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Effect of loneliness on social exclusion among older adults: A functional magnetic resonance imaging study

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ABSTRACT

Loneliness is a significant issue among older adults. However, few studies have explored the brain mechanisms underlying changes in social behavior related to loneliness among older adults. Therefore, this study aimed to examine how loneliness affects the response towards social exclusion among community-dwelling older people. The sample consisted of 37 older adults who made up the lonely ($n = 21$) and not-lonely control ($n = 16$) groups based on their scores on a loneliness scale. All participants underwent fMRI scanning whilst completing the classic Cyberball task. We found that the lonely group showed greater brain activation compared to those of the not-lonely group in response to the exclusion condition of the Cyberball task (versus inclusion condition), including the prefrontal lobes and anterior cingulate cortex. Based on the existing literature on Cyberball studies (including meta-analysis), the activations may represent a state of interoceptive reflection with a painful experience during the Cyberball task for the lonely older adults. The results contribute to improving our understanding of social experiences of older adults, and further unpack the potential negative consequences associated with loneliness.

1. Introduction

Loneliness can be understood as a subjective experience of lacking personally desired social relationships or social contacts. Nevertheless, in the literature, differences in definitions exist (Smith & Victor, 2019). This construct has been proposed to be a type of biological instinct for humans that signals problems with the status quo and motivates change (Masi et al., 2011). However, due to life changes or events resulting from ageing (e.g., physical deterioration and deaths of family or friends), people can develop negative thinking and mistrust of other people. In turn, they will become withdrawn and more hostile towards others, leading to chronic loneliness (Masi et al., 2011). Furthermore, loneliness can lead to significant damage to one's physical health and even pose mortality risks (Holt-Lunstad et al., 2010). Lonely older people are four to five times more likely to be re-admitted to the hospital within a year (Valtorta & Hanratty, 2012). Consequently, loneliness among older adults continues to be a pressing challenge facing developed countries and regions (Masi et al., 2011), and a recent meta-analysis has reported a prevalence rate of 32% for loneliness among community-dwelling older adults (Stegen et al., 2024). Despite the significance of this problem, there is a limited understanding of the brain mechanisms underlying any changes in social behavior related to loneliness among older adults.

An individual can feel lonely if he/she is being excluded from conversations, activities, and gatherings. Studies from European countries have shown that indicators of social exclusion can explain 15.1–21.5% of the variance in loneliness (Dahlberg et al., 2022). In contrast to social inclusion, social exclusion has been shown to consistently activate the left inferior orbito-frontal cortex, bilateral anterior insula, and the left anterior cingulate cortex, which are areas involved in attentional control and emotional processing (Cacioppo et al., 2013). Cacioppo et al. (2016)

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found that lonely and less-lonely young adults rated socially threatening stimuli (implying either social exclusion or loneliness) equally unpleasant and had similar reaction times to socially-related words. However, the two groups differed in their brain responses to the stimuli – the lonelier participants showed an earlier and more intensive response to the threatening pictures (Cacioppo et al., 2016). These studies highlight the importance of using a combination of self-report, behavioral, and fMRI measures when examining emotional experiences. However, the existing literature on social exclusion has focused primarily on children and young adults.

Cyberball, a virtual ball-toss game among multiple players, is a paradigm that is commonly used to study social exclusion. In the commonly adopted version by Eisenberger, Lieberman and Williams (Eisenberger et al., 2003), participants first experience a "normal" fair game (i.e., control condition), where they receive a virtual ball from two other "players" (virtual players controlled by a computer program), and can toss the ball back to either of these "players". After some time, the participant no longer receives the ball and is therefore socially excluded by the other "players" from the game (i.e., the experimental condition). Based on a recent meta-analysis of 53 studies by Mwilambwe-Tshilobo and Spreng (Mwilambwe-Tshilobo & Spreng, 2021), the Cyberball elicits activities partially overlapping with the default mode network, including the bilateral anterior cingulate cortex, left posterior cingulate cortex, right posterior insula, left inferior frontal gyrus, right superior frontal gyrus, and left occipital pole. Co-activations in the left parahippocampal gyrus, left inferior parietal lobule, right parahippocampal gyrus, left orbitofrontal cortex, left superior frontal gyrus, and left middle temporal gyrus were also reported.

