Systematic Review

Acceptability of Remote Monitoring in Assisted Living/Smart Homes in the United Kingdom and Associated Use of Sounds and Vibrations—A Systematic Review

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Abstract: The ageing of populations is increasing pressure on health and social care systems. Potentially, assistive technologies are a way to support the independence of older adults in their daily activities. Among existing assistive technologies, ambient sensing technologies have received less attention than wearable systems. Moreover, there has been little research into cheaper technologies capable of using multiple modalities. A systematic review of the acceptability of assisted living or smart homes in the United Kingdom and the simultaneous use of sounds and vibrations in remote monitoring of assisted living or smart homes will inform and encourage the use of digital monitoring technologies. The acceptability of sensing technologies depends on whether there is any social stigma about their use, for example, the extent to which they invade privacy. The United Kingdom studies reviewed suggest a lack of measurements of the perceived efficacy or effectiveness of the monitoring devices. The primary use of vibration or acoustic technologies has been for detecting falls rather than monitoring health. The review findings suggest the need for further exploration of the acceptability and applicability of remote monitoring technologies, as well as a need for more research into the simultaneous use of sounds and vibrations in health monitoring.

Keywords: vibration sensing; acoustic sensing; assisted living technology; smart home; remote sensing; ambient sensing

1. Introduction

The global population is ageing, and that in the United Kingdom is no exception since older adults aged 65 or older represent 18.2% of the population. This proportion is expected to increase to 24% by 2037 [1]. However, longer life expectancy does not necessarily translate into better health. For some, ageing may be associated with a higher incidence of disability, chronic diseases, and other conditions, which increases pressure on the health and social care systems [2]. Approximately 70% of older adults require total assistance for activities in daily living [3], and 35% require some support to manage their everyday lives, typically from family members and friends [4]. There are associated costs. For example, the costs of unpaid care for people with Alzheimer's or other dementia diseases provided by family members or relatives amounted to about $233.9 billion in the US [5]. Moreover, caring for older adults with chronic illness or deteriorating physical and mental health, making them less autonomous, can compromise caregivers' physical, mental, social, and economic status [6,7]. However, emerging assistive technologies help to maintain and enhance the physical and cognitive functions and well-being of vulnerable groups

challenged by daily living tasks. They enable older adults to age well, for example, by enabling them to maintain their participation and engagement in activities domestically and in community settings. Also, they improve the cost-effectiveness and quality of health and social services [8]. There is a lack of consensus on the definition of assistive technologies [9]. However, generally, they refer to information and communication technologies (ICT), stand-alone assistive devices, and smart home technologies developed to help older adults age in place safely, actively, and autonomously in the familiar environment of their homes [10,11].

The benefits of assistive technologies include decreasing the risk of falls and other accidents [12], improving inhibition and working memory [13], increased physical activity and reported quality-of-life scores [14], an enhanced sense of safety and security [15,16], augmented health monitoring and management [15,16], and better assisted daily life functioning [17]. Remote sensing technologies, a class of assistive technologies, are increasingly being used to deliver such benefits to older adults. These include wearable inertial sensors in smartphones for detecting falls [18], active infrared-based sensors for monitoring indoor wandering behaviour [19], and a combination of motion, light, and temperature sensors to maintain safety in daily activities [20]. As well as being used in the domestic setting, assistive technologies have been applied in institutional settings to inform carers when appropriate actions are required, thereby partly alleviating their burden of caring [21]. Remote sensing technologies have received growing attention given their potential to identify hazardous activities and monitor health conditions and safety in a wide range of living environments, such as sheltered housing, extra-care housing, and care homes [21].

Among the technologies available for health and well-being surveillance, ambient sensing technologies have received less attention than wearable sensors. The detection of environmental signals can be mechanical (e.g., vibrations via accelerometers, motion via gyroscopes), optical (e.g., fibre-optic detection or cameras), or electronic (e.g., semiconductor temperature sensors). Ambient sensing is preferable to wearable sensors since it is less intrusive. Moreover, ambient sensors do not need charging, operate twenty-four-seven, and do not cause discomfort from being carried [22], which is a major disadvantage of wearables. Also, they eliminate the risk associated with wearing devices in high-risk areas, such as bathrooms [23]. In addition, they enable monitoring even when the user forgets to carry or charge the wearable device. Hence, these technologies have considerable potential to provide sensing information at home or in more controlled environments, such as residential homes and care facilities.

Two examples of available ambient-assisted living sensor technologies involve the deployment of cameras and infrared sensors. The former requires a hard-wired power source, a high-bandwidth network connection, and a computer for the processing. Also, optical monitoring raises privacy issues. Furthermore, it is challenging to monitor the whole house with cameras [24]. Typically, infrared sensing generates data that is difficult to interpret, resulting in a higher occurrence of false alarms [25].

Remote sensing of vibrations and sounds, especially if processed appropriately, is unlikely to cause the same privacy issues as collecting images or videos. Typical hardware includes wireless sensor networks coupled with data analysis systems and distributed motion, pressure, vibration, and sound sensors [26]. An additional advantage of vibration and sound sensing systems is that they are cheaper than those incorporating more expensive modalities such as infrared and microwave [27]. However, sensing either vibrations or sounds alone can lead to inaccuracy because of the wide variety of vibrations and sounds around a domestic home throughout the day [28–30]. Since important events such as falls are associated with a particular combination of vibrations and sounds, identifying such combinations using a combined vibroacoustic approach would aid in the accurate identification and discrimination of these critical events from other events. Remote vibroacoustic sensors offer a way to address most of the issues associated with other remote sensing technologies, namely, discomfort (with wearable devices) and ethical challenges such as privacy, autonomy, dignity, safety, and trust [31]. However, it remains critical to ensure that

ambient sensing technologies are acceptable to older adults, deliver the intended benefits, and are applicable to any environmental setting.

In the context of working towards a future where the elderly, carers, and key professionals (such as organisations supporting carers) are more informed about and encouraged to use digital monitoring technologies, this review considers the following two research questions:

RQ1: What are the currently available non-intrusive technologies and their acceptability when utilised in monitoring older adults' activities and health conditions in the United Kingdom?

