking systems to determine a player’s head rotation and position within both the physical and virtual environment. With this information, the audio rendering engine will interpolate between the nearest HRTF pair [36,37]. Further to this, distance is replicated by controlling the amplitude, spectral content, and reverberant energy of a virtual sound source in response to the calculated distance between the listener and the position of the sound [33].
SoundFields, a novel virtual reality game designed to address auditory hypersensitivity in autistic children and young people, has the capability to present naturalistic representations of feared auditory stimuli to the player using binaural-based spatial audio [38,39]. Feared auditory stimuli are incorporated into serious game mechanics established in CBT approaches. Following participation, a significant decrease in the self-reported levels of anxiety scores in the pre- and post-study measurement sessions were observed. Additionally, the results showed a significant increase in tracked interaction time with those adverse stimuli between sessions one and four. These findings indicated that SoundFields may have the potential to support young autistic people with their hypersensitivity to sound. Despite the promising results, the participants engaged with the game under experimental conditions that would evaluate how autistic children would naturally engage with the intervention within the home.

1.3. This Study

This is the first study that aims to evaluate the use of a home-based intervention for reducing fear-based reactions towards problematic auditory stimuli deployed to consumer-grade virtual reality technology. The investigation involved a group of seven young people, all diagnosed with autism spectrum disorder and who experienced auditory hypersensitivity. Across the 10-week study, each participant would regularly engage with the framework at home, allowing for complete autonomy over the therapy. In addition to assessing SoundFields as a digital intervention for auditory hypersensitivity, this investigation extends upon previous studies and provides insight into how participants interact with the game away from the experimental environment. Following the 10-week study, it is hypothesised that participants will demonstrate a decrease in sensitivity towards target auditory stimuli.

2. Materials and Methods

2.1. Game Description

The game employs four mini-games that allow players to voluntarily expose themselves to feared target auditory stimuli. Given the heterogeneous nature of autism spectrum disorder (ASD), the game provides individualization options by allowing players to choose which mini-games they want to play and how many times they want to repeat them. This individualization enhances the game’s enjoyability and motivation for children with ASD and promotes generalisation by providing repeated exposure to stimuli [24,40,41]. While the mini-games provide ample opportunities for exposure to averse auditory stimuli, all exposure during gameplay is voluntary and incentivized by an embedded reward system. Additionally, players can move freely between the central hub and each mini-game. SoundFields also features an in-game currency in the form of gems that players can use to purchase cosmetic alterations for their magic wand. The shop items are organised into pricing tiers that encourage players to acquire more currency. Successful completion of game tasks awards players with at least one gem, but exposure to target sounds yields a higher reward of 10 gems. Such motivators are essential elements in the design of games for both educational and entertainment purposes.

2.1.1. Mini-Game 1: Orb Hunt

The orb hunt mini-game requires the player to locate orbs hidden within the virtual game environment. Once found, the player must then capture the orb by using their magic wand, which gradually moves the creature towards them. During gameplay, orbs will spawn randomly at predetermined locations within the virtual environment. Once active, the orbs will emit speech-like gibberish stimuli that aims to attract the player’s spatial attention towards their position and assist them in locating it. Once it moves into the player movement area, it disappears and the game score is updated.

Two variants of the orb are used during this mini-game. Type A will only emit speech-like stimuli throughout the length of time the player interacts with it. Once the player successfully catches the orb, they are rewarded with one gem. Type B, which is denoted
by its gold colour, will emit speech-like stimuli until the player interacts with it. Once interaction commences, the orb will play spatialised reproductions of averse sounds at the same time as speech-like stimuli. In addition, the orb will travel towards the player at a slower speed, maximising the exposure time. Once the player successfully collects this orb, they are rewarded with 10 gems. As a strategy to optimise the potential therapeutic outcomes, the spawn, locate, and collect game mechanic is looped until the player wishes to stop it. This creates multiple chances for the player to be exposed towards their target averse stimuli. Furthermore, it is based upon the repeated and predictable gameplay that can maintain interest and motivation to engage with serious games for this population.