There is emerging evidence showing that the socio-emotional needs of a person affect their response to social exclusion. People with chronic depression (versus healthy controls) experienced higher threats to their fundamental psychological needs during the Cyberball (Seidl et al., 2020). In another study on anxiety, people high on social anxiety were found to show greater activation in the posterior insula for social exclusion (than inclusion) on the Cyberball (Wang et al., 2019). In addition to studying clinical populations, studies have also explored the effects of risk factors on non-clinical populations. For example, people with a perception of being burdensome to others were slower to reciprocate social behaviors of ball-tossing during Cyberball and had more neural activations (in the ACC/dmPFC and MFG) in response to social exclusion (Le et al., 2020). Therefore, it appears that people with preexisting socio-emotional issues show hyperarousal when experiencing ostracism during a simulated social game such as the Cyberball. However, it should be noted that existing literature about social inclusion/exclusion using Cyberball mainly studied children, young or middle-aged adults.

Of the few studies that reported results of older adults' performance on the Cyberball, Wang et al. (Wang et al., 2020) examined the age differences in activations during ball-tossing among healthy participants aged 21–75 years old. They found that there were more activations among younger participants than the older participants in the pregenual anterior cingulate cortex (pgACC) in the exclusion (i.e., no ball toss) than the control condition (i.e., the fair game) for the whole sample (i.e., both male and female participants). The authors explained that the results with the pgACC may reflect a reduction in engagement with negative emotions related to ageing. However, the reduced activation in pgACC in older people could be due to an elevated anxiety score, and therefore would need further investigation with non-clinical populations to better understand any changes in response to social exclusion with healthy ageing. More recently, Kim et al. (Kim et al., 2023) examined the effect of the closeness of a relationship on brain connectivity during the Cyberball task among older adults from the same rural village in South Korea. They found that older adults who were less connected with others in the village showed stronger functional connectivity in areas including the medial frontal gyrus, middle temporal gyrus and inferior frontal gyrus, during social exclusion. It was proposed that the activities may reflect the attempt to better mentalise others' intentions. Although the feeling of closeness to neighbours is related to the sense of loneliness, the study did not measure loneliness directly and did not examine how it may affect the response towards social exclusion among older adults.

Sex differences in affect have been repeatedly reported in the literature. Negative cognitive styles, such as rumination and worry, were found to be more common among girls, and rumination and worry mediated the effect of gender on depressive symptoms (Espinosa et al., 2022). In another experimental study, it was found that on an emotional picture matching task, trait anxiety affected the behavioral performance of women only and not of men (Chaudhary et al., 2024). Moreover, among the female participants, activation elicited by negative pictures (versus neutral pictures) was found to correlate with trait anxiety level in the mPFC (Chaudhary et al., 2024). Therefore, apart from being affected by age alone, there might also be a sex effect in the experience of loneliness and social exclusion. For example, Wang et al. (Wang et al., 2020) reported an interaction effect with sex in the activations during ball-tossing among those aged 21–75 years old. They found that the left orbitofrontal cortex, thalamus and left occipital cortex showed a negative correlation with age among female participants only (and not among the male participants). Results of their study highlighted the importance of considering the roles of both ageing and sex in studying social exclusion among adults. Based on the self-report data by Dong and Chen (Dong & Chen, 2017), females are more likely than males to experience loneliness at an older age. Interestingly, it was recently reported that loneliness is a risk factor for cognitive impairment only for men but not for women (Huang et al., 2023). Therefore, to achieve a better understanding of healthy ageing, the possible interaction effect between age and biological sex on social exclusion and loneliness should be further explored.