The primary aim of this first research question is to identify what non-intrusive technologies are currently available to monitor older adults' activities and health conditions in the United Kingdom. A secondary aim is to identify the extent to which these technologies are considered acceptable and useful by older adults or/and their carers and the extent of any increased safety and security felt by the users or/and their carers.

RQ2: To what extent are remotely monitored sounds and vibrations used simultaneously in assisted living or smart homes?

The primary aim of this research question is to assess the extent to which non-intrusive monitoring devices use sound and vibration technologies and their associated advantages and disadvantages. A secondary aim is to identify the extent of research both into the acceptability and into the simultaneous use of sounds and vibrations in remote monitoring of assisted living or smart homes.

2. Materials and Methods

2.1. The Research Questions

RQ1 is intended to inform technology design and policy development in the United Kingdom, so the review only considers articles with samples based only in the United Kingdom. Given that there is a body of research showing that technology is not culturally neutral and that people's responses to technology vary according to their sociocultural context [32–34], RQ2 focuses on remote sensing applications beyond the United Kingdom. Culture can manifest through specific artefacts, including art, technology, and visible and audible behaviour patterns [30]. Therefore, culture is likely to play a major role in forming basic assumptions and impacting attitudes, beliefs, customs, norms, and other psychological constructs. National culture theories attempt to explain differences in user acceptance behaviours, such as Hofstede's culture dimensions theory [35,36] and Hall's culture classification [37]. These theories suggest that there are variations in perceptions of technology or decision-making patterns regarding technology adoption due to cultural differences.

Although the specifics of remote sensing technologies are studied by using standardised experiments and computer algorithms that are not subject to cultural differences in perception, in some countries the pace of their development could be slowed to meet a more urgent need for remote sensing technologies to cope with the increased social and health burden of care. This is a further justification for an international scope in responding to RQ2.

2.2. Protocol and Registration

The protocol has been registered with PROSPERO under the registration number CRD42022357469.

2.3. Information Sources

All existing literature from January 2005, including primary research studies and grey literature (academic dissertations, conference proceedings, third sector reports, and government reports), was sought. The following databases were included in the study: Web of Science, PubMed, PsychINFO, ASSIA, CIAHL, Cochrane Library, and Google Scholar. A final search before the completion of the study was performed to include any recent articles. The

search strategy was developed with all authors (Supplementary Material Figures S1 and S2). Only studies published in English were considered in this review.

2.4. Inclusion and Exclusion Criteria

The selection criteria aimed to identify all available studies that addressed the two research questions.

Research Question 1 examines what has been done regarding the acceptability of remote monitoring of assisted living or smart homes in the United Kingdom and how remote monitoring has been received by the persons being monitored. Table 1 shows the criteria for research question one.

Table 1. Inclusion and exclusion criteria for research question one.

|	Inclusion Criteria	Exclusion Criteria
Population	Older adults aged 50 or above. Residing in their own homes or a facility offering assisted living or having experiences with or knowledge of assisted living technologies.	People aged below 50. Residing outside their own homes or a facility offering assisted living, or inexperienced or without knowledge of assisted living technologies
Study design	Literature involving remote sensing technologies for non-clinical health monitoring purposes. Studies involving assisted living technologies as an intervention or where participants had experience using relevant technologies.	Literature not involving remote sensing technologies or clinical health monitoring purposes. Studies did not involve assisted living technologies as an intervention, or participants did not have experience using relevant technologies.
Location	Articles are based in the United Kingdom.	Articles are based outside the United Kingdom.

Research Question 2 examines the extent of remote monitoring using sounds and vibrations simultaneously in assisted living or smart homes. Although older adults are the focus, research on sensing technologies using simulation and trials with human dolls is included, as indicated in Table 2.

Table 2. Inclusion and exclusion criteria for research question two.

	Inclusion Criteria	Exclusion Criteria
Population	Studies involving human subjects or subjects/processes that simulate human responses	Studies that do not involve human subjects or subjects/processes that simulate human responses.
Study design	Literature involving remote monitoring technologies using either sounds or vibrations or using sounds and vibrations simultaneously. Technologies are non-intrusive and are not for clinical purposes.	Literature involving remote monitoring technologies not using sounds or vibrations. Technologies are intrusive or are for clinical purposes.