2.1.2. Mini-Game 2: Bubble Rescue

The mechanics for Bubble Rescue require players to find matching pairs presented on a grid and within an allocated time frame. For each successful pair the player is awarded one gem and once the entire grid has been completed, the amount of hidden pairs increases by one. If the player requires assistance to complete the level, they have the opportunity to use the hint system. To do so, the player must interact with the gold hint button continuously for three seconds. During this time the selected target stimulus is emitted. If the player stops interaction with the button, the timer is reset and the target stimulus playback stops.

2.1.3. Mini-Game 3: Simon Says

This mini-game requires the player to repeat a random sequence of coloured shapes and tones. If the player is successful, the series will become more complex by incrementing itself by one step. During gameplay, the mechanics are controlled by shooting the corresponding shape using the virtual magic wand, and, for each correctly repeated sequence, the player is awarded with one gem. If the player incorrectly repeats the sequence, they are given positive reinforcement in the form of visuals and music. If the player knows they cannot repeat the pattern or they require assistance, they can interact with the same hint system described in Mini-Game 3.

2.1.4. Mini-Game 4: Ghost Hunt

When the game begins, the player must use the virtual wand to target a group of moving non-playable characters resulting in them disappearing. When the entire group of characters has been successfully removed, a new cluster with increased numbers is rendered. For each character removed the player receives one gem. However, when interacting with gold coloured characters the selected problematic stimuli is emitted. One removed they are rewarded with ten gems. In order to challenge the player and maintain interest and motivation, non-playable characters generate virtual projectiles that reduce speed when within 2 metres radius of the player. This allowed the player to circumvent the projectile. Failing to do so results in the loss of one of three lives. When all three lives are spent there is an opportunity to restart the game.

2.2. Participants

Participants (n = 9, 6 male, 3 female, mean age of 10.5, SD 1.66, range of 8–13 years, all white British) were recruited via social media advertising (Meta and Twitter). Of the nine participants recruited, seven completed the 10-week trial (2 female, mean age 10.8, SD 1.57, range 8–13 years). Inclusion criteria: aged 8–18 years, diagnosis of autism received from the National Health Service or private healthcare provider, and self-reported experience of sound hypersensitivity. Exclusion criteria: photosensitive epilepsy.

2.3. Ethical Considerations

The sessions took place within the school where participants were recruited. This study and methods were approved by the University of York Department of Electronics board of ethical approval, and an information package was provided to the participants’ parent(s) or legal guardian(s). Participants were admitted into the study after informed
consent and assent was obtained from their parent(s) or legal guardian(s). A child and adolescent consultant psychiatrist was involved in the design and assessment.

2.4. Intervention Protocol

Participants were asked to play the SoundFields game for approximately 30 min each week in their own homes. Participants were given an individual logon code to access the SoundFields application. Upon logon, they were prompted to select the problem sound out of a selection for use within the game along with the exposure level of the auditory stimuli. In order to reproduce exposure hierarchies implemented within clinical in-vivo desensitisation interventions, the auditory stimuli would be played at the corresponding virtual distances outlined in Table 1. Participants were encouraged to increase this level as and when they felt comfortable as they progressed through the study. Table 2 displays the target stimuli used in the study linked to the participants who interacted with them.

Table 1. Exposure hierarchy. Each exposure level corresponds to the distance between the participant and the virtual sound source; distance is represented in metres.

<table>
<thead>
<tr>
<th>Exposure Level</th>
<th>Virtual Distance between Player and Stimulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25 m</td>
</tr>
<tr>
<td>2</td>
<td>15 m</td>
</tr>
<tr>
<td>3</td>
<td>5 m</td>
</tr>
<tr>
<td>4</td>
<td>2.5 m</td>
</tr>
</tbody>
</table>

Table 2. Target stimuli and participants interacting with them. Target stimuli represent sounds with a negative self-reported emotional response (≥4) recorded at baseline that were subsequently interacted with by the participant.