This study aimed to examine how loneliness affects the response towards social exclusion among community older people. We hypothesised that lonely older adults would show higher activations in the frontal regions of the brain (e.g., orbitofrontal cortex, ACC) compared to older adults who are not lonely. Furthermore, considering the previous literature suggesting a sex difference on this issue, we also wanted to explore potential sex differences in the response towards social exclusion among healthy older adults. Together, we expect the results of our study to improve our understanding of social experiences of older adults, and further unpack the potential negative consequences associated with loneliness. Such improved knowledge could also become the basis for more tailored interventions for enhancing the social well-being of older adults.

2. Methodology

2.1. Participants

To determine the appropriate sample size for this study, we conducted an a priori power analysis based on previous cross-sectional studies comparing loneliness and normal cases (Spreng et al., 2020). According to G*Power 3.1, to detect a significant difference between groups, we need at least 17 participants per group, assuming a medium effect size ($d = 0.5$), a power of 0.90, and a significance level of 5%. Taking into account an attrition rate of approximately 18% (Chatfield et al., 2005), the final sample size should be about 40 participants (20 in each arm).

Forty volunteers (61–69 years old; 22 males & 18 females) were recruited using community advertisements and existing research cohorts. Ethical approval of the research protocol was obtained from the Institutional Review Board of the Hong Kong Polytechnic University (HSEARS20211026002). Written informed consent was obtained from all participants prior to their inclusion in the study. The participants were also interviewed before the experiment to gather information regarding loneliness and sociodemographics.

2.2. Inclusion and exclusion criteria

The inclusion criteria were: individuals aged 60 years and older who did not meet the DSM-5 criteria for a Major Neurocognitive Disorder, as determined by scores at or below the 2nd percentile on the age- and education-specific cut-offs of the Hong Kong Montreal Cognitive Assessment (HK-MoCA) (Wong et al., 2015).

Participants were excluded if they have (i) a clinical dementia rating (CDR) larger than or equal to 1 (Morris, 1997); (ii) major neurological disorders, including a history of stroke, transient ischemic attack, traumatic brain injury (TBI), or Parkinson's disease (PD); (iii) a history of major depressive episode, bipolar affective disorders and psychosis; (iv) any MRI-incompatible implants or other imaging contra-indications; (v) on psychotropic or other medications known to affect cognition (e.g., benzodiazepines, anti-dementia medication, etc.); (vi) significant communicative impairment; or (vii) being institutionalized for mental health problems.

2.3. Allocation into groups

All participants underwent an initial screening to determine their eligibility. Those who qualified were then formed into two groups based on whether they experienced loneliness (Leung et al., 2008). The total score of the Chinese version of the 6-item De Jong Gierverg Loneliness Scale ranges from 0 to 6, with a higher score indicating a higher level of loneliness. A cutoff value of $\geq$2 indicates the presence of loneliness (Leung et al., 2008). This cut-off has been used previously by a recent study on loneliness among older Chinese adults (Ruan et al., 2023). Therefore, loneliness was defined as a score of 2 or higher on the Chinese version of the 6-item De Jong Gierveld Loneliness Scale.

The Revised Clinical Interview Schedule (CIS-R) was also used to assess symptoms of common mental disorders such as depression and anxiety (Lewis et al., 1992). The scores of this measure range from 0 to 57, with higher scores indicating poorer mental health. A cutoff score of $\geq$12 for significant risk of CMDs has been validated (Lam et al., 2014).

2.4. Experimental procedure: Cyberball task

All participants took part in a virtual ball-tossing game known as the Cyberball (Eisenberger et al., 2003) inside the MRI scanner. During this task, they were led to believe that they were playing with two other players while inside an MRI scanner.

