The longitudinal impact of psychosocial factors on cognition and hearing in younger and older adults during the COVID-19 pandemic.

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ABSTRACT

Purpose. In March 2020, a unique situation unfolded wherein the UK government announced social restriction measures to reduce the spread of the virus that causes COVID-19. Various measures remained in place until April 2021, with older adults, who were considered clinically vulnerable, being placed under stricter restrictions. This study aimed to determine the effect of psychosocial factors, including loneliness, depression, and engagement in various recreational lifestyle activities, on hearing and cognitive function in younger and older adults during the COVID-19 pandemic.

Methods. 112 older adults aged 60-82 (M = 70.08, SD = 5.89), and 121 younger adults aged 18-29 (M = 20.52, SD = 2.63) participated online between June 2020 - February 2022. Participants completed questionnaires assessing loneliness, depression, auditory and lifestyle engagement, and hearing ability, as well as behavioural tasks assessing auditory function and global cognition. All measures were completed 12 times at 4-week intervals.

Results. Linear mixed effects analyses found that, of the variables examined, increased loneliness was significantly associated with poorer auditory function. There were no main effects of time during the pandemic on auditory or cognitive outcomes. However, the interaction between time and age group significantly affected global cognition; in younger adults, global cognition decreased overtime, whereas older adults displayed an unexpected positive change.

Conclusions. These data show that there are associations between loneliness and auditory function but provide a lack of support for the impact of time experiencing auditory deprivation, or other psychosocial factors, on hearing and cognitive function. Such observations may be underpinned by motivational differences, learning effects, or sample biases. Future research may wish to investigate these factors further, to determine how psychological factors like loneliness affect hearing and cognitive processes across diverse participant groups.

Keywords: Hearing; Cognition; Socialisation

1. INTRODUCTION

As the population ages, health issues grow in prevalence, placing increasing pressure on health care systems. Hearing loss (HL) is one of the most common conditions in older age, affecting over 70% of people aged 70+ in the UK (Royal National Institute for Deaf People (RNID), 2020). Many age-related health conditions are associated with, or have been shown to exacerbate, one another. For example, HL is associated with increased levels of loneliness and depression (Lawrence et al., 2020; Mick et al., 2014; Shukla et al., 2020). It has also been recognised internationally that both social isolation and HL are potentially modifiable risk factors for dementia. In fact, if the risk factors of social isolation and HL are indeed causal for dementia and were removed, then it is hypothesised that dementia cases could be reduced by as much as 4% and 8% respectively (Livingston et al., 2024). However, further high-quality longitudinal data are required to elucidate the true nature of the HL-dementia relationship.

Several hypotheses have been proposed to explain the association between age-related HL (ARHL) and dementia (Lindenberger & Baltes, 1994; Powell et al., 2021) A number of these hypotheses suggest that hearing loss has a causal effect on cognitive function. In brief, hearing loss has been suggested to effect cognitive function directly via 1) increasing listening effort depleting cognitive resources (Pichora-Fuller et al., 2016), 2) increasing auditory deprivation, which occurs when the brain is deprived of sound, leading to neuroanatomical changes (e.g. Lin et al., 2014). These direct pathways are suggested to effect global brain function and structure in a way that compromises cognitive functioning (Fitzhugh et al., 2019; Panouillères & Möttönen, 2018).

Researchers have also suggested that hearing loss may causally affect cognition via an indirect psychosocial pathway (Shukla et al., 2020). Hearing loss significantly impacts psychosocial factors, including feelings of loneliness, isolation, and depression due to a reduction in the quantity and quality of social interactions (Jayakody et al., 2018). Difficulty listening, particularly in noisy environments, may lead older adults with hearing loss to withdraw from social interactions due to communication challenges, or embarrassment and stigma (David et al., 2018). This social withdrawal may exacerbate auditory deprivation, due to reduced engagement with auditory rich and cognitively stimulating environments. This, in turn, may modulate the association between HL and cognitive decline. Importantly, older people may be particularly vulnerable to loneliness and depression due to the higher prevalence of living alone (Age UK, 2019), and this risk may be further increased by HL (Bott & Saunders, 2021; Maharani et al., 2019). Understanding the effect of psychosocial factors on both HL and cognition in older age is essential to shed light on the factors that might contribute to increased wellbeing and healthy brain ageing.

During the height of the COVID-19 pandemic, the UK public experienced social distancing, enforced isolation, and restricted means of communication in various forms, from March 2020 until January 2022. This overwhelming period of unprecedented change enabled researchers to investigate how loneliness and isolation might affect sensory and cognitive function across age ranges. Considering that older adults may be more likely to experience loneliness and isolation as well as hearing loss (Age UK, 2019), compared to younger adults, it is conceivable that older adults may have been disproportionately affected by pandemic-related restrictions. Associations between sensory impairments and psychosocial factors including social participation, social network size, and loneliness have been widely reported (Mick et al., 2018; Ray et al., 2018); and theoretical frameworks have been proposed detailing anchor stages (from listening disengagement to social withdrawal and loneliness) to describe the relation between hearing loss and social isolation (Motala et al., 2024). Importantly, during the height of the pandemic, older adults and other clinically vulnerable populations were provided with stricter social distancing guidance. As such, older adults may have been at greater risk of social withdrawal and reduced social communication, leading to auditory deprivation, particularly in terms of reduced in-person social contact. This could have led to long-term consequences for hearing and cognitive function. Understanding how social factors relate to both cognitive and hearing function is imperative for identifying intervention pathways targeting HL and cognitive decline.

Hearing could be affected if environmental auditory deprivation, due to social distancing and isolation, leads to tangible changes in the auditory cortex and associated brain areas used for processing speech in noise. Deprivation of auditory input, due to hearing loss, is associated with atrophy of the brain regions associated with hearing (Slade et al., 2022), which could negatively affect speech perception ability. This atrophy may occur because HL-related damage to the auditory periphery leads to distorted auditory representations, reduces access to verbal and emotional information in speech, and decreases the amount of auditory information sent to the brain, leading to atrophy of auditory and association areas (Griffiths et al., 2020). Similarly, during the height of the pandemic, a deprived auditory environment was created due to social restrictions and poor listening environments (i.e., use of face coverings, online calls, Perspex screens), which could have negatively affected the capacity for speech understanding. Indeed, deprivation of auditory input, due to prolonged wearing of earplugs, has been shown to alter neural responses to speech (Munro & Blount, 2009). Further, social distancing has been shown to negatively impact the quality of communication and connection with others (Wood et al., 2024).

Cognition may also be affected in a similar way. Increased social interactions give rise to mentally stimulating situations that benefit cognitive function (Sommerlad et al., 2019). According to the cognitive reserve hypothesis, engaging in social activities are a key aspect of building cognitive reserve that may help to protect against age- and disease- related declines in cognitive function (Oosterhuis et al., 2023; Stern et al., 2020). Similarly, social contact has been internationally recognised as a protective factor against dementia (Livingston et al., 2024), and a recent scoping review indicates that social isolation and loneliness relate to poor cognitive function in older adults (Cardona & Andrés, 2023). A variety of assessments may be employed to measure cognition such as the Mini Mental State Examination (MMSE: Folstein et al., 1975) and the Montréal Cognitive Assessment (MoCA: Hobson, 2015). These standardised assessments are generally employed to test the presence of cognitive impairment. They comprise several domains of cognition including short-term and working memory, executive functioning, processing speed, or reaction time. Importantly, these domains are considered to be sensitive to age-related declines in cognition (Deary et al., 2009; Murman, 2015). Further, studies indicate these cognitive domains may be affected by psychosocial factors. For example, memory recall and executive function abilities have been found to be related to loneliness (Lara et al., 2019; Luchetti et al., 2020; Sin et al., 2021), and processing speed has been found to be related to social isolation (Hajek et al., 2020).

During the COVID-19 pandemic, we explored the indirect psychosocial pathway hypothesis, also known as the ‘cascade hypothesis’ (Dawes et al., 2015; Dhanda et al., 2024).

According to this hypothesis, social withdrawal, isolation, and possibly resulting loneliness, further exacerbates auditory deprivation, due to reduced engagement with auditory rich and cognitively stimulating environments. This deprivation then negatively affects hearing and/or cognitive function. In a previous study, subjective hearing disability (measured by the Speech and Spatial Qualities of Hearing Scale: (Noble et al., 2013)), exacerbated the impact of social distancing on depression, loneliness, and memory in older adults (Littlejohn et al., 2022). The present study builds on these findings, taking a lifespan approach by comparing younger and older adults, and measuring longitudinal outcomes of auditory function (comprising both subjective hearing ability and speech-in-noise perception) and global cognitive function across a period of 12 months during the pandemic.

Consistent with our preregistration protocol, data were collected between June 2020 and January 2022. All participants joined the study between June 2020 and February 2021, and data were collected over the subsequent 48-weeks for each participant. For context, the first UK national lockdown, the government ordered mandate to stay at home, was announced in March 2020, a second national lockdown was then announced in November 2020, and a third was announced in January 2021. Between these dates, the UK experienced numerous changes to social contact, including various local lockdowns and a tiered system of restrictions. Restrictions to social contact remained in place until the end of 2021, with the last measures of compulsory face mask wearing, and mandatory NHS Covid Passes finally being removed in January 2022 (Institute For Government, 2022).

The aim of this preregistered study was to determine the effect of a period of enforced social isolation and restriction on both hearing and cognitive function in younger and older adults. As such, the primary predictors were: 1) loneliness, determined via self-report scales; and 2) time, which ranged from time point 1 to time point 12, with each time point separated by 4 weeks. We also included secondary predictors which we hypothesised to interact with the primary variables, including: 1) age group (older vs. younger); 2) hearing status (ARHL vs. no HL); 3) depression; 4) engagement in auditory activities; and 5) engagement in lifestyle activities. Table 1 outlines the hypotheses.