2.5. Study Selection

Only studies fulfilling the criteria above were selected for the study. The screening and selection of articles followed the recommended procedures of the PRISMA evidence-based minimum set of items for reporting in systematic reviews [38]. After removing duplicated studies, an initial screening of titles and abstracts took place to exclude records that did not match the inclusion criteria. Each identified record was categorised according to 'include', 'exclude', or 'maybe'. For RQ1 and RQ2, the screening was performed by three reviewers. Reviewer 1 did the initial screening, and two reviewers divided the number of abstracts and each screened half. In the case of a 'maybe', all three reviewers discussed/agreed on inclusion or exclusion, and the same process was followed for full-text screening. Figures 1 and 2 indicate the number of records that went through the review process.
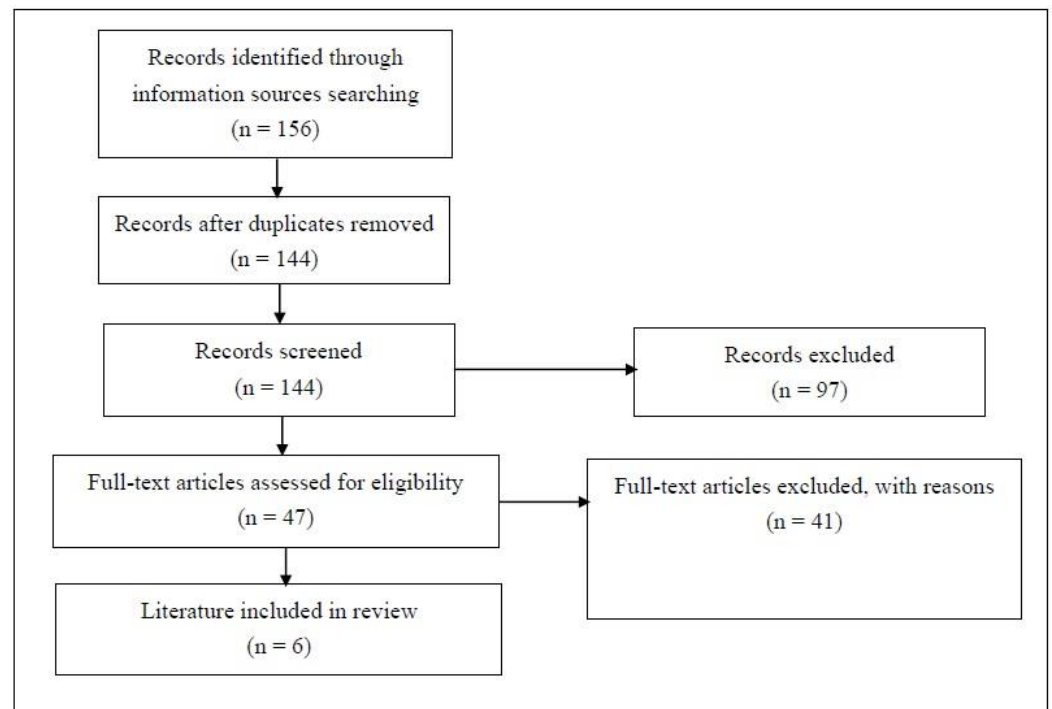
Figure 1. PRISMA flow diagram for research question one, January 2005 to September 2022, Preferred Reporting Items for Systematic Reviews.
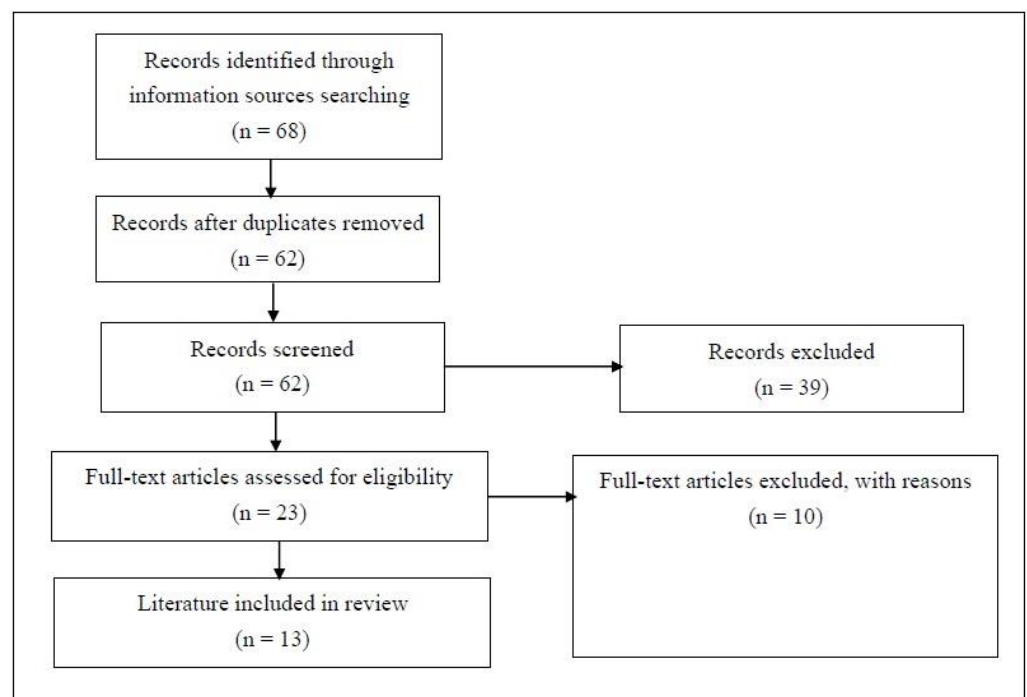
Figure 2. PRISMA flow diagram for research question two, January 2005 to September 2022, Preferred Reporting Items for Systematic Reviews.

2.6. Data Extraction and Synthesis

The complete information on a reference, including the author, date of publication, participants, and data collection methods, was obtained by one reviewer (K.T.) for both research questions. For RQ1, interventions applied in the study for promoting remote monitoring, overall receptibility of the monitoring technologies, self-reported physical and mental well-being, issues with privacy, and effectiveness associated with the monitoring

devices were identified. Information on the extent of simultaneous adoption of remote sensing using acoustics and vibrations and the advantages and disadvantages associated with the technology was obtained for RQ2. The information about the references was checked for consistency and completeness by all reviewers, and disagreements were resolved through discussion. The reviewers commented on the information according to the 'Guidance on the Conduct of Narrative Synthesis in Systematic Reviews' [39].

2.7. Critical Appraisal and Overview of Studies Included

The review adopted the Mixed Methods Appraisal Tool (MMAT) due to its applicability for qualitative, quantitative, and mixed methods studies. Detailed scoring for each paper for each question is available in Supplementary Material Tables S3 and S4.

To answer RQ1, the PRISMA workflow resulted in six articles to be critically appraised. Five of the six articles demonstrated medium to high quality as they contained information to fulfil the criteria in MMAT [40–44]. The sixth article did not offer enough information to help understand the quality of the qualitative method used [45]. Therefore, it was excluded. The five studies [40–44] included answered the research question by focusing on the acceptability of ambient assistive technologies. They ensured that research methods were appropriate for the research question by referring to methods in precedent studies or theoretical frameworks. They included direct responses and a range of responses to ensure the data were sufficiently substantiated. The discussion for all five studies provided a summary corresponding with the research intent, the data collected, and the analysed results to ensure a coherent, logical presentation of the arguments. One of the studies [43] did not provide the exact research methods or sampling procedure. The results and discussion sessions were not available. The lack of details for critical appraisal excluded this study from further review.