Each scan started with a static image showing two virtual players positioned in the upper corners of the screen and an arm, representing the participant, located in the lower center. The participant's name appeared beneath the arm, while the names of the two virtual players were displayed below their respective animated cartoon representations. After 9 s, the cartoon player in the upper left corner initiated the game by throwing the ball to one of the players. The participant could pass the ball back to either player by pressing one of two buttons on a button box. The scanning session consisted of four blocks: two inclusion conditions and two exclusion conditions. During the inclusion condition, participants received 30 out of 60 ball tosses, representing social inclusion. In contrast, the exclusion condition involved participants receiving only 5 out of 60 ball tosses, simulating social exclusion. Each block involved 60 tosses, with the computer players waiting 0.5 to 3.0 s before making a throw to enhance the impression that the participant was interacting with real individuals. Following each round, participants completed a 16-item questionnaire inside the MRI scanner, with each block (including the game and questionnaire) lasting approximately 500 s. The questionnaires were based on two previous studies, Hawkley et al. (Hawkley et al., 2011) and Zadro et al. (Zadro et al., 2004), which explore the effects of short periods of face-to-face or Internet ostracism (Cyberball task). They specifically address self-reported decreases in five fundamental needs resulting from ostracism: belonging needs, control needs, self-esteem needs, meaningful existence needs and emotional experience (with higher scores indicating a more positive state).

2.5. fMRI image acquisition and data analysis

All structural and fMRI data were acquired on a Siemens-3 T (Prisma) MR scanner using a 32-channel head coil.

Structural images were acquired with a three-dimensional (3D) MPRAGE for fast T1-weighted volume measurements for the head with the repetition time (TR) = 2500 ms, the echo time (TE) = 2.22 ms, flip angle = 8 degrees, voxel size = $0.8 \times 0.8 \times 0.8$ mm^3, and FOV = $240 \times 256 \times 167$ (mm).

Functional images were collected by using the gradient-echo sequence in axial orientation sensitive to blood oxygen level dependent contrast: TR = 2000 ms, TE = 32 ms, flip angle = 71 degrees, voxel size = $3 \times 3 \times 3$ mm^3, FOV = $192 \times 192 \times 114$ (mm) and 38 slices.

Post-processing was performed using Statistical Parametric Mapping (SPM12, Wellcome Department of Imaging Neuroscience, London, UK) within the MATLAB environment (The Mathworks Inc., Natick, MA, USA). Firstly, functional data were spatially realigned to the first volume of the first run to correct for head motion. Subjects who exhibited head movements exceeding 3 mm in any direction of x, y and z or rotational changes greater than 3° were excluded. Then, the data were co-registered to the anatomical images. The structural images underwent a segmentation process that resulted in the creation of tissue maps. A standard EPI template was used for normalization, and the images were resampled into $3 \times 3 \times 3$ mm^3 isotropic resolution in the Montreal Neurological Institute (MNI) brain using the transformation parameters established through the segmentation. Subsequently, the images were smoothed with an 8-mm Gaussian kernel at full-width half maximum (FWHM). Low-frequency fluctuations were removed using a high-pass filter with a cutoff period of approximately 4 times the block duration (2000 s), minimizing signal loss while mitigating low-frequency drift. Temporal autocorrelation was addressed using the FAST option in SPM12, which allows for a dictionary of covariance components based on exponential covariance functions within the restricted maximum likelihood (ReML) framework (Friston et al., 2002). Given the relatively long block durations and limited resting periods that may have affected the signal-to-noise ratio, a higher high-pass filter cutoff and the more sophisticated FAST noise model were applied to better preserve signal integrity while controlling for temporal noise.

2.6. Imaging data modelling and statistics

We modelled the BOLD signals to identify brain responses by contrasting social exclusion versus inclusion blocks using the contrast [exclusion - inclusion]. A statistical analytical block design was constructed for each subject, employing a general linear model (GLM) with block onsets and durations of exclusion or inclusion blocks convolved with a canonical hemodynamic response function.

In the first-level analysis, contrast images were generated for parameter estimates in the context of a GLM based on two conditions: inclusion and exclusion. The primary contrast of interest was the difference between two conditions [exclusion - inclusion]. The contrast images (difference in β) of the first level analysis were then used for the second-level group analysis.