[Table 1 here]

2. MATERIALS AND METHODS

Ethical approval was obtained from Lancaster University's Faculty of Science and Technology Ethics Committee (FST19175).

2.1 Transparency and Openness Statement

The study was preregistered on the Open Science Framework (https://osf.io/67rwh/). Any deviations from the protocol are described below.

2.1.1 Deviations from Pre-Registration

Statistical Inference: In our pre-registered analysis plan, we reported that the statistical inference criteria would be $p < .05$ for determining significant results. However, on reflection, in identifying the need to test multiple hypotheses, we decided to apply a correction factor to this criterion to reduce the likelihood of Type I error. We corrected the *p*-value for determining statistical significance, over the number of hypotheses tested ($n = 24$), to the more conservative threshold where *p*-value < .002 would be classed as significant.

Analysis: As detailed in our pre-registered analysis plan, the start date (i.e., the number of months since the first UK lockdown) was included as a fixed-effect covariate. However, despite indicating a plan to model how this this variable interacted with other variables of interest, we chose not to do this to simplify the amount of statistical analysis in the absence of clear hypotheses concerning this parameter.

2.2 Participants

The sample initially consisted of 112 older adults (62 female, 50 male) aged 60-82 ($M = 70.08$, $SD = 5.89$) both with ($N = 55$) and without ($N = 57$) self-reported hearing loss, and 121 younger adults (85 female, 36 male) aged 18-29 ($M = 20.52$, $SD = 2.63$) with self-reported normal hearing. The required sample size was determined by an a-priori power analysis to detect a moderate effect size of Cohen's $f = .25$ at 90% power and alpha at .05, using GLIMMPSE software (Version 3) for calculating power and sample size for linear mixed models (Kreidler et al., 2013), as detailed in the associated preregistration (https://osf.io/67rwh/).

The sample was self-selected with participants recruited through advertisements on Lancaster University's Research Participation (SONA) System and Centre for Ageing Research Participant Panel, as well as the University of the Third Age, social media, and local print media. Inclusion criteria required that participants be right-handed, monolingual speakers of English, have normal or corrected to normal vision, and present no history of neurological, language, or speech disorders. Participants completed a cognitive screening questionnaire, the Self-Report version of the Short Form Informant Questionnaire on Cognitive Decline (IQCODE-SR), and participants scoring 3.65 or higher were excluded before participation, as this has been suggested as an appropriate cut-off (Jansen et al., 2008), where scores >3.65 indicate potential cognitive decline. The study was approved by Lancaster University Faculty of Science and Technology Research Ethics Committee (Reference: FST20091).

2.2.1 Participant Attrition

At month 12, the sample consisted of 165 participants, an attrition rate of 29.18%. At this time point, there were 58 younger adults (36 female, $M^{\text{AGE}} = 20.90$), and 107 older adults (59 female, $M^{\text{AGE}} = 70.11$). Due to attrition, there were missing datapoints across the months, which are detailed in the Supplementary Materials (Table A).

2.3 Materials

2.3.1 Self-Report Predictor Measures

a) Hearing Status

Participants were asked to self-report any clinical or perceived hearing loss, using a single item question: "Do you have any hearing disorders or hearing loss?". Response options included "life-long hearing loss", "age-related hearing loss", "other hearing disorder", or "no hearing loss". All younger adults reported no hearing loss, as required for study participation. Only older participants who either had no hearing loss or experienced acquired hearing loss in later life were able to participate, as we were primarily interested in age-related hearing loss rather than lifelong hearing loss or deafness. As such, any older adults who had experienced life-long deafness or hearing loss were ineligible and any who selected the 'other' category were asked further questions about their hearing to check for eligibility.

These data were used to group older adults into two hearing status groups: age-related hearing loss (herein *ARHL*) or no hearing loss. For older adults, 57 reported no hearing loss (M^{AGE} = 68.70, *SD* = 5.58), and 55 reported having ARHL (M^{AGE} = 71.51, *SD* = 5.92). Of those who reported having ARHL, 31 reported being bilateral hearing aid users, and 5 reported being unilateral users.

b) Loneliness

Loneliness was measured using two questionnaires: the Lubben Social Network Scale (LSNS-6) (Lubben et al., 2006) and the UCLA Loneliness Scale Version 3 (UCLA-LS3) (Russell, 1996). The LSNS-6 is a six-item questionnaire used to assess an individual's perception of social support available to them and frequency of contact with their social networks. An example question is "how many relatives did you see or hear from at least once a month?". Participants responded using a six-point scale containing the following choices: "none", "one", "two", "three or four", "five to eight", or "nine or more". The questionnaire is reported to have good reliability (Cronbach's α = .83) in older adult populations (Lubben et al., 2006). The UCLA-LS3 is a 20-item questionnaire used to assess feelings of loneliness and disconnection from others. An example question is "how often do you feel alone?", and "how often did you feel that you lacked companionship?". Participants respond using a four-point rating scale containing the following choices: never, rarely, sometimes, or always. The questionnaire has been shown to have high reliability, in terms of internal consistency (Cronbach's α ranging from .89 to .94) and test-retest reliability (r = .73), across age ranges (Russell, 1996). Two questionnaires were employed here to ensure that the index captured both social network size (social loneliness), and feelings of loneliness (emotional loneliness). By assessing both constructs, we ensure that we capture multiple constructs of loneliness that may have been affected during the pandemic. A composite measure of loneliness was created by standardising the total scores within each questionnaire and then calculating the mean of the total scores on each measure, per person, with higher scores indicating greater loneliness.

The test-retest reliability for the loneliness composite across the 12 time points of data collection was estimated with intraclass correlation coefficients (ICCs) using the 'psych' package in R (Revelle, 2024). ICCs were conducted on the data after influential outliers were removed for both linear mixed effects models (see details of this procedure in the Results section), in which either global cognition or auditory function was the outcome of interest, because different data points may have been excluded as influential data points across the two models. We report the results of two-way mixed-effects models for absolute agreement, ICC(2,1), and consistency, ICC(3,1). For the data included in the global cognition model and in the auditory function model, the estimated agreement was .90, 95% confidence interval (CI) = [.88, .92], and the estimated consistency was .90, 95% CI = [.88, .92]. The loneliness composite was found to have good internal consistency across the 12 time points of data collection (Koo & Li, 2016).

c) Depression

Depression was measured using the Beck Depression Inventory (BDI-I) (Beck et al., 1961). The BDI-I is a 21-item questionnaire used to evaluate the severity of depressive symptoms experienced by a participant over the previous week. For each item, the participant selected one of four statements which range in intensity, each scored on a scale from 0 to 3. For example, “I do not feel sad” (0), “I feel sad” (1), “I am sad all the time and I can’t snap out of it” (2), or “I am so sad or unhappy that I can’t stand it” (3). The questionnaire has been shown to have high reliability (Cronbach’s $\alpha < .75$) and validity (Beck et al., 1988; Richter et al., 1998). The measure of depression was created by calculating the total score, with higher scores indicating greater depressive symptoms.

We estimated test-retest reliability for the depression scores across the 12 time points of data collection with ICCs in R using ‘psych’ (Revelle, 2024). For the data included in the global cognition model, the estimated agreement was .77, CI = [.73, .80], and the estimated consistency was .77, CI = [.73, .80]. For the data included in the auditory function model, the estimated agreement was .76, CI = [.73, .80], and the estimated consistency was .77, CI = [.73, .80]. The depression measure was found to have good internal consistency (Koo & Li, 2016).

d) Auditory and Lifestyle Engagement

A 10-item self-report questionnaire measured engagement in auditory and lifestyle activities (Slade et al., 2023). Participants estimated how many hours they spent doing certain activities in an average week in the previous month on a scale of 0-50 hours.

Auditory engagement was measured using the first seven items, which measured how much time participants estimated they spent doing auditory activities across active (e.g., in-person or online socialising) and passive listening domains (e.g., listening to audiobooks). The questionnaire assessed three factors: items 1-3 assessed in-person communicative auditory engagement; items 4-5 assessed online communicative auditory engagement; and items 6-7 assessed online non-communicative auditory engagement. The questionnaire items were weighted based on the level of auditory engagement they were designed to assess. The score obtained items 1-3 for in-person communication, was multiplied by 0.3. The score from items 4-5 for remote communication, was multiplied by 0.2. The score from items 6-7 for non-communication activities was multiplied by 0.1. The decision to employ these weightings was made a-priori and preregistered and was designed to ensure that activities which involved greater in-person communication were given greater importance in the total score derived for this measure. The measure intended to tap into the auditory and social exposures of the participants in the study during the pandemic, comprising both passive listening and socially active listening. Greater weighting is placed on more active, and thus more cognitively involved, auditory activities. The resulting scores were totalled to provide an auditory engagement score, with higher scores indicating greater auditory engagement.

We estimated test-retest reliability for the auditory engagement scores across the 12 time points of data collection with ICCs in R using ‘psych’ (Revelle, 2024). For the data included in the global cognition model and in the auditory function model, the estimated agreement was .61, CI = [.56, .65], and the estimated consistency was .61, CI = [.56, .65]. The auditory engagement measure was found to have moderate internal consistency (Koo & Li, 2016).

Lifestyle engagement was measured using the final three items of the engagement questionnaire, which measured the time participants estimated that they spent engaged in various lifestyle activities such as hobbies or sports. The total score obtained from the summed responses to the three items provided a total lifestyle engagement score with higher scores indicating greater lifestyle engagement, or participation.

We estimated test-retest reliability for the lifestyle engagement scores across the 12 time points of data collection with ICCs in R using ‘psych’ (Revelle, 2024). For the data included in the global cognition model, the estimated agreement was .66, CI = [.62, .71], and the estimated consistency was .67, CI = [.62, .71]. For the data included in the auditory function model, the estimated agreement was .67, CI = [.62, .71], and the estimated consistency was .67, CI = [.63, .71]. The lifestyle engagement measure was found to have moderate internal consistency (Koo & Li, 2016).