The five included studies [40–44], retrieved from published journals, involved three in-depth interviews, one focus group, and one mixed-method study. The search did not result in grey literature. Four studies investigated more than one type of ambient technology [40–42,44]. One of these four focused on alarms [40], encompassing smoke detectors and social and environmental alarms. The other three [41,42,44] did not specify a particular type of sensor, with questions based on the impression of general use of sensors, encompassing both remote and wearable sensors. Two of the five articles [41,43] concerned exploratory research on innovative remote sensing technologies; one of these considered installing a system of sensors to provide comprehensive surveillance throughout a residential home [41], and the other [43] replaced the subject in real-person video monitoring footage with other representations, including cartoons, sticky figures, and silhouettes.

In answering RQ2, the searches and screening process resulted in thirteen articles to be critically appraised. Twelve [46–57] of the thirteen studies demonstrated medium to high quality, as the twelve studies had information to answer all criteria in the MMAT, with the thirteenth [56] study falling short of answering S2 and the rest of the criteria. The research hypothesis of these twelve studies was clear and relevant, focusing on vibration and/or acoustic sensing technologies in monitoring human activities. All showed reliable data collection methods, using experiments or mixed methods to ensure the sampling strategy was appropriate and relevant to the population. Experimental studies [46–48,50–57] involving model development considered relevant parameters to simulate human activity. Those involving sensor development used dummy models, dolls, or human actors for sampling. The only mixed-methods study [49] included a qualitative human focus group study to inform model development using parameters identified. Issues with missing data were not observed for the mixed-method study. Appropriate constructs and statistical analysis were applied to draw evidence-based conclusions. Among the thirteen studies, one did not have information on detailed sampling strategies, or the methods adopted for analysis. Since the information in it was inadequate to determine its quality, the article was exempted from further review [58].

The twelve articles selected for the review comprised eleven experiments [46–48,50–57] and one mixed method [49]. Unlike RQ1, RQ2 resulted in three conference papers [46,52,57] as well as nine published journals [47–56]. Although all related to applying vibration or acoustic technologies for remote sensing, only two studies [52,53] used both vibrations and sounds simultaneously, with an additional one mentioning that the hybrid use of both technologies should be considered. Regarding geographical location, only one was published and conducted in the United Kingdom [49]. Four were based in the US [46,47,51,56]. Two were from Israel [52,53], one from Italy [48], one from Spain [50], one from China [55], one from Columbia [54], and one was based in an unspecified location in the EU [57]. To ensure relevance with real-life applications, five studies involved human subjects (participants recruited or stunt actors or experimenters themselves) [47,54,56,57], four involved human-mimicking objects (e.g., a doll) [48,52,53,55], and the rest focused on algorithmic simulations that did not involve subjects at the date of publication.

3. Results

3.1. Overview

Five and twelve articles were selected for review in connection with Research Questions 1 and 2, respectively. The data synthesis identified five common themes for RQ1 and three common themes for RQ2 based on the primary and secondary outcomes identified. The following discussion accounts for the characteristics of the included studies and the extent to which the selected studies addressed the primary and secondary outcomes for RQ1 and RQ2, respectively. The characteristics of the included studies for each research question are summarised in Supplementary Material Tables S7 and S8. Figures 3 and 4 summarise the common themes for RQ1 and 2, respectively.

3.2. Common Themes for RQ1

RQ1: What are the currently available non-intrusive technologies and their acceptability when utilised in monitoring older adults' activities and health conditions in the United Kingdom?

3.2.1. Theme 1: Available Non-Intrusive Technologies

Only two of the five selected articles studied ambient assistive technologies and tested them as interventions. Also, they were relatively recent publications. One of these studies was based on a combination of environmental, video, and wearable sensors installed in the homes of older adults [41]. The environmental sensors of the system extracted information on humidity, temperature, air quality, noise level, luminosity, occupancy, door contacts, and water and electricity consumption, whereas the video sensors extracted silhouettes of occupants' motions and activities. The system was one of the first to integrate many modalities into one central platform for monitoring purposes in a residential setting in the United Kingdom. The other intervention study focused on addressing privacy issues [43]. It attempted to protect the person's identity by replacing real-person video-monitoring information with other representations, including sticky figures, cartoons, and silhouettes.

While the above were examples of more recent developments, the remaining three articles that were reviewed evaluated remote monitoring technologies more commonly adopted in homes or care facilities. Two articles evaluated remote monitoring technologies as a whole without specifying a particular type [40,42]. The other article considered sensors for hazards, including smoke detectors and social and environmental alarms [44]. In addition to monitoring the interior climate and energy consumption, the study evaluated video monitoring for movements and activities. Therefore, results suggest that existing remote monitoring technologies focus on identifying, notifying, and preventing risks in the daily routine.

3.2.2. Theme 2: Acceptability and Usefulness for Older Adults and Their Carers

The qualitative research reported in the selected studies inferred the extent of acceptability and usefulness from the responses rather than directly by asking the question. Older adults, in general, welcomed assistive technologies if they could address a perceived need.

However, there were factors discouraging adoption among older adults. Some were related to the assisted person, such as their characteristics (health condition and mobility were examples) and the housing type and design in which they resided [40]. Some were associated with the attributes of the assistive technologies, including reliability, ease of use, whether the technology enables customisation, security and protection, and the consideration of privacy [40–42,44]. Contextual factors such as cost, access to, and availability of assistive technologies were also relevant and mentioned in all studies. One study mentioned high installation costs, the inadequacy of contractors to install the technology, and concerns about altering the building's appearance to adapt to the technologies as contextual factors that hinder acceptance of the technologies [41].

Also, receptibility to technologies varied according to age, sensor types, and technology-use time. Younger age groups appeared to be more accepting than older ones. They also considered themselves more likely to use environmental sensors in the future [44]. The same study showed that motion and door sensors were relatively more acceptable, whereas pressure sensors were the least acceptable. One study showed increased acceptance over time after trying out the intervention, which involved a system of sensors installed in residential homes [41].