In the group analysis, we examined the regional brain responses to exclusion versus inclusion among both lonely and not-lonely participants. A two-sample *t*-test was utilized to measure the activation differences between groups. Additionally, to explore the interaction of group by sex for the contrasts between exclusion and inclusion conditions, we conducted an analysis using a GLM with four explanatory variables (group 1 (lonely), group 2 (non-lonely), male (demeaned), and female (demeaned)). Higher-level contrasts were set up to test for the group by sex interaction. The Alphasim program in the software of Resting-State fMRI Data Analysis Toolkit (Song et al., 2011) was applied for the correction of multiple comparisons, with significance set at $p < 0.01$ and a minimum cluster size of 71 voxel (surface connected, spatial smoothness = 8 mm).

Statistical analyses were carried out using SPSS package v. 28 (SPSS Inc., Chicago, USA). To assess sex differences between lonely and not lonely groups, Pearson's chi-square test was utilized. Additionally, two-sample *t*-tests were conducted to examine differences in age and total loneliness score across the groups. Comparisons between groups for the questionnaire data were conducted using independent *t*-tests to compare exclusion versus inclusion conditions.

2.7. Disclosure statement

All studies, measures, manipulations, and data/participant exclusions are reported in the manuscript or its Supplementary Material.

3. Results

3.1. Behavioral findings

Forty volunteers (61–69 years old; 22 males and 18 females) attended this study. However, three were excluded from the analysis due to excessive head motion during the fMRI scans (exceeding 3 mm in translation and 3° in rotation). Consequently, the final dataset included 16 individuals in the 'not lonely' group and 21 in the 'lonely' group (See Table 1). No significant differences were observed in terms of age and sex for these two groups. As expected, notable differences emerged in the loneliness scores (Table 1, $p < 0.001$). There was no difference on mental health symptoms as measured by the CIS-R ($t = -1.317$, $p = 0.196$) and in global cognition as assessed by the HK-MoCA ($t = 1.208$, $p = 0.235$) between the two groups.

The questionnaire assessed five domains: belonging needs, control needs, self-esteem needs, meaningful existence needs, and emotional experience. To verify the effectiveness of the inclusion/exclusion manipulation and to ensure consistency with prior studies, five independent-samples Mann–Whitney *U* tests were conducted across the areas measured by the questionnaire. According to Table 2, all comparisons yielded statistically significant results. Specifically, during the exclusion condition, participants reported more negative experiences in all these domains compared to the inclusion condition. No significant differences were observed between the groups in terms of questionnaire responses, which may be attributed to the limited sample size.

3.2. Imaging findings

Fig. 1 A-C provides a summary of the regions activated across all

Table 1
Demographic information, neuropsychological test results of the 'not lonely' group and the 'lonely' group.

	Not Lonely	Lonely	*df*	*t* /Chi/U	*p*
Number(N)	16	21		–	–
Sex (female/ male)	9/7	7/14	1	1.943 [a]	0.163
Age	65.01 ± 2.72	64.40 ± 2.04	35	0.789 [b]	0.436
HK-MoCA	28.00 ± 1.41	27.29 ± 2.17	35	139.0 [c]	0.387
CIS-R	2.81 ± 3.19	4.71 ± 5.05	35	194.5 [c]	0.421
Loneliness total	0.75 ± 0.45	3.24 ± 1.30	35	336.0 [c]	<0.001***

"-" indicates not applicable. Unless otherwise noted, values are presented as mean ± standard deviation.
*** indicates $p < 0.001$.
[a] no cells have expected count less than 5 in the Chi-square test.
[b] Complied with the normality and homogeneity of variance assumptions for two sample *t*-test.
[c] Independent-samples Mann–Whitney *U* Test (Nonparametric Comparison).

Table 2
Outcomes of the questionnaires following the inclusion and exclusion sessions.