2.3.2 Outcome Measures

a) Global Cognition

Global cognition was measured using a battery of four cognitive assessments: 1) the forward digit span (e.g., Wechsler Adult Intelligence Scale: WAIS (Wechsler, 1997)); 2) the backwards digit span (e.g., WAIS (Wechsler, 1997)); 3) the Deary-Liewald choice reaction time task (Deary et al., 2011); and 4) the Stroop colour-word test (Scarpina & Tagini, 2017; Stroop, 1935). These measures were employed to assess aspects of cognitive functioning (short-term and working memory, executive functioning, and processing speed) that may not necessarily be relevant to auditory cognitive performance during speech understanding but are typically assessed in standard assessments of cognitive decline; these aspects have shown age-related declines in previous research (Bopp & Verhaeghen, 2005; Folstein et al., 1975; Hobson, 2015). The scores calculated within each task were standardised (*z*-scored), then totalled to provide a composite score, following the preregistered protocol. Higher scores indicate better global cognitive performance.

We estimated test-retest reliability for the composite global cognition measure across the 12 time points of data collection with ICCs in R using ‘psych’ (Revelle, 2024). The estimated agreement was .56, CI = [.51, .61], and the estimated consistency was .56, CI = [.51, .61]. The global cognition measure was found to have moderate internal consistency (Koo & Li, 2016).

1. Forward digit span. This task was used to assess short-term memory (e.g., Wechsler, 1997). Participants were presented with eight sets of number sequences containing two sequences per set, in order of difficulty. The sequence length ranged from two digits in set one to nine digits in set eight. In a trial, participants saw a fixation cross (1sec), followed by each number in the sequence (1sec for each number), and then a response screen, where they were asked to type the number sequence. After the response, participants saw a blank screen for 1sec before the next trial began. The task ended if two sequences in a set were recalled incorrectly. The number of correctly recalled sequences was totalled, with higher scores indicating better short-term memory performance; scores ranged from 0-16.

2. Backward digit span. This task was used to assess working memory (e.g., Wechsler, 1997). Participants were presented with seven sets of number sequences containing two sequences per set, in order of difficulty. The sequence length ranged from two digits in set one to eight digits in set seven. In a trial, participants were presented with a fixation cross (for 1sec), followed by each number in the sequence (1sec for each number), and then a response screen, where they were asked to type the number sequence in the reverse order. After the response, participants saw a blank screen for 1sec before the next trial began. The task ended if two sequences in a set were recalled incorrectly. The number of correctly recalled sequences was totalled, with higher scores indicating better working memory performance; scores ranged from 0-14.

3. Deary-Liewald choice reaction time. This task was used to assess processing speed (Deary et al., 2011). Participants were presented with four on-screen squares in a horizontal line in a randomised order. In a trial, a target 'x' appeared in one of the four squares, and the participant used their number keys to indicate which box the target appeared in, where 1 indicated the box furthest left, and 4 indicated the box furthest right. The inter-trial interval varied between 1 and 3 secs, and there were 40 trials in total. The response time for when the target position was identified was recorded to provide a mean reaction time. The mean was reversed (i.e., raw score * -1) prior to calculating the global cognition composite so that better reaction time performance was indicated by higher numbers to be consistent with the other cognitive measures.

4. Stroop colour-word. This task was used to assess executive function (Cohen et al., 1990; Stroop, 1935). The task consisted of three conditions each containing 48 trials: words only (W), colours only (C), or colour-words (CW), resulting in 144 trials in total, with trials presented in condition blocks. In the words-only condition, participants were presented with a fixation cross (1sec) followed by a word (either RED, GREEN, YELLOW, or BLUE) in white text on a grey background. The participant was instructed to recall the word they saw by pressing one of the ‘R,’ ’G’, ’Y’, or ’B’ keys. The keys corresponded to colours sharing the same initial: R = red; G = green; Y = yellow; B = blue. In the colours-only condition, participants were presented with the repeated letter X in either red, green, yellow, or blue text. Participants were instructed to recall the colour of the Xs by pressing one of the ‘R,’ ’G’, ’Y’, or ’B’ keys. In the colour-words condition, participants were presented with the colour word (either RED, GREEN, YELLOW, or BLUE) printed in incongruent coloured text (e.g., the word BLUE printed in red colour). Participants were instructed to recall the colour of the text, not the word itself, by pressing one of the ‘R’, ’G’, ’Y’, or ’B’ keys. An interference score was calculated using a method adapted from Golden (1978). First, the number of correct responses out of a possible 48 in each condition was calculated (i.e., W, C, CW) and then the predicted colour-word score (PCW) was calculated, as below:

$$\mathrm{PCW} = \frac{48}{\left(\frac{\left((48 \times \mathrm{W}) + (48 \times \mathrm{C})\right)}{(\mathrm{W} \times \mathrm{C})}\right)}$$

The PCW value is then subtracted from participant’s score in the incongruent colour-words condition to provide an interference score, with higher scores indicating better ability to inhibit interference: Interference score = CW - PCW

b) Auditory Function

Auditory function was measured using two assessments: 1) Speech, Spatial and Qualities of Hearing scale short version (SSQ-12, Noble et al., 2013); 2) An online speech-in-noise perception (SPiN) test, based on the Bamford-Kowal-Bench Speech-in-Noise test (BKB-SIN, Etymotic Research). The scores calculated within each task were standardised (*z*-scored) then totalled to provide a composite score, following the preregistered protocol. Higher scores indicate better auditory function.

We estimated test-retest reliability for the composite auditory function scores across the 12 time points of data collection with ICCs in R using ‘psych’ (Revelle, 2024). The estimated agreement was .83, CI = [.80, .86], and the estimated consistency was .83, CI = [.80, .86]. The auditory function measure was found to have good internal consistency (Koo & Li, 2016).

a) Subjective Hearing Ability

Subjective hearing ability was measured using the SSQ-12 (Noble et al., 2013). This 12-item questionnaire assessed subjective hearing ability. Participants responded on a 10-point Likert scale, with 0 indicating very poor hearing ability and 10 indicating perfect hearing ability. The scores were averaged over all items with better hearing ability indicated by higher scores.

b) Speech-in-noise Perception (SPiN)

SPiN was assessed using an online behavioural test (based on the Bamford-Kowal-Bench Speech-in-Noise test: BKB-SIN, Etymotic Research). Before the task, participants were asked to adjust their volume to a level that was audible but comfortable. To do this, sample sentences were presented at the highest overall level that would be presented during the test (fixed at 70 dB HL), and participants could then manually adjust their volume in response to these sentences. Once participants were happy that the volume was at a loud but comfortable level, this volume was fixed for the entire test. The speech-in-noise stimuli consisted of target sentences from the IEEE (or Harvard) corpus spoken by a British-English male, in the presence of four-talker babble. The babble was created from the IEEE sentences, all voiced by a British-English male, in MATLAB (The MathWorks Inc., 2024). The Praat software application (Boersma & Weenink, 2022) was used to combine the speech with different levels of babble noise to create 10 signal-to-noise ratios (SNRs) ranging from -6 dB SNR to +21 dB SNR, in 3 dB steps, with four trials at each SNR. Therefore, the task consisted of 10 blocks, each containing four trials. The trials were ordered from most easy (e.g., +21 dB SNR) to most difficult (e.g., -6 dB SNR) to represent an equivalent process as employed in the clinical standard speech-in-noise assessment (BKB-SIN: Etymotic Research), on which this online task was based. The scripts used to create the stimuli can be accessed from the associated OSF repository (https://osf.io/67rwh/).

Participants were instructed to wear headphones or earphones during the task. In a trial, participants saw a fixation cross (1sec), then heard a sentence, after which they were asked to type the sentence in a response window. In each sentence, there were five pre-determined target words, each worth a point if correctly recalled. The points awarded in each SNR block were averaged across trials to create a mean score per SNR block. The test scoring method was based on the formula employed in the BKB-SIN (Etymotic Research). This scoring formula is derived from the Tillman-Olsen method (Tillman & Olsen, 1973) and was adapted for this online task to estimate the SNR required for a person to identify 50% of target words correctly (SNR-50). This calculation is based on that used for calculating spondee thresholds in a speech-in-noise task in which the SNR increases in 2 dB steps and two key words need to be identified per trial (BKB-SIN Manual, Etymotic Research). The calculation was adapted to account for the five key words per 3 dB step in this task:

$$\text{SNR-50} = 21 + 1.5 + (2 \times Y) - A$$

Wherein: 21 refers to the starting SNR level; 1.5 is half the step size; 2 is the number of additional pre-determined target words in each trial above the step size (i.e., 5 key words – 3 dB steps = 2); Y is the number of SNR blocks where the participant's mean score was greater than 2; and A is the sum of the participant's mean scores across all SNR blocks. The score was reversed prior to calculating the auditory function score, so that a lower SNR50 would indicate poorer performance.

2.4 Procedure

Each participant was contacted through email, where they were also asked to confirm their eligibility to participate. Data were collected remotely from the participant using online platforms that controlled the presentation of experimental stimuli and collected participants' responses: Qualtrics (Qualtrics, Provo, UT) was used to collect self-report data, and PsychoPy3 (Peirce et al., 2019) in combination with the hosting platform Pavlovia (Bridges et al., 2020) was used to collect behavioural responses. Participants were provided with URL links to the self-report measures, as well as individual links to each of the behavioural tasks. They completed the measures and tasks in the following order: 1) self-report measures; 2) forward digit span; 3) backward digit span; 4) choice reaction time; 5) Stroop colour-word; 5) speech-in-noise test. In the case of a technical issue, participants were asked to move onto the next task while the researcher resolved the potential issue. The participant was informed that they could take breaks between but not during tasks and were asked to complete all questionnaires and tasks on the same day where possible. The date of participation was recorded. After completing all measures, the participant was provided with follow-up dates for completing the measures again. Participants were then contacted after 4 weeks to repeat the questionnaires and tasks.