<table>
<thead>
<tr>
<th>Stimuli</th>
<th>Participant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Alarm</td>
<td>P01, P02, P03, P09</td>
</tr>
<tr>
<td>Children Fighting</td>
<td>P01</td>
</tr>
<tr>
<td>Fireworks</td>
<td>P02, P03</td>
</tr>
<tr>
<td>Hairdryer</td>
<td>P02, P03, P04, P05</td>
</tr>
<tr>
<td>Car Engine</td>
<td>P04</td>
</tr>
<tr>
<td>Baby Crying</td>
<td>P05</td>
</tr>
</tbody>
</table>

2.5. Equipment

All stimuli were rendered using the PICO Neo 3 Pro Eye head-mounted display (HMD). Player input was achieved using the PICO Neo 3 controllers. Audio was presented to the participant using Superlux HD-681 headphones.

2.6. Outcome Measures

2.6.1. Self-Reported Emotional Response

Each participant completed an emotional response audio-based questionnaire, which involved rating their perception of specific sounds using a series of emojis, designed to translate an analogue scale into graphical information (see Figure 1). This was completed 1 week prior to the invention and following completion of the 10-week study. Sounds that prompted the most anxiety as indicated on the emotional response questionnaire were selected as sounds to be used in the application. A total of twenty-two types of sounds were included, based on parental responses in Johnston et al’s [38] questionnaire on problematic sounds, and eleven “relaxing” soundscapes taken from the Eigenscape database [42]. The audio questionnaire was developed in the Unity3D 2018.4.20 game engine software.
2.6.2. Tracked Interactions (In-Game)

Throughout each intervention session, data was captured within the SoundFields application that recorded voluntary interaction with target stimuli. This was achieved by measuring the amount of time each participant interacts with the exposure-based mechanics for each mini-game, resulting in the rendering of their chosen stimuli. In addition to time, the name of the stimulus and the exposure level was also recorded.

While the smiley face Likert scale has been used successfully in research, there is some evidence suggesting validity issues due to communication difficulties and social desirability bias. To address these potential concerns, tracking voluntary interactions with exposure-based mechanics aimed to overcome any communication impairments and circumvent any challenges the autistic participants may have experienced in recognising and describing their own emotions.

2.6.3. Qualitative Questionnaire

A study-specific questionnaire was used to gather qualitative data from children and young people and their parents in relation to their experiences of taking part in the trial, use of the application, and their perception surrounding its impacts to sound hypersensitivity. The questionnaire allowed for free-text responses. The questionnaire was read aloud by the researcher, and responses were provided verbally and recorded verbatim by the researcher.

3. Results

The results of the 10-week longitudinal study are divided into two categories: quantitative results display participant self-reported anxiety, as well as the tracked interaction times and exposure levels across the experimental period. Qualitative findings present the participant and parent feedback recorded at the end of the trial.

3.1. Quantitative Findings

3.1.1. Self-Reported Emotional Response

The self-reported emotional response (SRER) to all sounds was assessed at baseline and post-study (10-week measurement) to determine any changes in sensitivity amongst participants. After 10 weeks, four participants reported a decrease in sensitivity to at least one target stimulus (sounds that were perceived as negative [SRER ≥ 4] by the participant and subsequently interacted with during the game). In contrast, one participant reported...
an increase in sensitivity to one target stimulus, while another participant reported both a decrease in sensitivity to one and an increase in sensitivity to another target stimulus (see Figure 2). We found that the final participant (P08) did not interact with any auditory stimuli they rated negatively (≥4) by SRER at baseline and as such found no changes in sensitivity to target sounds.