In summary, the emergence of felt needs is critical for accepting remote monitoring technologies. Other factors related to the assisted person's characteristics, the technology's design, and contextual barriers should be considered to make the technology more accessible. In the selected studies, usefulness, like acceptability, was interpreted from responses instead of being solicited directly through a question. One study reported assistive technologies were constructive in providing reassurance, aiding early diagnosis, and identifying sedentary behaviour [44]. Another report reported that a remote sensor monitoring the eating habits of the assisted person for the benefit of the carer would be informative as the carer resided separately from the assisted person [43]. The same study also identified one carer who reported remote monitoring as helpful because the technology provided information on the movement of the assisted person even though the carer was in a different room. Although these comments were not explicitly related to tangible benefits, such as the safety or well-being of the assisted person, they enhanced carers' understanding of the assisted person.

Only three of the five studies commented on the extent of safety and security felt by using monitoring technologies, and the results were positive [40–42]. One emphasised that the technologies would be particularly relevant to those with physical health issues. Only one of the three studies elaborated that enabling older adults to perform tasks more independently, easily, and safely contributed to an increased sense of security [41]. Although two of the five studies did not mention specific safety and security comments, participants in one study remarked that safety was an attribute for deciding to accept monitoring technologies [43]. Nonetheless, improving safety might come at a cost. Older adults were paradoxical about improved safety in one study. Although recognising that assistive technologies could make them more independent and that decreasing interactions with carers offered more opportunity to interact socially, these were not preferred outcomes [43]. The selected study reveals that positioning assistive technologies as augmenting rather than replacing carers is critical to their acceptance.

Most of the studies considered the perspective of older adults [43]. Only one study considered the carers' perspective. Carers in this study reported that monitoring technologies appeared to address issue-specific risks without the ability to evolve and prevent future risks as the health condition of the assisted person got worse [43]. That is, the technology should detect non-emergency incidents. While focusing on present, observable

risks could promote safety and security, enabling assistive technologies to evolve and address foreseeable long-term risks is critical to sustaining such feelings.

Two of the five studies identified that the stigma inflicted by the monitoring devices was a concern [41,43]. Participants in one study considered smart home technologies themselves to signify frailty [41]. Similarly, participants in another study considered the negative association of technologies with 'disability' to be a barrier to adopting assistive technologies. Participants in the same study added that, to address stigmatisation, the design of the appearance of these sensors could perhaps be made less physically intrusive.

Participants in another study reported they were uncomfortable in the presence of the sensing device because that led to behavioural change [43]. The example was specific to door sensors. Given that they were not in the habit of closing the door, they had to learn to close the door regularly to prevent the sensor from alarming. Although the result did not affect acceptability or perceived usefulness, the inconvenience was an issue the participant hoped future technologies could address.

There is no doubt that negative social perceptions and individual living habits should be considered when considering the adoption experience.

3.2.3. Theme 3: Self-Reported Changes in Physical and Mental Health and Wellbeing

Although the selected studies did not include questions or comments specifically related to physical and mental health and well-being, participants in one study reported that using ambient assistive technologies would reduce their dependency on carers, and the assisted person might feel lonely and socially excluded because of decreased interactions with carers [43]. Although not directly related to mental health, loneliness and the experience of exclusion could be detrimental to general psychological well-being. That is, negative emotions could result from the benefits brought about by the monitoring technology instead of from the weaknesses or disadvantages of the design.

One exciting aspect emerged from the study, where carers were the subjects, and they found tracking well-being to be informative [43]. Carers showed interest in knowing if the assisted person was lonely or upset with the help of remote monitoring. The participants considered emotional changes relevant to improving general understanding of the assisted person and offered early help if appropriate. While the specific health benefits have not been explored in the literature, tracking emotional and mood changes (and potentially physical signs) regularly, if available by remote sensors, would be informative to carers.

These results suggest the need to explore the unintuitive impact on physical and mental health of using ambient assistive technologies and to keep and make the information available for stakeholders.

3.2.4. Theme 4: The Extent of Concerns about the Potential Loss of Privacy and Understanding Who Can Access the Data from Monitoring

Privacy remained an issue despite the technology being non-intrusive. Three studies identified privacy as the common theme where participants worried about the assisted person being watched regularly [41,43,44]. The other concern with video monitoring was the use of real-person footage. Some carers in one of the studies preferred representations of the subject in the footage using cartoons or sticky figures because researchers or external entities could view the footage [43]. However, one carer in the same study argued that facial expressions were critical to reading and interpreting the assisted person's needs comprehensively; therefore, cartoons and sticky figures were inadequate. The participant added that controlling the release of who was eligible to view the footage was critical to determining representation types.
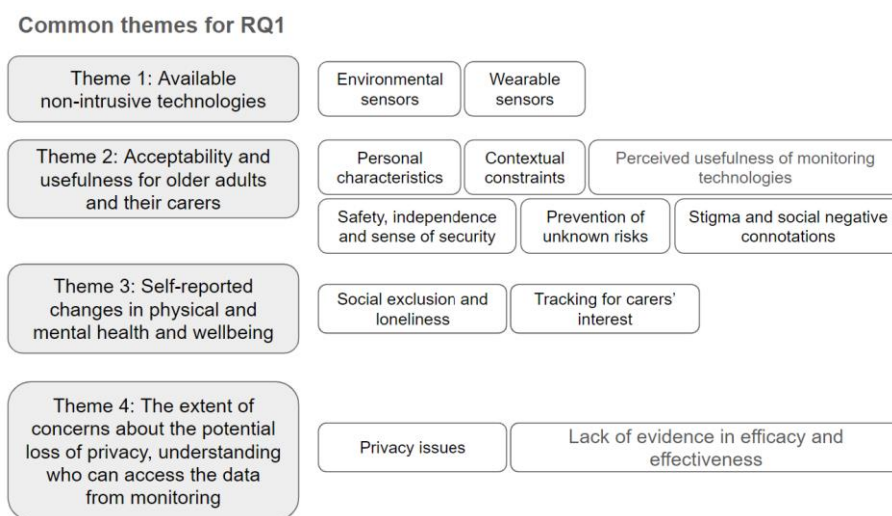
The extent of concern varied depending on the experience with the sensors. Older adults who tried out the monitoring system showed less concern with privacy issues compared with those who did not try the system [41]. Comments concerning security were inferred from the privacy concerns. In one study, participants recommended that a PIN-protected view for gatekeeping the transmission of the footage could be a solution to

representing real-person footage with cartoons or sticky figures [43]. In the same study, older adults reported that content-release control functions similar to those in Facebook (which determined who could see your detailed personal information) could be added to the monitoring system to regulate data release to uphold security.