2.5 Statistical Analysis

Data pre-processing and analyses were conducted in R (R Core Team, 2022). To determine the effect of the predictors on hearing and cognitive outcomes, analyses using linear mixed effects models were conducted in R using 'lme4' (Bates et al., 2015) and *p*-values were derived using 'lmerTest' (Kuznetsova et al., 2017). To test the hypotheses, two linear mixed effects models were conducted. Linear mixed effects models are appropriate for the analysis of data over time. They are sometimes considered preferrable over alternatives, such as cross-lagged panel or latent change score models, due to their ability to handle missing data at random across time points (Ghisletta et al., 2015; McNeish & Matta, 2018); and reliance on fewer unknown assumptions (Lucas, 2023; Rohrer & Murayama, 2023).

We report the nominal *p*-values, but we use $p < .002$ as the statistical inference criteria, which reduces likelihood of Type I error by correcting the original alpha level ($p < .05$) over the number of hypotheses tested ($n = 24$).

2.5.1 Linear Mixed Effects Models

Two linear mixed effects models were conducted to investigate the effects of time and loneliness, as well as the interactions between additional variables with time and loneliness, separately on the two key outcome variables: global cognition and overall auditory function. The predictors in each of the two models were: time (from time points 1-12); loneliness (a composite measure from scores on the UCLA-LS3 and the LSNS-6); and the interactions between each additional variable (age, hearing status, depressive symptoms, auditory engagement, and lifestyle engagement) with time and loneliness. The start date (i.e., the number of months since the first UK lockdown) was included as a covariate. The outcomes in each of the models were: 1) global cognition, a composite score calculated from standardised scores on a forward digit span, a backward digit span, a choice reaction time task, and a Stroop task; 2) auditory function, a composite score calculated from standardised scores on a measure of self-reported hearing ability (SSQ-12) and a measure of speech-in-noise perception (SPIN). Following best practice guidelines for linear mixed effects analyses (Jaeger, 2008; Meteyard & Davies, 2020), the categorical predictor variables age group and hearing status were sum coded using the 'memisc' R package (Elff, 2024), and all other variables, measured on a continuous scale, were standardised (sample grand mean centered, and divided by sample SD) to ensure they were all on the same scale. Further, both models were random intercepts-only models, incorporating estimation of the variance associated with random between-participants in intercepts. A random slopes model was inappropriate because between-participants variation in the slopes of the effects of by-participants individual differences are not identifiable, given the study design (Barr et al., 2013).

2.5.1.1 Influential Observations and Model Assumptions

Influential data points were investigated using Cook's distance to detect any data points with a Cook's distance greater than 3 times the mean Cook's distance. For the global cognition model, 109 data points (of 2796 data points; 4.22% of the data) were flagged as influential. For the auditory function model, 145 data points (of 2796; 5.19% of the data) were flagged as influential. We investigated the effect of the removal of influential data points by fitting models without these data. For both the global cognition and auditory function models, removal of these data had no effect on statistical interpretation of the model results. We then removed influential data points for analyses. This is because the models without influential observations are likely to be less biased, as model outcomes are not as bound to specific (influential) sample data points. Across both models, the data met assumptions for linearity, homoscedasticity, and normality of residuals, and there was no multicollinearity among the variables (variance inflation factors ≤ 1.57 for the global cognition model and ≤ 1.54 for the auditory function model).

2.5.1.2 Model Fitting and Comparison

[Table 2 here]

To determine best fit and justify the inclusion of random effects and interaction effects across our models, we compared models by obtaining the Akaike Information Criterion (AIC; Akaike, 1998) for various model specifications. The AIC was used as the comparison measure, because the criterion does not rely on the assumption that the true model is among the candidate models, which some researchers argue can never be the case (Burnham & Anderson, 2004). Across all models, the outcome variable (indicated by Y) was either Global Cognition or Auditory Function. For the global cognition models, the lower AIC value indicated that Model 1 was a better fit (see Table 2). Therefore, the data for the full global cognition model are reported here.

For the auditory function models, the lower AIC value indicated that Model 1 was a better fit compared to Model 3 and 4 (see Table 2). However, Model 2 offered a lower AIC than the full model. Despite this, a comparison of these two models (Model 2: main effects vs. Model 1: full model) indicated that the likelihood ratio test statistic was not significant (χ^2 = 16.487, df = 10, p = .087), suggesting that neither model was better able to explain more variance. Therefore, the data for the model driven by our hypotheses, the full auditory function model, are reported here.

3. RESULTS

3.1 Descriptive Statistics

Tables 3 and 4 provide the means and standard deviations observed in older (OA) and younger adults (YA) for each variable of interest across the two linear mixed effects models. These statistics are represented across time points 3, 6, 9, and 12.

[Table 3 here]

[Table 4 here]

3.2 Linear Mixed Effects Models

3.2.1.3 Model Results

Results for the global cognition model are reported in Table 5. We calculated marginal and conditional R^2 according to the approach set out by Nakagawa et al. (2017: using the 'performance' package (Lüdecke et al., 2021)). The fixed effects explained 6.5% of the variance in the data, and 57.4% was explained by both fixed and random effects. Further, semi-partial R^2 statistics were calculated for each fixed predictor using the approach set out by Nakagawa et al. (2013: using the 'r2glmm' package (B. Jaeger, 2017)). Of the predictors of interest for the primary and secondary hypotheses, the interaction between age and time explained 1.1% of the variance in the data, loneliness explained 0.1% of the variance, the interaction between loneliness and depression explained 0.2% of the variance, and the interactions between loneliness and age, between loneliness and auditory engagement, and loneliness and lifestyle engagement each explained 0.1% of the variance.

[Table 5 here]

Results for the auditory function model are reported in Table 6. Marginal and conditional R^2 values indicated that the fixed effects explained 30.5% of the variance in the data, and 83.5% was explained by both fixed and random effects. Semi-partial R^2 statistics indicated that, of the predictors of interest for the primary and secondary hypotheses, loneliness explained 1.5% of the variance in the data, the interaction between loneliness and hearing status explained 0.7% of the variance, time explained 0.1% of the variance, and the interaction between loneliness and age explained a further 0.1% of the variance.

[Table 6 here]

3.2.1.4 Primary Hypotheses

There was no significant main effect of time [$\beta = -0.009$, $t(1892.72) = -0.49$, $p = .624$], nor a main effect of loneliness [$\beta = -0.031$, $t(949.22) = -0.69$, $p = .490$] on cognitive function. These data do not support H1a or H1b, which predicted that global cognition would worsen with time and with increased loneliness. There was also no significant main effect of time [$\beta = 0.028$, $t(1835.43) = 2.42$, $p = .016$] on auditory function at the $p < .002$ criterion level, providing no support for H2a, which predicted that auditory function would decrease with time. There was, however, a significant main effect of loneliness [$\beta = -0.135$, $t(1675.49) = -4.04$, $p < .001$] on auditory function, providing support for H2b, which predicted that auditory function would decrease with increased loneliness.

3.2.1.5 Secondary Hypotheses

There was a significant interaction effect between time and age group on global cognition [$\beta = 0.133$, $t(1918.58) = 6.76$, $p < .001$]. The shape of the interaction is inconsistent with hypothesis H3a, which predicted that any negative change in cognition with time would be greater for older adults. Instead, we find that the negative change in cognition over time only occurs in younger adults, while an unexpected positive change in cognition over time is observed in older adults (see Figure 1).

[Figure 1 here]

Despite the differing association between time and global cognition in different age groups, the effect of the interaction between loneliness and age group on global cognition was not significant [$\beta = 0.036$, $t(983.90) = 0.78$, $p = .434$]. These data do not support H3b, which predicted that older adults would show more negative changes in cognition (than younger adults) with increased loneliness. There were also no significant interaction effects between time and hearing status [$\beta = -0.026$, $t(1869.31) = -1.34$, $p = .179$] or between loneliness and hearing status [$\beta = 0.016$, $t(84049) = 0.31$, $p = .755$] on global cognition; providing no support for hypotheses H3c or H3d, which predicted that older adults with hearing loss would show increased negative changes in cognition with increased time and increased loneliness.

Similarly, in the model of auditory function outcomes, we observed no significant interaction effects between time and age [$\beta = 0.011$, $t(1864.00) = 0.87$, $p = .387$] or between loneliness and age [$\beta = 0.025$, $t(1739.28) = 0.76$, $p = .451$], providing no support for hypotheses H4a or H4b which predicted that older adults would show poorer auditory function with increased time and increased loneliness. There was also no significant interaction effect between time and hearing status [$\beta = -0.005$, $t(1837.49) = -0.40$, $p = .687$] on auditory function, providing no support for hypothesis H4c which predicted that older adults with hearing loss would show increased negative changes in auditory function with increased time. Further, using $p < .002$ as the inferential statistical criterion, there was no significant interaction effect between loneliness and hearing status [$\beta = -0.093$, $t(1630.03) = -2.52$, $p = .012$] on auditory function, providing no support for hypotheses H4b, which predicted that older adults with hearing loss would show increased negative changes in auditory function with increased loneliness.

For depressive symptoms, we found no significant interaction effects between depression and time nor between depression and loneliness on cognitive function [$ps > .002$].

Similarly, we found no significant interaction effects between depression and time nor between depression and loneliness on auditory function [*p*s > .002]. These data do not support hypotheses H5a – H5d, which predicted that participants with increased depressive symptoms would show increased negative changes in cognitive and auditory function with increased time and increased loneliness.

For auditory engagement, we found no significant interaction effects between engagement in auditory activities and time nor between engagement in auditory activities and loneliness on global cognition [*p*s > .002]. Similarly, we found no significant interaction effects between engagement in auditory activities and time nor between engagement in auditory activities and loneliness on auditory function [*p*s > .002]. These data provide no support for hypotheses H6a – H6d, which predicted that participants with lower engagement in auditory activities would show increased negative changes in cognitive and auditory function with increased time and increased loneliness.