![Change in SRER baseline - 10-week](image)

**Figure 2.** Number of children reporting changes in sensitivity towards target stimuli between baseline and 10-week assessment. Sensitivity was measured using self-reported emotional response (SRER). Reduction in sensitivity = reduced SRER score for one or more target sounds. Increase in sensitivity = increased SRER score for one or more target sounds. Reduction + Increase = lowered SRER score for one and increased SRER score for another target sound. No changes = participant did not interact with target stimuli.

Analysing baseline and 10-week post-study SRER scores for all target stimuli shows a similar distribution: the participants reported a decrease in sensitivity to seven individual sounds, an increase in sensitivity to two sounds, and no change in sensitivity to four sounds (Figure 3).

![Change in SRER baseline - 10-week](image)

**Figure 3.** Number of target sounds that have been interacted with and their changes in SRER between baseline and 10-week assessment.

The mean change in SRER for all target sounds was a decrease of 0.31, with a mean baseline level of 5.23 and a post-trial measurement of 4.92. Figure 4 displays the changes in SRER across all target stimuli for each participant.
Figure 4. Quantitative changes in SRER between baseline and 10-week assessment, with associated target sounds and interacting participants. SRER scale ranges from 1 (very happy) to 6 (very unhappy); all target sounds had a SRER $\geq 4$ at baseline. Negative values in the graph represent a reduction in sensitivity, while positive values indicate an increase in sensitivity.

Finally, analysis of SRER scores for non-target stimuli (stimuli assessed at baseline and post-trial at 10-weeks that provoked a negative response but were not interacted with) for all participants showed an average increase of 0.14 with an average baseline measurement of 4.67 and a post-trial measurement of 4.81.

3.1.2. Tracked Interactions (In-Game)

All voluntary interactions with the target sounds were tracked and sound intensity as well as duration of the interaction were recorded and analysed. Figure 5 displays the change in time each participant voluntarily interacted with target auditory stimuli between their first quartile of recorded interaction and their last quartile of interactions during the study (the total number of voluntary interactions with target stimuli varied between participants, with a range of 4–14 interactions). Out of the seven participants, four participants showed an increase in interaction time over the course of the study. On average, the total increase was 33 s, which is 28% of the average initial interaction length.

Figure 5. Changes in length of interaction with target stimuli for each participant, comparing the first quartile of interactions to the last quartile of interactions. Data are shown in seconds.
In addition to recording the time participants voluntarily interacted with target stimuli, data were also captured for the intensity of the exposure level, 1 being the lowest and 4 being the highest (see Table 1). Figure 6 shows the change in intensity between the first quarter of recorded interactions and the last quarter of interactions. It is noticeable that four of the seven participants chose to lower the exposure level over the course of the trial, with only one participant increasing the intensity and two remaining constant. On average, the intensity was lowered from 2.9 to 2.3 over the course of the study.

![Figure 6. Changes in average exposure level of target stimuli for each participant, comparing the first quartile of interactions to the last quartile of interactions. Exposure levels range from 1 to 4 (see Table 1).](image)

3.1.3. Qualitative Findings

Qualitative interviews were analysed using thematic analysis to identify common themes and patterns in the data (Braun and Clarke 2006).

**Effects of playing Soundfields:** Feedback was varied as to whether it helped desensitise the young person to specific sounds. One participant stated they were unsure as they were not often exposed to the sound.

‘I feel a bit better, but I don’t usually hear those things’

(Participant 3).

Participants described no concerns or discomfort at being exposed to sounds. Many described their choices of sound, with one stating the choice they made was to avoid a sound they disliked. This could indicate that guidance is required when choosing sounds that should be targeted. One participant found that the background music made it possible to tune out the sound altogether. None of the participants described the sounds as being too loud at any point. Some described the sounds as being much lower than they experience in real life, which may indicate a need for the intensity level to increase in any future trial. However, this may be due to their selected intensity.

Parents sometimes described an overall improvement, but it was difficult to determine if this was due to the game, due to observer bias, or due to other changes in the child’s environment (such as having a new teacher).

‘He doesn’t seem to be as worried in some situations, seems more chilled out. Has gone into town no problem which has previously been hard. Doesn’t seem to be complaining about school as much but could be to do with new teacher.’