Despite the privacy issues, one study remarked that ambient monitoring was better than wearable sensors and that the level of intrusion was less [44]. None of the studies explicitly acknowledged the association between assisted technologies' acceptability or perceived usefulness and privacy issues.

These Themes are summarised in Figure 3.

It is noteworthy also that none of the studies included questions about the monitoring device's perceived efficacy or effectiveness.

Common themes for RQ1

Theme 1: Available non-intrusive technologies	Environmental sensors	Wearable sensors	
Theme 2: Acceptability and usefulness for older adults and their carers	Personal characteristics	Contextual constraints	Perceived usefulness of monitoring technologies
	Safety, independence and sense of security	Prevention of unknown risks	Stigma and social negative connotations
Theme 3: Self-reported changes in physical and mental health and wellbeing	Social exclusion and loneliness	Tracking for carers' interest	
Theme 4: The extent of concerns about the potential loss of privacy, understanding who can access the data from monitoring	Privacy issues	Lack of evidence in efficacy and effectiveness	

Figure 3. A summary of common themes for RQ1.

3.3. Common Themes for RQ2

RQ2: To what extent are remotely monitored sounds and vibrations used simultaneously in assisted living or smart homes?

3.3.1. Theme 1: The Extent of Simultaneous or Independent Remote Monitoring of Sounds and Vibrations Other Than for Detecting Falls

There is limited evidence that acoustic and vibration technologies have been used simultaneously for remote monitoring. Only two studies tried to monitor remotely using sounds and vibrations simultaneously, and both studies originated from the same authors [50,51]. Six articles adopted acoustic technologies only [46–51,54], whereas four adopted vibration technologies only [47,55–57]. Of the two articles that involved using both acoustic and vibration technologies, one was a conference paper [52], representing work-in-progress prior to the publication of the other [53]. Together with the observation that other articles reviewed tried either acoustic or vibration technologies alone, the results showed limited attempts to apply both technologies simultaneously. Also, no attempt has been made to correlate airborne and structure-borne signals and, thereby, to discriminate between the sources based on any such correlation.

The two studies that used sounds and vibrations simultaneously were focused on detecting falls [52,53]. The system comprised an accelerometer and a microphone to detect floor-borne and air-borne signals from a fall and to differentiate these signals from other sounds and vibrations around a home to enhance the reliability of remote monitoring in a residential environment. However, the combined system was not tested with applications other than falls, so its potential usefulness in this respect has not been explored.

Although the variety of applications for vibration technologies was wider, the majority primarily focused on detecting falls. One study showed an attempt to detect and

differentiate human activity patterns in general [47]. However, the other four articles were all related to identifying fall patterns [55–57].

The variety of applications for acoustic technologies was wider than for either vibration alone or combined use. Only one out of five studies focused on detecting falls [48]. One study attempted to follow a similar line. However, it started with a qualitative interview that related most to the habitual living patterns of older adults in a care home, then gathered relevant acoustic information and trained artificial intelligence to recognise human activity indoors [49].

Another one attempted to identify patterns to recognise events using machine learning based on acoustic and other low-level sensory data (light, humidity, temperature) [46]. The remaining studies approached detection in a similar manner to the above. However, they utilised only acoustic data in an indoor environment and then employed a machine-learning approach to training the recognition and differentiation of human activities [50,51,54]. While vibration monitoring focused more on detecting vibration, acoustic technologies appeared to have a broader application, although they emphasised the development of machine learning algorithms rather than hardware.

3.3.2. Theme 2: Principles, Availability of Technologies, and the Associated Advantages and Disadvantages

The two studies, which simultaneously adopted vibration and acoustic technologies, used an accelerometer and microphone as the sensors [52,53]. For studies involving only vibration technologies, three studies utilised accelerometers [45,53,54], and one utilised a radar system coupled with Doppler sensors. However, in both systems, the sensors were floor-based [57]. Studies involving acoustic technologies used microphones [5,46,48–51].

The review section of these articles mentioned the range of technologies used to monitor older adults' conditions remotely and their respective advantages and disadvantages. Older adults may forget or resist wearing or carrying wearable sensors or other devices, or their batteries may run out of charge. Wi-Fi and radar-based systems were expensive upfront and accompanied by high development overhead costs. Vision-based systems had issues detecting in low-light environments, restricted fields of view, and privacy invasions.

There are advantages to remote sensing of vibrations and sounds. Even though the user might forget to engage with the device, continuity in operation was an advantage compared with wearables. Moreover, vibration and acoustic technologies were relatively cheap. By identifying patterns of vibrations or sounds rather than raw signals, the system was minimally intrusive or invasive of privacy compared with vision-based monitoring systems. Nevertheless, remote sensing technologies have disadvantages.

One study argued that remote sensing could still be expensive because the system would typically be installed in a confined area where multiple sensors are needed to deliver the intended outcomes and there could be blind spots [48]. The overall cost would then be elevated over the cost of radar-based systems.

The accuracy of the acoustic technologies depended on the choice of classifier and signal processing techniques. Differentiating some sounds in the physical indoor environment was challenging; sounds from door knocking and door closing were difficult to distinguish. Environmental noise remained an issue affecting the accuracy of detection for acoustic technologies [51,53].

According to the two articles [52,53], vibration technologies were easier to install than acoustic technologies with high accuracy. However, there was not enough evidence to show the extent to which accuracy would change if subjects fell onto carpeted surfaces. Also, there is little detail on the range to which a mobile phone accelerometer would be able to measure the vibration pattern of a fall adequately.

For the combined approach, recalibration was necessary for different floor materials, and the system fell short of differentiating between 'soft' and 'slow' falls. The system also did not consider the correlation between vibration and acoustic signals, thereby not taking

advantage of its ability to distinguish airborne sources from those resulting only from ground contact.