For lifestyle engagement, we found no significant interaction effects between engagement in lifestyle activities and time nor between lifestyle engagement and loneliness on global cognition [*p*s > .002]. Similarly, we found no significant interaction effects between engagement in lifestyle activities and time nor between lifestyle engagement and loneliness on auditory function [*p*s > .002]. These data do not support hypotheses H7a – H7d, which predicted that participants with lower engagement in lifestyle activities would show increased negative changes in cognitive and auditory function with increased time and increased loneliness.

3.2.1.6 Exploratory Analyses

We also report whether any of the predictor variables or covariates included in the linear mixed effects models showed a significant main effect on either global cognition or auditory function. Despite initially not hypothesising any main effects of these predictors (age group, hearing status, depression, auditory engagement, and lifestyle engagement), they may affect hearing or cognitive outcomes. We also included how many months had passed since the first lockdown when each person participated as a covariate, which we will explore as a main effect.

For the linear mixed effects model predicting global cognition, none of these main effects were statistically significant, see Table 5. For the linear mixed effects model predicting auditory function, see Table 6, there was a significant main effect of Hearing Status [$\beta = -0.586$, $t(225.69) = -8.53$, $p < .001$, Cohen's $d = -1.13$], whereby older adults who reported having hearing loss showed significantly poorer auditory function than those who did not report having hearing loss (both older and younger adults).

4. DISCUSSION

4.1 Primary hypotheses: The effect of time and loneliness on cognitive and auditory function.

We observed no significant effect of time nor loneliness on global cognitive function. This finding was unexpected because this research took place during a time of reduced social contact, which was predicted to effect both the time and loneliness variables, and thus cognitive performance. Previous research indicates that maintaining social contact is preventative against dementia through maintaining and strengthening cognitive reserve (Livingston et al., 2024). For example, increased contact with friends is associated with better cognitive outcomes on a global cognitive function measure (Sommerlad et al., 2019). The contradictory findings may be in part due to differences between measurements of social contact employed in previous research, and our measure of self-reported loneliness. The loneliness composite we employed comprised both social and emotional loneliness, considering both perceptions of social networks and emotional support. A previous meta-analysis investigating the associations between loneliness and risk of dementia found that risk of dementia was increased with poor social engagement and poor social networks, but not with increased loneliness (Penninkilampi et al., 2018). Considering this, our use of a composite self-report measure that comprised both these components (social and emotional loneliness) may have diluted our findings, obscuring any trends or contributions of the individual sub-components.

Further, it is possible that the timeframe employed in this study time (i.e., our 48-week testing period) was not long enough to capture the effect of social distancing or loneliness on cognitive outcomes. In another study, relationships between loneliness and all cause dementia were observed in a 20-year follow up (Sundström et al., 2020). Additionally, in previous studies, a clinical measure of dementia or Alzheimer's Disease was employed (Livingston et al., 2024; Penninkilampi et al., 2018; Sundström et al., 2020). It is possible that associations between loneliness and cognition only occur in populations with clinically significant memory declines, which were not captured within our research. For example, in a meta-analysis, loneliness was found to be associated with increased risk of Alzheimer's Disease and dementia but was not associated with mild cognitive impairment (Qiao et al., 2022).

Interestingly, our findings are in line with a similar previous study conducted during the COVID-19 pandemic. The researchers found no significant associations between loneliness (as measured similarly with both the UCLA-LS3 and the LSNS-6) and behavioural tests of cognitive performance (Nogueira et al., 2022). However, they did observe significant associations between loneliness and self-reported cognitive function, which may indicate that participants perceived more subtle changes in their memory during the pandemic which were not sensitive to behavioural testing. The relationship between psychosocial factors, including feelings of loneliness, and cognition is clearly complex. Previous researchers have suggested that the association may be bidirectional (Yin et al., 2019), or that cognition may affect loneliness outcomes but not the other way around (McHugh Power et al., 2020), or may only occur significantly in specific populations (Zhou et al., 2019).

We observed a significant main effect of loneliness on auditory function; increased loneliness was associated with poorer auditory function. Associations between social factors, loneliness and hearing difficulties are commonly reported (Bott & Saunders, 2021; Shukla et al., 2020). Hearing loss is thought to increase perceptions of loneliness through reduced social contact due to the demands of coping in challenging auditory environments. However, the effect of restricted social contact or enforced isolation on hearing outcomes is less well known; the pandemic could have theoretically exacerbated this relationship. The pandemic listening environment may have been incredibly challenging, due to increases in distance, use of face coverings (Tofanelli et al., 2022), and reliance on online communication. These factors may have increased listening difficulty and social withdrawal leading to increased auditory deprivation. Also, poorer auditory quality reduces the emotional information conveyed through the speech to the listener. Indeed, social distancing has been found to impact quality of communication and connection with others (Wood et al., 2024). In line with the “use it or lose it” view, a lack of auditory stimulation may affect auditory functioning.

However, we did not observe associations between time and auditory function, indicating that the time course of the pandemic, captured in this study, did not exacerbate hearing difficulties. It is possible that the pandemic created a unique situation in which some individuals felt speech understanding was easier or not vastly affected, which may have affected the self-reported part of our auditory composite measure. In another study, participants with cochlear implants felt less lonely and less isolated at home in a more manageable auditory environment; and they reported better speech understanding with little effort during the pandemic (Dunn et al., 2021).

The presence of an effect of loneliness on auditory functioning, but not cognitive functioning is interesting, given that some previous research indicates a relationship between feeling lonely and poorer cognition (Cardona & Andrés, 2023). However, it is possible that if previous research employs cognitive assessments in the auditory modality (as is traditional for standardised cognitive assessments e.g. MoCA and MMSE) then outcomes may be affected by hearing acuity, leading to over estimation of cognitive decline, or poorer cognitive performance due misheard stimuli or instructions rather than cognitive factors (Füllgrabe, 2020a, 2020b; Goodwin et al., 2021). However, this study employed cognitive assessments in the visual modality only, enabling the isolation of cognitive ability from hearing acuity or speech perception.

4.2 Secondary hypotheses: The interaction effects between time or loneliness and additional variables of age, hearing status, depression, engagement in auditory and lifestyle activities on cognitive or hearing function.

In this study, we observed no significant interaction effects between time nor loneliness and additional variables of age, hearing status, depression, engagement in auditory and lifestyle activities on auditory function. It is notable that while the interaction between hearing status and loneliness was not significant at the $p < .002$ level, it would have reached significance at the $p < .05$ level. The trend indicates that individuals with higher self-reported loneliness showed poorer auditory function. In exploratory correlations, the trend was strongest amongst older participants with hearing loss (R = -.33) but still present amongst the remaining sample with self-reported normal hearing (R = -.16). However, the effect size for this interaction was very small (Cohen's d = .12), and the interaction explained only 0.7% of the variance data.

We also found no significant interaction effects between time nor loneliness and additional variables of hearing status, depression, engagement in auditory and lifestyle activities on global cognition. Global cognition was also not affected by any interaction effects between loneliness and age. However, there was a significant interaction between time and age, indicating interesting differences in the effect of time on cognitive performance across the different age groups. The effect size for this interaction effect on global cognition was small-moderate (Cohen's d = .31). Whilst older adults showed improved performance over time, younger adult performance worsened. A possible explanation for this is motivational differences in younger and older listeners, which may affect how they engage in cognitive tasks.

There is evidence from previous research that age-related differences in motivation effect effort investment in cognitive tasks (Ennis et al., 2013). The authors found that older adults were more influenced by the importance of performing well on cognitive tasks, relative to younger adults. Several reasons may underpin such age-related differences in task motivation, or in motivation to participate in research more generally. In one study, older adults were found to be motivated by the desire to understand more about their health and gain cognitive benefit (Carr et al., 2022); such motivators may arise due to increased concerns about health and memory as we age. Researchers also perceive motivational differences amongst participants; a surveyed group of researchers (n = 88) believed older, vs. younger, adults to be more motivated participants who take part to learn about their cognitive health, further science, and out of curiosity, rather than for course credits or monetary compensation favoured by younger adults (Ryan & Campbell, 2021). Of course, such generalisations do not apply across all older and younger adults, with many factors influencing motivation. Indeed, age, employment status, and previous participation have been found to underpin the motivations to take part in research (Carr et al., 2022). Importantly, psychological factors also affect motivation; depressive symptoms are found to negatively impact reward-seeking and motivational behaviour (Franzen & Brinkmann, 2016). This is important as previous research suggests that younger adults consistently reported increased psychological distress and reduced wellbeing during the pandemic, compared to older adults (Best et al., 2023). These age-related differences may explain the differences in cognitive performance as well as increased attrition rate observed in the younger cohort involved in this research study. Compared to the older adult sample, of which only 10 didn't participate at time point 12, 65 younger adults dropped out by time point 12.

4.3 Exploratory analyses: The main effects of age, hearing status, depression, engagement in auditory and lifestyle activities, or months since lockdown on cognitive or auditory function.

Of these variables, there was only a significant main effect of hearing status on the outcome of auditory function, wherein older adults who self-reported having ARHL displayed poorer auditory function than their peers, and younger adults, who did not report having hearing loss. The effect size for this hearing status effect on auditory function was large (Cohen's $d = 1.13$). This indicates that the online measures of auditory function may be sensitive to detecting hearing difficulty.

4.4 Limitations and future directions

Understanding the associations between psychosocial factors such as loneliness and age-related changes in hearing and cognitive function is important for identifying individuals at risk of loneliness and health declines, and to design appropriate interventions. This study investigated the effect of time exposed to the COVID-19 pandemic related social restrictions on cognitive and auditory outcomes.