(Parent 1).

‘He seems calmer after playing.’

(Parent 8).
Positive feedback: Overall, participants provided positive feedback on the game and their ability to tolerate playing on it. They described a variety of positive aspects of the game, including the “lobby” area, the orb, and bubble game. They identified the game as easy to use and most parents and young people did not feel the need to read the instructions.

‘I knew what to do so didn’t need any other instructions’

(Participant 2).

‘The game was intuitive, didn’t read the instructions.’

(Parent 2).

The game was described as “fun” and “exciting”. They liked the “look” of the game, with one participant stating “it reminded me of Mario” (Participant 1).

Most participants liked the music that played over the top of the sounds they were being desensitised to, noting the music helped reduce the intensity of the sounds.

‘I chose the alarm. The music was playing over the top, so it was bearable. The music that played over the top was nice.’

(Participant 9).

Negative feedback: Negative feedback provided described some games as “boring” or “babyish” by one participant. Most participants felt the worst game was ‘Simon Says’ due to few rewards and confusing instructions.

‘I didn’t like Simon says, I found it a bit difficult. I was fine until it started doing the double thing. I liked how the points worked.’

(Participant 9).

A number of parents stated their child could not manage playing the game for more than about 10 min as they lost focus after this time. One parent expressed concern that the background music masked the sound the child needed to be desensitised to too much. Another parent felt the sounds were too generic and that the ability to record bespoke noises their child was sensitive to would be helpful.

‘He found it hard to keep attention for so long so we broke it up into smaller times’.

(Parent 8).

The headsets were sometimes described as slightly “uncomfortable” or “hot”, but, overall, participants described no significant difficulties wearing them. One participant wore glasses, which were difficult with the headset, and described some headaches from use.

‘Gave (NAME) a headache could be to do with her glasses, was uncomfortable with glasses on.’

(Parent 3).

4. Discussion

This feasibility study is the first to explore the use of SoundFields as a means of addressing auditory hypersensitivity within a home environment. This provided the opportunity to not only evaluate the intervention as a desensitisation framework but also, importantly, to gain an understanding of how participants naturally engage with the game environment and mechanics within a home environment.

The software evaluated over the course of the 10-week study was successful at reducing negative emotional responses towards target auditory stimuli for five of the seven participants (71%). This is noticeable from the decrease in SRER recorded at the pre- and post-intervention sessions displayed in Figures 2 and 3. These results are supported by previous research that utilised the SoundFields framework [38,39]. However, it is important to note that each participant experienced varying amounts of reduction (see Figure 4). One possible explanation for this variance could be the amount of stimuli each child interacted
with over the course of the 10-weeks, with those focusing on just the singular target stimuli (P01) experiencing the highest levels of reduction.

This study expanded upon previous research to understand the impact of the intervention upon the lives of the participants outside of the experiment. This was achieved through exit interviews involving the participants and their parents. Parental feedback indicated that there was an overall improvement in the child’s reaction towards difficult sounds following the intervention, with one stating that the participant can visit the local town despite it being difficult in the past. In addition to providing some support for the SRER measurements, this is consistent with previous studies that utilise systematic desensitisation methods to target auditory hypersensitivity, resulting in participants being able to visit acoustic environments not possible prior to the intervention [43]. However, it is important to note that, although promising, it is not possible to eliminate other contributing factors, such as observer bias, or other changes in the child’s environment.

Similar to their neurotypical peers, autistic children enjoy engaging with and playing computer games during their spare time [44,45]. Because of this, many digital interventions deliver therapeutics by utilising a game-based approach, the aim of which is to maximise the motivation of the child to repeatedly interact with the system over time. This is a critical factor of SoundFields as interaction with exposure-based mechanics is entirely voluntary. Therefore, each participant could complete the 10-week study without listening to any problematic stimuli. Despite this, tracked interactions within the software demonstrate that each participant engaged with these mechanisms, with varying amounts between each child. Additionally, participants described the game as being fun and exciting whilst also liking the design of the virtual environment. Finally, players enjoyed the lobby area, which was the central environment for interactions with the game’s reward system.