3.3.3. Theme 3: Paucity of Research around Acceptability and Simultaneous Use of Sounds and Vibrations in Remote Monitoring of Assisted Living or Smart Homes in the United Kingdom

There is limited evidence in the United Kingdom concerning the simultaneous application of acoustic and vibration technologies. Only one study identified was based in the United Kingdom, and it examined acoustic technologies only [49]. The lack of information in other forms of application, the absence of simultaneous consideration of acoustic and vibration data, and the limited number of studies identified in the United Kingdom all suggest a paucity of research in the area. These Themes are summarised in Figure 4.
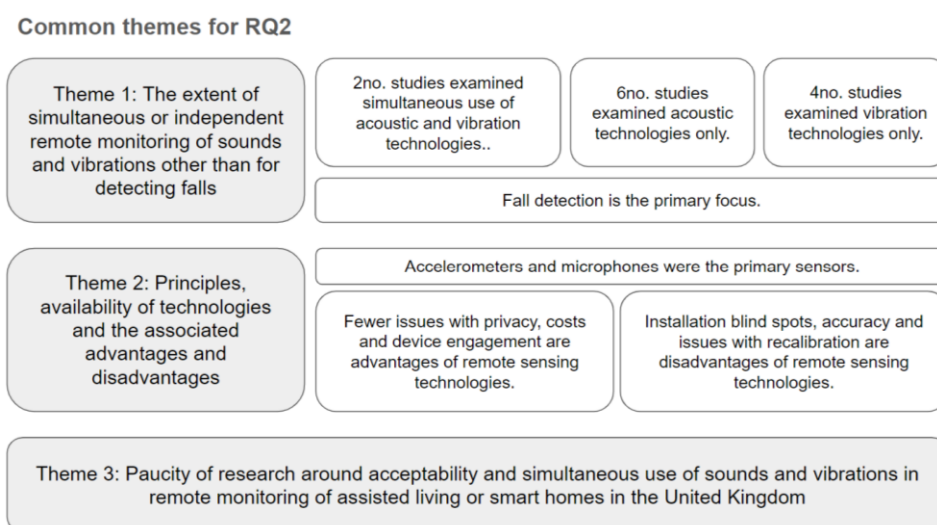
Figure 4. A summary of common themes for RQ2.

4. Discussion

The review provides some insights into the extent of receptivity of remote sensing technologies and specific technological applications. Following is a discussion of the implications and directions of future research.

RQ1: What has been done regarding the acceptability of remote monitoring of assisted or smart homes in the United Kingdom?

4.1. More Exploration of the Acceptability and Application of Sensing Technology Needed

Considering that only five studies were identified and selected for the review, remote surveillance appeared to receive less attention than wearable technologies. Most studies explored a range of technologies, which suggested limited evidence to explore the acceptability of specific technology types. Video monitoring was more commonly discussed than other technologies in the reviewed articles. Therefore, the lack of comments concerning other technologies represented a potential research gap in understanding receptibility.

Limited research on other technology types could indirectly and negatively impact remote sensing technologies' overall acceptability. Compared with other relatively non-intrusive sensing technologies, video monitoring is associated with more privacy concerns [59,60]. However, the lack of research on other technologies that could perform some functions of video monitoring means users are less informed about their possibilities or presence. The absence of such knowledge might facilitate the notion that video monitoring, a technology associated with stigma, was the only technology for remote sensing. These negative connotations might prevent adoption.

Among the reviewed studies, none explored the acceptability of vibration and/or acoustic technologies in assisted living. Therefore, the exploration of their acceptability could be a future research initiative.

4.2. More Focus Needed on Health Changes

Although remote monitoring of clinical conditions has demonstrated positive outcomes in reducing psychological stress [61], physical and psychological health changes following ambient assistive technologies have received less attention and have not been explored in the selected literature. This warrants further research, especially as the literature has identified that adverse mental health consequences could arise from the positive outcomes of ambient assistive technologies. Investigating the many complicating psychological factors is critical to future technological developments.

The other aspect worthy of further research is the potential to track emotional changes using remote sensing, as mentioned by the participants in the study that assessed the carers' perception of remote sensing [43]. Carers reported they might be worried about their emotional states as they could not be physically present or geographically proximate to assist the older adults, which justifies the need for tracking psychological states.

4.3. Perceived Need Is Critical to Adoption

Awareness of a perceived need for technology is critical for accepting and using it. However, acceptance does not equate to adoption. There are barriers typically related to the characteristics of the person, the attributes of the technologies, and how accessible the technologies are.

4.4. Exploration of the Effectiveness of Technologies Is Lacking

The review did not identify articles discussing the perceived efficacy or effectiveness of monitoring devices. Sample sizes are relatively small, with minimal quantitative assessments of efficacy or efficiency. However, these results will inform the cost-benefit analysis for the development of application policies. Hence, demand future attention for research.

4.5. Stigma and Negative Connotations Are Barriers to Adoption

Although ambient sensing technologies are less intrusive, the feeling of being watched over by someone regularly remains a privacy concern. Suggestions emerged in the reviewed literature that password-based and customisable data gatekeeping to control the release of information could be solutions to uphold security and dignity [43].

Stigma and negative associations with disability due to the mere presence of the technology harmed users' experiences, although they were not directly related to the quality of the technology. As reported in one of the studies [43], some technologies might involve changes in living patterns, such as closing the door regularly to avoid triggering a sensor. Together with the inferences drawn from stigma, the design of technology should ensure it is integrated subtly into the environment to minimise awareness and to accommodate users who might differ slightly in terms of lifestyle patterns. As suggested in recent research, the design of sensing technologies should be more appropriate to users' needs and expectations using a person-centred, participatory approach [62]. This also relates to customisation, as mentioned above, in that not only the release of information should be controlled, but the application of technologies should enable slight adaptation to suit individual lifestyle patterns.

These barriers were critical factors affecting adoption as they were consistent with the key constructs identified in motivation and environmental press theories.