The UK experienced vast changes across the pandemic period, including local lockdowns, tiered restrictions, and incentives like the "Eat Out to Help Out Scheme" (HM Revenue & Customs, 2020), as well as individuals engaging in differing levels of compliance. Additionally, participants will have likely been affected differently depending on whether they were experiencing COVID-19 symptoms, as well as variances in their living, work and study situations across the period. As such, there is variation across the study, which may have affected the linearity of the time variable and the outcomes. Additionally, the study may be limited by reliance on a self-reported measure of social and emotional loneliness. Admitting to feeling lonely can be incredibly stigmatising (Department for Culture Media & Sport, 2023), thus leading to biases in the measure.

Further, it is possible that results were biased through the recruitment of a self-selected participant sample consisting of active, and socially engaged older adults, who potentially feel less impacted by pandemic-related restrictions or guidance. Factors such as computer-literacy, social contacts, or socioeconomic position, may play a role in mitigating feelings of loneliness, isolation, or even cognitive decline in our sample (Cotten et al., 2013; Fakoya et al., 2020). The online nature of this research study required that participants had access to email, internet connection, and a level of technical skill and digital literacy. It is probable that the participants were comfortable technology users and relatedly experienced higher levels of online social connection and auditory stimulation. It is important to note that the findings we observed may not generalise to a population of older adults with poorer digital literacy or reduced access to technology; such individuals were likely more significantly affected by pandemic-related restrictions which may have resulted in changes to their hearing or cognitive function, which we were not able to capture in this study. This highlights a potential issue for online research, in that sample recruitment may be biased to include participants who are online regularly, excluding those from different social or economic backgrounds. Importantly, research suggests that socioeconomic position (SEP), and health inequalities, play a critical role in hearing health, with lower SEP significantly related to increased hearing loss (Tsimpida et al., 2019).

A further limitation that resulted from the self-selected sample is that most of the participants were female, and thus assigned sex was not balanced across the sample. This factor was also not included in analyses. Evidence suggest that the prevalence of hearing loss is higher in males, and importantly, both engagement with hearing healthcare or assistive devices, and the effects of hearing loss on other health outcomes may vary by sex (Mick et al., 2014; Reavis et al., 2022). To understand both sex and gender differences in hearing and hearing health outcomes, future researchers may wish to account for these factors. In future studies, researchers may also wish to account for SEP and additional biases within the participant sample. Further, research which includes an objective measure of social connection through quantifying social interactions in the real world would provide the next step in understanding the effect of socialisation on hearing and brain health. Additionally, researchers may want to consider the effect of positive social interventions in diverse populations on both cognitive and auditory outcomes to best understand future pathways for intervention for loneliness and associated health conditions in older age.

4.5 Conclusion

This study sought to understand the effect of loneliness and isolation experienced during a global pandemic on sensory and cognitive function across age ranges. During the COVID-19 pandemic, the public experienced social distancing, enforced isolation, and restricted means of communication, creating a changed auditory environment. Previous research suggests that reduced levels of auditory stimulation may affect both cognitive and auditory processing, however, in this sample we did not find consistent significant effects of such psychosocial factors on hearing and cognitive outcomes.

Instead, cognitive performance was found to be affected only by interactions between participant's age and time (improving over time in older adults and decreasing over time in younger adults). Auditory function, however, was associated with loneliness; across all time points poorer auditory function was related to increased self-reported loneliness. Auditory function was also affected by participant's hearing status (poorer auditory function was observed in older adults who self-reported having HL, compared to participants without HL).

Aside from the association between loneliness and auditory function, these data appear to show a lack of support for our preregistered hypotheses that auditory deprivation and reduced socialisation impact hearing and cognitive function. Nevertheless, the patterns observed in the data may be underpinned by motivational differences, learning effects, sample biases, or a lack of statistical power. Interesting trends indicate an effect of the relationship between loneliness and hearing status on auditory function, wherein, the correlation between increased loneliness and poorer auditory function is greater for older adults with hearing loss. Future research may wish to investigate these effects further, over a greater period, to understand how this relationship manifests. This would provide insight into how social and psychological factors relate to both cognitive and hearing function, to identify intervention pathways targeting HL and cognitive decline.

Data Availability Statement: All experimental scripts, stimuli, the study preregistration, and research data are openly available on the Open Science Framework (OSF) at https://osf.io/67rwh/

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5. REFERENCES

Age UK. (2019). *Later Life in the United Kingdom 2019*. https://www.ageuk.org.uk/globalassets/age-uk/documents/reports-and-publications/later_life_uk_factsheet.pdf

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Beck, A. T., Steer, R. A., & Carbin, M. G. (1988). Psychometric properties of the Beck Depression Inventory: Twenty-five years of evaluation. *Clinical Psychology Review*, *8*(1), 77–100. https://doi.org/10.1016/0272-7358(88)90050-5

Beck, A. T., Ward, C. H., Mendelson, M., Mock, J., & Erbaugh, J. (1961). An inventory for measuring depression. *Archives of General Psychiatry*, *4*(6), 561-571. https://doi.org/10.1001/archpsyc.1961.01710120031004

Best, R., Strough, J., & Bruine de Bruin, W. (2023). Age differences in psychological distress during the COVID-19 pandemic: March 2020 – June 2021. *Frontiers in Psychology*, *14*, 1101353. https://doi.org/10.3389/fpsyg.2023.1101353

Boersma, P., & Weenink, D. (2022). Praat: doing phonetics by computer [Computer program]. Version 6.2.23, retrieved 23 March 2020 from http://www.praat.org/

Bopp, K. L., & Verhaeghen, P. (2005). Aging and verbal memory span: A meta-analysis. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *60*(5), 223–233. https://doi.org/10.1093/geronb/60.5.P223

Bott, A., & Saunders, G. (2021). A scoping review of studies investigating hearing loss, social isolation and/or loneliness in adults. *International Journal of Audiology*, *60*(sup2), 30–46. https://doi.org/10.1080/14992027.2021.1915506

Bridges, D., Pitiot, A., MacAskill, M. R., & Peirce, J. W. (2020). The timing mega-study: comparing a range of experiment generators, both lab-based and online. *PeerJ*, *8*, e9414. https://doi.org/10.7717/peerj.9414

Burnham, K. P., & Anderson, D. R. (2004). Multimodel inference: Understanding AIC and BIC in model selection. *Sociological Methods and Research*, *33*(2), 261–304. https://doi.org/10.1177/0049124104268644

Cardona, M., & Andrés, P. (2023). Are social isolation and loneliness associated with cognitive decline in ageing? *Frontiers in Aging Neuroscience*, *15*, 1075563. https://doi.org/10.3389/fnagi.2023.1075563

Carr, D. C., Tian, S., He, Z., Chakraborty, S., Dieciuc, M., Gray, N., Agharazidermani, M., Lustria, M. L. A., Dilanchian, A., Zhang, S., Charness, N., Terracciano, A., & Boot, W. R. (2022). Motivation to engage in aging research: Are there typologies and predictors? *The Gerontologist*, *62*(10), 1466–1476. https://doi.org/10.1093/geront/gnac035

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*(3), 332–361. https://doi.org/10.1037/0033-295X.97.3.332

Cotten, S. R., Anderson, W. A., & McCullough, B. M. (2013). Impact of internet use on loneliness and contact with others among older adults: Cross-sectional analysis. *Journal of Medical Internet Research*, *15*(2), e39. https://doi.org/10.2196/jmir.2306

David, D., Zoizner, G., & Werner, P. (2018). Self-stigma and age-related hearing loss: A qualitative study of stigma formation and dimensions. *American Journal of Audiology*, *27*(1), 126–136. https://doi.org/10.1044/2017_AJA-17-0050

Dawes, P., Emsley, R., Cruickshanks, K. J., Moore, D. R., Fortnum, H., Edmondson-Jones, M., McCormack, A., & Munro, K. J. (2015). Hearing loss and cognition: The role of hearing aids, social isolation and depression. *PLOS ONE, 10*(3), e0119616. https://doi.org/10.1371/journal.pone.0119616

Deary, I. J., Corley, J., Gow, A. J., Harris, S. E., Houlihan, L. M., Marioni, R. E., Penke, L., Rafnsson, S. B., & Starr, J. M. (2009). Age-associated cognitive decline. *British Medical Bulletin, 92*(1), 135–152. https://doi.org/10.1093/bmb/ldp033

Deary, I. J., Liewald, D., & Nissan, J. (2011). A free, easy-to-use, computer-based simple and four-choice reaction time programme: The Deary-Liewald reaction time task. *Behavior Research Methods*, *43*(1), 258–268. https://doi.org/10.3758/s13428-010-0024-1

Department for Culture Media & Sport. (2023, June 12). *Loneliness Stigma Rapid Evidence Assessment (REA)*. GOV.UK. https://www.gov.uk/government/publications/research-exploring-the-stigma-associated-with-loneliness/loneliness-stigma-rapid-evidence-assessment-rea

Dhanda, N., Hall, A., & Martin, J. (2024). Does social isolation mediate the association between hearing loss and cognition in adults? A systematic review and meta-analysis of longitudinal studies. *Frontiers in Public Health, 12*, 1347794. https://doi.org/10.3389/fpubh.2024.1347794

Dunn, C. C., Stangl, E., Oleson, J., Smith, M., Chipara, O., & Wu, Y.-H. (2021). The influence of forced social isolation on the auditory ecology and psychosocial functions of listeners with cochlear implants during COVID-19 mitigation efforts. *Ear & Hearing*, *42*(1), 20–28. https://doi.org/10.1097/AUD.0000000000000991

Elff, M. (2024). *memisc: Management of Survey Data and Presentation of Analysis Results.* R package version 0.99.31.8. https://CRAN.R-project.org/package=memisc

Ennis, G. E., Hess, T. M., & Smith, B. T. (2013). The impact of age and motivation on cognitive effort: Implications for cognitive engagement in older adulthood. *Psychology and Aging*, *28*(2), 495–504. https://doi.org/10.1037/a0031255