Questionnaires	Inclusion	Exclusion	*U* value	*p* value
Belonging needs	3.41 ± 0.42	1.7 ± 0.62	31.00 [c]	<0.001***
Control needs	3.27 ± 0.62	1.79 ± 0.64	83.50 [c]	<0.001***
Self-esteem needs	3.54 ± 0.41	2.27 ± 0.64	82.50 [c]	<0.001***
Meaningful existence needs	3.39 ± 0.44	1.88 ± 0.73	79.00 [c]	<0.001***
Emotional experience	3.68 ± 0.36	2.33 ± 0.82	99.50 [c]	<0.001***

Values are presented as mean ± standard deviation.
*** indicates $p < 0.001$.
[c] Independent-samples Mann–Whitney U Test (Nonparametric Comparison) because normality and homogeneity of variance assumptions were not met.

individuals from the lonely group and the not-lonely group (details included in Supplementary Table 1). The lonely group exhibited greater activation across more regions than the not-lonely group, particularly in the frontal regions and anterior cingulate cortex—key areas within the default mode network. In the not-lonely group, the activation during the inclusion block was greater than that of the exclusion block, especially in the medial prefrontal cortex, precuneus, inferior parietal/angular gyrus, and temporal cortices—all core DMN regions.

Fig. 2 and Table 3 illustrate the differences between the 'lonely' and the 'not-lonely' groups. The contrasts presented are based on a two-sample *t*-test that compares 'exclusion' and 'inclusion' conditions. Significant increased activations in the lonely group compared to the not-lonely group were observed in several regions: bilateral medial superior frontal gyrus, bilateral medial orbital part of superior frontal gyrus, left anterior cingulate gyrus, left middle frontal gyrus, and left superior dorsolateral frontal gyrus (AlphaSim corrected $p < 0.01$, cluster size ≥ 71 voxels). These findings suggest a broad neural basis for the experiences associated with loneliness.

Specifically, we calculated the correlation between activations in the regions showing significant differences and the questionnaire ratings. In the lonely group, self-esteem needs (exclusion > inclusion) were significantly and negatively correlated with the peak *t*-values in the bilateral superior medial frontal gyrus (left: $r = -0.55$, $p = 0.01$; right: $r = -0.51$, $p = 0.02$). In the non-lonely group, significant negative correlations were observed between meaningful-existence needs and peak t-values in the left superior dorsolateral frontal gyrus ($r = -0.69$, $p = 0.003$), as well as between positive emotional experience and the same region ($r = -0.58$, $p = 0.02$). These patterns suggest that individuals with different levels of loneliness engage distinct frontal mechanisms when processing self-related and social-emotional information (Fig. 3).

The interaction (Group * Sex) in the model indicated whether the relationship between loneliness and relevant neural activity during Cyberball varies depending on biological sex. Fig. 4 and Table 4 display the results of this interaction model. For consistency with previous findings, Fig. 4 and Table 4 use a significance threshold of $p < 0.01$ (AlphaSim corrected), cluster size ≥ 71 voxels. A significant positive coefficient for this interaction suggests that for males, greater loneliness elicited significantly greater regional brain activation when they experienced more exclusion during Cyberball. These regions include: right hippocampus, left superior temporal gyrus, and left heschl gyrus.

4. Discussion

This study examined the effect of loneliness on the experience of social exclusion. The final sample consisted of 37 older adults who made up the lonely ($n = 21$) and not-lonely control ($n = 16$) groups based on their score on the 6-item De Jong Gierveld Loneliness Scale. All participants underwent fMRI scanning whilst completing the classic Cyberball task. As expected, the exclusion/inclusion manipulation was successful, based on the self-reported ratings of all participants on four fundamental needs resulting from ostracism and on emotional experience (Zadro et al., 2004). More importantly, as hypothesised, we found that the