Self-Determination Theory [63] is one of the motivational theories that considers the adoption of technology as dependent on competence, autonomy, and relatedness to others. Behavioural change is more likely if the assisted person felt competent in using the technology and was based on personal free will, where the results encouraged connection with others. As observed in the discussion above, there were barriers associated with all

three constructs. For instance, forced changes in lifestyle patterns to adapt to technology represent a challenge in competence. Loss of privacy could be an example of decreased autonomy. Negative associations and stigma inflicted by technology were associated with social relatedness. Therefore, addressing all three factors was critical to initiating behavioural change in adopting technologies.

However, the three constructs are not equally weighted regarding their impact on initiating a behavioural change among older adults. Environmental Press Theory [64] suggests that environmental stimuli have a greater demand quality as the competence of the individual decreases. Older people will be affected disproportionately by their environments as their 'competence' is reduced. Therefore, in addition to changing the appearance of design to alleviate stigma, which is associated with relatedness, the two theories combine to suggest that the design of technologies needs to cater to different levels of competence as older adults tend to be more affected by the environment. There should be consideration of customisation to enable more seamless integration with their living pattern.

4.6. An Innovative Solution to Address Stigma and Negative Connotations

Societal education and the involvement of carers also help shape a more friendly environment that minimises environmental 'presses' and enhances acceptance. One exempted study proposed using smart fabric as a sensor to be incorporated into home furniture to detect physiological changes such as hydration. The study was excluded because the design workshop was performed outside the United Kingdom. Although some design workshops were based in the United Kingdom, those workshops focused on developing wearable sensors instead of installing sensors at homes [65]. The emerging technology is a method to make sensors even less intrusive (as they are integrated into the furniture). However, these are contact-based sensors, which might induce discomfort or awkwardness when used. The uncertainty in this regard warrants further research regarding acceptability and usefulness.

4.7. The Paucity of Intervention-Based Studies

Only two of the reviewed studies [41,43] were remote-sensing and intervention-based in the United Kingdom. The limited number of studies that examined the acceptability of specific remote sensing technologies among older adults warrants further research.

RQ2: To what extent are remotely monitored sounds and vibrations used simultaneously in assisted living or smart homes?

4.8. The Development of Vibration and Acoustic Technologies

Only two studies tried using acoustic and vibration technologies simultaneously. However, they did not attempt applications other than to detect falls. The observation persisted even when reviewing the excluded articles. Therefore, there have been few, if any, efforts at using both technologies in remote monitoring non-fall applications. Most of the reviewed articles utilised either vibration or acoustic technologies for remote monitoring, with the former primarily focused on detecting falls. In contrast, the latter covered a broader range of applications and tended towards training machine learning to recognise different activity patterns. These results suggest that research in the field diverged from each other instead of converging to explore any common ground between the two technologies. However, the two studies using both technologies showed that the combination could enhance the accuracy of sensors in detecting human falls. Exploring the convergence between the two technologies represents an opportunity for future research.

4.9. The Need for More Research on Vibration and Acoustic Technologies

Accelerometers and microphones were adopted as sensors for vibration and acoustic studies, respectively. While most of the studies attempted in vibration and acoustic technologies separately were related to pattern recognition and differentiation, no articles discussed limitations in hardware, which could explain the limited extent of attempts to

apply both technologies simultaneously. Understanding the hardware's limitations and exploring the potential of converging the two technologies represent another opportunity for further research.

4.10. Disadvantages to Be Overcome

Remote sensing provides ongoing detection without issues of low battery or disengagement due to forgetful acts and is minimally intrusive to uphold privacy. However, there remain disadvantages that require further exploration.

Overall, improvements in specificity and sensitivity are critical, as residential layouts might have blind spots beyond the coverage of remote sensors. As a general observation from the identified articles, experiment-based research did not consider different application scenarios sufficiently. The granular difference between environmental noise and its impact on acoustic technologies, and different floor materials and the associated changes in vibration technologies, should be further studied to improve specificity and sensitivity. The same observation applies to the combined use of acoustic and vibration technologies, where re-calibration for a range of hard and soft interior surfaces should be examined.

4.11. The Paucity of Vibracoustic Technology Research in the United Kingdom

Most importantly, only one article identified was based in the United Kingdom, and this study used acoustic sensing alone rather than a combination of acoustic and vibration technologies. It should be noted, however, that the excluded papers mention that combining both technologies could be a future direction of research.

4.12. Useful Further Developments

It is worth expanding the review of the acceptability of remote sensing technologies to articles based in countries outside the United Kingdom to acquire a more comprehensive understanding of the factors affecting acceptability, which will also heighten the probability of including quantitative studies. This provides figures to help compare the magnitude of factors affecting acceptability and how these magnitudes vary depending on the technologies.

However, focusing only on the United Kingdom narrowed the research into a more manageable scope to provide inferences more applicable to the geographical area. This aids in the granularity of discussion in the findings.

5. Conclusions

In summary, despite the benefits of remote sensing technologies, there is limited evidence to conclude their acceptability due to an over-emphasis on video monitoring compared with other forms of remote monitoring technologies. Stigma and negative connotations associated with remote video monitoring represent a major challenge to promoting adoption. Extended intervention-based research and a trial of innovative technology hardware are potential directions to complete the understanding of receptibility. In addition, there should be more quantitative assessments of the efficacy and efficiency of sensing technologies involving a larger sample size. The simultaneous use of acoustic and vibration technologies represents an opportunity to address the privacy and stigma associated with remote video monitoring. It should be incorporated into future research agendas to address the paucity of technology research and to make the best use of the technologies in the United Kingdom.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14020843/s1, Figure S1: Search string for RQ1; Figure S2: Search string for RQ2; Table S3: Mixed Methods Appraisal Tool (MMAT) for RQ1; Table S4: Mixed Methods Appraisal Tool (MMAT) for RQ2; Table S5: Excluded studies for RQ1; Table S6: Excluded studies for RQ2; Table S7: Characteristics of included studies for RQ1; Table S8: Characteristics of included studies for RQ2.

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