Fakoya, O. A., McCorry, N. K., & Donnelly, M. (2020). Loneliness and social isolation interventions for older adults: a scoping review of reviews. *BMC Public Health*, *20*, 129. https://doi.org/10.1186/s12889-020-8251-6

Fitzhugh, M. C., Hemesath, A., Schaefer, S. Y., Baxter, L. C., & Rogalsky, C. (2019). Functional connectivity of Heschl's Gyrus associated with age-related hearing loss: A resting-state fMRI study. *Frontiers in Psychology*, *10*, 2485. https://doi.org/10.3389/fpsyg.2019.02485

Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). "Mini-mental state": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*(3), 189–198. https://doi.org/10.1016/0022-3956(75)90026-6

Franzen, J., & Brinkmann, K. (2016). Anhedonic symptoms of depression are linked to reduced motivation to obtain a reward. *Motivation and Emotion*, *40*(2), 300–308. https://doi.org/10.1007/s11031-015-9529-3

Füllgrabe, C. (2020a). On the possible overestimation of cognitive decline: The impact of age-related hearing loss on cognitive-test performance. *Frontiers in Neuroscience, 14*, 454. https://doi.org/10.3389/fnins.2020.00454

Füllgrabe, C. (2020b). When hearing loss masquerades as cognitive decline. *Journal of Neurology, Neurosurgery & Psychiatry, 91*(12), 1248–1248. https://doi.org/10.1136/jnnp-2020-324707

Golden, C. J. (1978). *Stroop Color and Word Test: A manual for clinical and experimental uses*. Stoelting Company.

Goodwin, M. V, Hogervorst, E., & Maidment, D. W. (2021). The impact of presentation modality on cognitive test performance for adults with hearing loss. *Alzheimer's & Dementia, 17*(12), e058571. https://doi.org/10.1002/alz.058571

Griffiths, T. D., Lad, M., Kumar, S., Holmes, E., McMurray, B., Maguire, E. A., Billig, A. J., & Sedley, W. (2020). How can hearing loss cause dementia? *Neuron*, *108*(3), 401–412. https://doi.org/10.1016/j.neuron.2020.08.003

Hajek, A., Riedel-Heller, S. G., & König, H. (2020). Perceived social isolation and cognitive functioning. Longitudinal findings based on the German Ageing Survey. *International Journal of Geriatric Psychiatry, 35*(3), 276–281. https://doi.org/10.1002/gps.5243

HM Revenue & Customs. (2020, July 15). *Get a discount with the Eat Out to Help Out Scheme*. GOV.UK. https://www.gov.uk/guidance/get-a-discount-with-the-eat-out-to-help-out-scheme#full-publication-update-history

Hobson, J. (2015). The Montreal Cognitive Assessment (MoCA). *Occupational Medicine*, *65*(9), 764–765. https://doi.org/10.1093/occmed/kqv078

Institute For Government. (2022, December 9). *Timeline of UK government coronavirus lockdowns and restrictions*. Institute for Government. https://www.instituteforgovernment.org.uk/data-visualisation/timeline-coronavirus-lockdowns

Jaeger, B. (2017). *r2glmm: Computes R Squared for Mixed (Multilevel) Models*. R package version 0.1.2. https://CRAN.R-project.org/package=r2glmm

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language*, *59*(4), 434–446. https://doi.org/10.1016/j.jml.2007.11.007

Jansen, A. P. D., van Hout, H. P. J., Nijpels, G., van Marwijk, H. W. J., Gundy, C., de Vet, H. C. W., & Stalman, W. A. B. (2008). Self-reports on the IQCODE in older adults: A psychometric evaluation. *Journal of Geriatric Psychiatry and Neurology*, *21*(2), 83–92. https://doi.org/10.1177/0891988707311558

Jayakody, D. M. P., Almeida, O. P., Speelman, C. P., Bennett, R. J., Moyle, T. C., Yiannos, J. M., & Friedland, P. L. (2018). Association between speech and high-frequency hearing loss and depression, anxiety and stress in older adults. *Maturitas*, *110*, 86–91. https://doi.org/10.1016/j.maturitas.2018.02.002

Kleiman, E. (2021). *EMAtools: Data Management Tools for Real-Time Monitoring/Ecological Momentary Assessment Data*. R package version 0.1.4. https://CRAN.R-project.org/package=EMAtools

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Kreidler, S. M., Muller, K. E., Grunwald, G. K., Ringham, B. M., Coker-Dukowitz, Z., Sakhadeo, U. R., Baron, A. E., & Glueck, D. H. (2013). GLIMMPSE: Online power computation for linear models with and without a baseline covariate. *Journal of Statistical Software*, *54*(10), 1–26. https://doi.org/10.18637/jss.v054.i10

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13). https://doi.org/10.18637/jss.v082.i13

Lara, E., Caballero, F. F., Rico-Uribe, L. A., Olaya, B., Haro, J. M., Ayuso-Mateos, J. L., & Miret, M. (2019). Are loneliness and social isolation associated with cognitive decline? *International Journal of Geriatric Psychiatry, 34*(11), 1613–1622. https://doi.org/10.1002/GPS.5174

Lawrence, B. J., Jayakody, D. M. P., Bennett, R. J., Eikelboom, R. H., Gasson, N., & Friedland, P. L. (2020). Hearing loss and depression in older adults: A systematic review and meta-analysis. *The Gerontologist*, *60*(3), 137–154. https://doi.org/10.1093/geront/gnz009

Lin, F. R., Ferrucci, L., An, Y., Goh, J. O., Doshi, J., Metter, E. J., Davatzikos, C., Kraut, M. A., & Resnick, S. M. (2014). Association of hearing impairment with brain volume changes in older adults. *NeuroImage*, *90*, 84–92. https://doi.org/10.1016/j.neuroimage.2013.12.059

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging*, *9*(3), 339–355. https://doi.org/10.1037/0882-7974.9.3.339

Littlejohn, J., Venneri, A., Marsden, A., & Plack, C. J. (2022). Self-reported hearing difficulties are associated with loneliness, depression and cognitive dysfunction during the COVID-19 pandemic. *International Journal of Audiology*, *61*(2), 97–101. https://doi.org/10.1080/14992027.2021.1894492

Livingston, G., Huntley, J., Liu, K. Y., Costafreda, S. G., Selbæk, G., Alladi, S., Ames, D., Banerjee, S., Burns, A., Brayne, C., Fox, N. C., Ferri, C. P., Gitlin, L. N., Howard, R., Kales, H. C., Kivimäki, M., Larson, E. B., Nakasujja, N., Rockwood, K., … Mukadam, N. (2024). Dementia prevention, intervention, and care: 2024 report of the Lancet standing Commission. *The Lancet*, *404*(10452), 572–628. https://doi.org/10.1016/S0140-6736(24)01296-0

Lubben, J., Blozik, E., Gillmann, G., Iliffe, S., von Renteln Kruse, W., Beck, J. C., & Stuck, A. E. (2006). Performance of an abbreviated version of the Lubben Social Network Scale among three European community-dwelling older adult populations. *The Gerontologist*, *46*(4), 503–513. https://doi.org/10.1093/geront/46.4.503

Luchetti, M., Terracciano, A., Aschwanden, D., Lee, J. H., Stephan, Y., & Sutin, A. R. (2020). Loneliness is associated with risk of cognitive impairment in the Survey of Health, Ageing and Retirement in Europe. *International Journal of Geriatric Psychiatry, 35*(7), 794–801. https://doi.org/10.1002/gps.5304

Lüdecke, D. (2024). *sjPlot: Data Visualization for Statistics in Social Science*. R package version 2.8.16. https://CRAN.R-project.org/package=sjPlot

Lüdecke, D., Ben-Shachar, M., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R package for assessment, comparison and testing of statistical models. *Journal of Open Source Software*, *6*(60), 3139. https://doi.org/10.21105/joss.03139

Maharani, A., Pendleton, N., & Leroi, I. (2019). Hearing impairment, loneliness, social isolation, and cognitive function: Longitudinal analysis using English Longitudinal Study on

Ageing. *The American Journal of Geriatric Psychiatry*, *27*(12), 1348–1356. https://doi.org/10.1016/j.jagp.2019.07.010

McHugh Power, J. E., Hannigan, C., Carney, S., Feeney, J., Kenny, R. A., Kee, F., & Lawlor, B. A. (2020). Lonely SARTs: loneliness and sustained attention in the Irish longitudinal study of aging. *Aging, Neuropsychology, and Cognition, 27*(2), 197–206. https://doi.org/10.1080/13825585.2019.1602705

Meteyard, L., & Davies, R. A. I. (2020). Best practice guidance for linear mixed-effects models in psychological science. *Journal of Memory and Language*, *112*, 104092. https://doi.org/10.1016/j.jml.2020.104092

Mick, P., Kawachi, I., & Lin, F. R. (2014). The association between hearing loss and social isolation in older adults. *Otolaryngology–Head and Neck Surgery*, *150*(3), 378–384. https://doi.org/10.1177/0194599813518021

Mick, P., Parfyonov, M., Wittich, W., Phillips, N., Guthrie, D., & Kathleen Pichora-Fuller, M. (2018). Associations between sensory loss and social networks, participation, support, and loneliness: Analysis of the Canadian Longitudinal Study on Aging. *Canadian Family Physician Medecin de Famille Canadien*, *64*(1), e33–e41. http://www.ncbi.nlm.nih.gov/pubmed/29358266

Motala, A., Johnsrude, I. S., & Herrmann, B. (2024). A Longitudinal Framework to Describe the Relation Between Age-Related Hearing Loss and Social Isolation. *Trends in Hearing*, *28*. https://doi.org/10.1177/23312165241236041