Although this is encouraging, exit interviews suggest that adherence to the intervention was impacted by the gameplay mechanics, with a couple of participants stating that certain games were too childish. This is further reflected in parental feedback, which notes that participants found it difficult to play the game for longer than 10 min at a time. This highlights the importance of delivering therapy through the utilisation of engaging gaming mechanics, especially when delivering such a system at home in the presence of games designed for entertainment purposes. However, importantly, this also reflects the flexibility granted by conducting digital interventions away from the clinical environment.

Virtual reality is a new approach to delivering therapy that targets auditory hypersensitivity experienced by autistic young people, and the development of cheaper consumer-grade VR devices now allows for this form of therapy to be carried out within a home environment. In the case of SoundFields, parents were able to choose to deliver the therapy at a time most appropriate to their child and lifestyle. Furthermore, parents and participants found the software intuitive and easy to use and throughout the study received limited instructions from the researchers. With this in mind, home-based interventions such as SoundFields could provide an accessible option that can be conducted with limited training, potentially having a positive impact upon healthcare systems that have difficulties implementing behavioural therapy due to a lack of resources, time, and specialist training [25,26].

Despite the positive results, there are a number of considerations to improve SoundFields and its validation as a digital intervention. Firstly, as shown in Figure 6, tracked voluntary interactions indicated that several participants reduced the exposure level of the target stimuli over the experimental period, which may have impacted the effectiveness of the therapy. Therefore, it should be considered to remove all ability for children to control intervention parameters. Instead, it is suggested that, after initial selection of exposure level, these could be set to increase at consistent intervals to improve desensitisation. Furthermore options could include to allow parents an override function should they notice their children struggling with the exposure to target sounds.

Although the majority of participants and their parents stated that it had a positive impact, the correlation between SRER and the qualitative feedback was not always consistent.
This highlights the requirement for an improved assessment of auditory hypersensitivity. Firstly, parental feedback indicates that they sometimes have a different perspective on the impact of the intervention from their child. Therefore, a formalised questionnaire, such as the Parent Stress Index, could provide evidence of any habituation towards real-world auditory stimuli that would normally cause emotional distress. Secondly, biometric measurements could scaffold the primary outcome measurements and parental questionnaires, bypassing any social, communicative, and cognitive impairments. Similar approaches have been utilised in the validation of noise-cancelling headphones in aiding to reduce negative reactions to environmental auditory stimuli.

5. Conclusions

This paper presented a longitudinal feasibility study designed to expand on previous research, evaluating SoundFields as a home-based intervention that targets auditory hypersensitivity experienced by autistic children. Self-reported levels of emotional response towards auditory stimuli recorded before and after the 10-week intervention period measured any changes in sensitivity towards both target and non-target sounds. This was also supported by recording the total amount of voluntary interactions with exposure-based mechanics, as well as questionnaire responses from participants and their parents.

Recorded self-reported emotional responses indicate that, for most participants, engagement with the VR framework over multiple sessions leads to a reduction in sensitivity towards target auditory stimuli. This was overall reflected in the qualitative work, with the majority of participants and their parents stating that it had a positive impact upon their day-to-day lives. Furthermore, by taking advantage of consumer-grade VR technology, it was possible to deliver exposure-based therapy at home. This allowed the participants the opportunity to engage with the intervention when convenient and in an environment that is comfortable for the child, therefore minimising anxiety and enhancing accessibility to an intervention that aims to improve their quality of life.

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Data Availability Statement: The data presented in this study are openly available in Pure York Research Database at https://doi.org/10.15124/e77bc12f-5973-404a-b883-a0f042f5d5c, accessed on 20 March 2023. Requests for access to SoundFields can be made by contacting the corresponding author.

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