Munro, K. J., & Blount, J. (2009). Adaptive plasticity in brainstem of adult listeners following earplug-induced deprivation. *The Journal of the Acoustical Society of America*, *126*(2), 568–571. https://doi.org/10.1121/1.3161829

Murman, D. (2015). The Impact of Age on Cognition. *Seminars in Hearing, 36*(03), 111–121. https://doi.org/10.1055/s-0035-1555115

Nakagawa, S., Johnson, P. C. D., & Schielzeth, H. (2017). The coefficient of determination R2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *Journal of The Royal Society Interface*, *14*(134), 20170213. https://doi.org/10.1098/rsif.2017.0213

Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R2 from generalized linear mixed-effects models. *Methods in Ecology and Evolution*, *4*(2), 133–142. https://doi.org/10.1111/j.2041-210x.2012.00261.x

Noble, W., Jensen, N. S., Naylor, G., Bhullar, N., & Akeroyd, M. A. (2013). A short form of the Speech, Spatial and Qualities of Hearing scale suitable for clinical use: The SSQ12. *International Journal of Audiology*, *52*(6), 409–412. https://doi.org/10.3109/14992027.2013.781278

Nogueira, J., Gerardo, B., Silva, A. R., Pinto, P., Barbosa, R., Soares, S., Baptista, B., Paquete, C., Cabral-Pinto, M., Vilar, M. M., Simões, M. R., & Freitas, S. (2022). Effects of restraining measures due to COVID-19: Pre- and post-lockdown cognitive status and mental health. *Current Psychology*, *41*(10), 7383–7392. https://doi.org/10.1007/s12144-021-01747-y

Oosterhuis, E. J., Slade, K., May, P. J. C., & Nuttall, H. E. (2023). Toward an understanding of healthy cognitive aging: The importance of lifestyle in Cognitive Reserve and the Scaffolding Theory of Aging and Cognition. *The Journals of Gerontology: Series B*, *78*(5), 777–788. https://doi.org/10.1093/geronb/gbac197

Panouillères, M. T. N., & Möttönen, R. (2018). Decline of auditory-motor speech processing in older adults with hearing loss. *Neurobiology of Aging*, *72*, 89–97. https://doi.org/10.1016/j.neurobiolaging.2018.07.013

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Penninkilampi, R., Casey, A.-N., Singh, M. F., & Brodaty, H. (2018). The association between social engagement, loneliness, and risk of dementia: A systematic review and meta-analysis. *Journal of Alzheimer's Disease*, *66*(4), 1619–1633. https://doi.org/10.3233/JAD-180439

Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W. Y., Humes, L. E., Lemke, U., Lunner, T., Matthen, M., Mackersie, C. L., Naylor, G., Phillips, N. A., Richter, M., Rudner, M., Sommers, M. S., Tremblay, K. L., & Wingfield, A. (2016). Hearing impairment and cognitive energy: The Framework for Understanding Effortful Listening (FUEL). *Ear & Hearing*, *37*(1), 5–27. https://doi.org/10.1097/AUD.0000000000000312

Powell, D. S., Oh, E. S., Lin, F. R., & Deal, J. A. (2021). Hearing impairment and cognition in an aging world. *Journal of the Association for Research in Otolaryngology*, *22*(4), 387–403. https://doi.org/10.1007/s10162-021-00799-y

Qiao, L., Wang, G., Tang, Z., Zhou, S., Min, J., Yin, M., & Li, M. (2022). Association between loneliness and dementia risk: A systematic review and meta-analysis of cohort studies. *Frontiers in Human Neuroscience*, *16*, 899814. https://doi.org/10.3389/fnhum.2022.899814

R Core Team. (2022). *R: A language and environment for statistical computing* [Computer program]. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Ray, J., Popli, G., & Fell, G. (2018). Association of cognition and age-related hearing impairment in the English Longitudinal Study of Ageing. *JAMA Otolaryngology–Head & Neck Surgery*, *144*(10), 876. https://doi.org/10.1001/jamaoto.2018.1656

Revelle, W. (2024). *psych: Procedures for Psychological, Psychometric, and Personality Research*. R package version 2.4.6. https://CRAN.R-project.org/package=psych.

Richter, P., Werner, J., Heerlein, A., Kraus, A., & Sauer, H. (1998). On the validity of the Beck Depression Inventory. *Psychopathology*, *31*(3), 160–168. https://doi.org/10.1159/000066239

Royal National Institute for Deaf People (RNID). (2020). *Hearing Matters*. https://rnid.org.uk/wp-content/uploads/2020/05/Hearing-Matters-Report.pdf

Russell, D. W. (1996). UCLA Loneliness Scale (version 3): Reliability, validity, and factor structure. *Journal of Personality Assessment*, *66*(1), 20–40. https://doi.org/10.1207/s15327752jpa6601_2

Ryan, A. D., & Campbell, K. L. (2021). The ironic effect of older adults' increased task motivation: Implications for neurocognitive aging. *Psychonomic Bulletin & Review*, *28*(6), 1743–1754. https://doi.org/10.3758/s13423-021-01963-4

Scarpina, F., & Tagini, S. (2017). The Stroop Color and Word Test. *Frontiers in Psychology*, *8*, 557. https://doi.org/10.3389/fpsyg.2017.00557

Shukla, A., Harper, M., Pedersen, E., Goman, A., Suen, J. J., Price, C., Applebaum, J., Hoyer, M., Lin, F. R., & Reed, N. S. (2020). Hearing loss, loneliness, and social isolation: A systematic review. *Otolaryngology–Head and Neck Surgery*, *162*(5), 622–633. https://doi.org/10.1177/0194599820910377

Sin, E., Shao, R., & Lee, T. M. C. (2021). The executive control correlate of loneliness in healthy older people. *Aging & Mental Health, 25*(7), 1224–1231. https://doi.org/10.1080/13607863.2020.1749832

Slade, K., Davies, R., Pennington, C. R., Plack, C. J., & Nuttall, H. E. (2023). The impact of age and psychosocial factors on cognitive and auditory outcomes during the COVID-19 pandemic. *Journal of Speech, Language, and Hearing Research*, *66*(9), 3689–3695. https://doi.org/10.1044/2023_JSLHR-22-00703

Slade, K., Reilly, J. H., Jablonska, K., Smith, E., Hayes, L. D., Plack, C. J., & Nuttall, H. E. (2022). The impact of age-related hearing loss on structural neuroanatomy: A meta-analysis. *Frontiers in Neurology*, *13*. https://doi.org/10.3389/fneur.2022.950997

Sommerlad, A., Sabia, S., Singh-Manoux, A., Lewis, G., & Livingston, G. (2019). Association of social contact with dementia and cognition: 28-year follow-up of the Whitehall II cohort study. *PLOS Medicine*, *16*(8), e1002862. https://doi.org/10.1371/journal.pmed.1002862

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., Ewers, M., Franzmeier, N., Kempermann, G., Kremen, W. S., Okonkwo, O., Scarmeas, N., Soldan, A., Udeh-Momoh, C., Valenzuela, M., Vemuri, P., & Vuoksimaa, E. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's & Dementia*, *16*(9), 1305–1311. https://doi.org/10.1016/j.jalz.2018.07.219

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/h0054651

Sundström, A., Adolfsson, A. N., Nordin, M., & Adolfsson, R. (2020). Loneliness increases the risk of all-cause dementia and Alzheimer's Disease. *The Journals of Gerontology: Series B*, *75*(5), 919–926. https://doi.org/10.1093/geronb/gbz139

The MathWorks Inc. (2024). *MATLAB (R2024a)*. https://www.mathworks.com

Tillman, T. W., & Olsen, W. O. (1973). Speech audiometry. In J. Jerger (Ed.), *Modern developments in audiology* (2nd ed., pp. 37–74). Academic Press.

Tofanelli, M., Capriotti, V., Gatto, A., Boscolo-Rizzo, P., Rizzo, S., & Tirelli, G. (2022). COVID-19 and deafness: Impact of face masks on speech perception. *Journal of the American Academy of Audiology*, *33*(2), 98–104. https://doi.org/10.1055/s-0041-1736577

Tsimpida, D., Kontopantelis, E., Ashcroft, D., & Panagioti, M. (2019). Socioeconomic and lifestyle factors associated with hearing loss in older adults: A cross-sectional study of the English Longitudinal Study of Ageing (ELSA). *BMJ Open*, *9*(9), e031030. https://doi.org/10.1136/bmjopen-2019-031030

Waters, G. S., & Caplan, D. (2003). The reliability and stability of verbal working memory measures. *Behavior Research Methods, Instruments, & Computers*, *35*(4), 550–564. https://doi.org/10.3758/BF03195534

Wechsler, D. (1997). *Wechsler Adult Intelligence Scale (WAIS-3R).* The Psychological Corporation.

Wood, C., Guynes, K., Lugo, V., Baker, L., & Snowden, S. (2024). Pandemic impacts on communication and social well-being: Considerations for individuals who are D/HH. *Communication Disorders Quarterly*, *45*(4), 211–220. https://doi.org/10.1177/15257401231181506

Yin, J., Lassale, C., Steptoe, A., & Cadar, D. (2019). Exploring the bidirectional associations between loneliness and cognitive functioning over 10 years: the English longitudinal study of ageing. *International Journal of Epidemiology, 48*(6), 1937–1948. https://doi.org/10.1093/ije/dyz085

Zhou, Z., Mao, F., Zhang, W., Towne, S. D., Wang, P., & Fang, Y. (2019). The association between loneliness and cognitive impairment among older men and women in China: A nationwide longitudinal study. *International Journal of Environmental Research and Public Health, 16*(16), 2877. https://doi.org/10.3390/ijerph16162877

Figure 1. Marginal effects plot generated using 'sjPlot' (Lüdecke, 2024) showing the predicted values (95% CIs) for Global Cognition across timepoints (from 1-12) in younger (left-hand plot) and older adults (right-hand plot).

The supplemental file provides a table (Table A) detailing participant attrition rate.