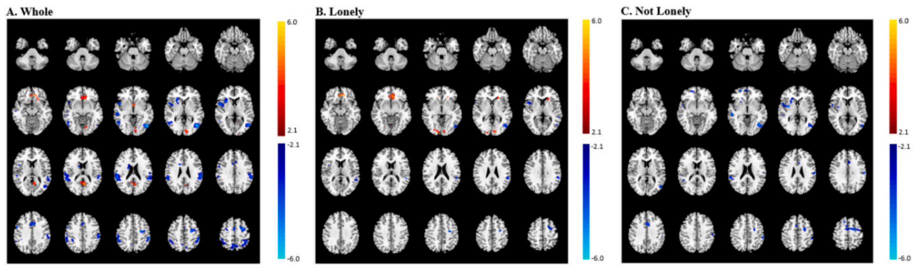

Fig. 1. Activated Regions (contrast: Exclusion > Inclusion) A) across the entire group, B) lonely group, C) not-lonely group. Statistical significance was achieved using AlphaSim correction with $p < 0.01$ and a minimum cluster size of 71 voxels.

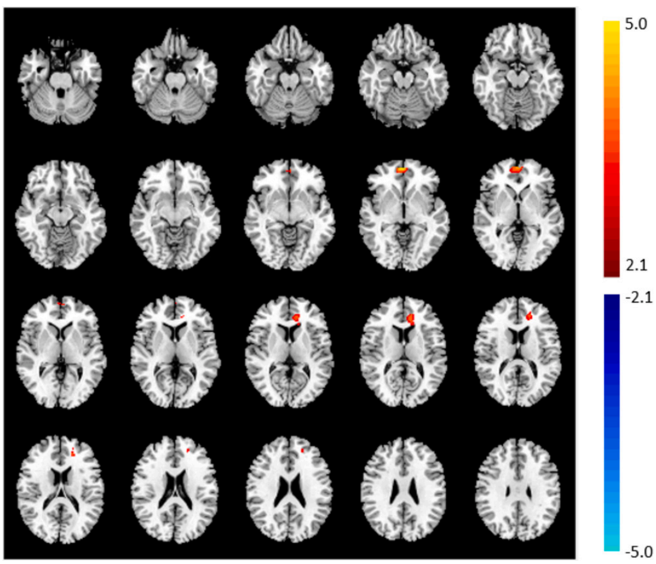

Fig. 2. Comparative imaging results for the 'lonely' group ($N = 21$) and the 'not-lonely' group ($N = 16$). The displayed contrasts are derived from a two-sample *t*-test comparing the 'exclusion' and 'inclusion' conditions (lonely > not-lonely, exclusion > inclusion). AlphaSim correction with $p < 0.01$ and a minimum cluster size of 71 voxels.

lonely group showed more brain activations compared to those of the not-lonely group in response to the exclusion condition of the Cyberball task (versus inclusion condition; whole-brain analysis).

The lonely group had higher activation in the bilateral medial superior frontal gyrus, as well as in the anterior cingulate for exclusion (vs. inclusion) compared to the not-lonely group. This network is similar to a previous study for less socially-connected older adults undergoing the Cyberball task (Kim et al., 2023). The superior frontal gyrus is a part of the default mode network that supports cognitive processes related to the self (Mwilambwe-Tshilobo & Spreng, 2021). The cingulate cortex was found to be activated more for exclusion in a previous study (Wang et al., 2020). These areas overlap with the meta-analytic results reported for Cyberball studies (Mwilambwe-Tshilobo & Spreng, 2021), as well as the pain network that was previously reported (Mayr et al., 2022). It is likely that the activations represent a state of interoceptive reflection with a painful or unpleasant experience during the Cyberball task (Mayr et al., 2022). Activations in the bilateral superior frontal gyri were associated with threats to the self-esteem of the lonely group (based on ROI results). Therefore, it is possible that the lonely group was more emotionally sensitive to the exclusion condition, such that they experienced more arousal and engaged more with self-reflection. This explanation also aligns with the recent findings from a similar study with young adults. An adapted version of the Cyberball was used by (Kanterman et al., 2024) where the young-adult participant could press a button to increase the chance of receiving the ball. Participants who are lonelier showed faster presses during the inclusion condition. The authors interpreted this as a higher urgency for social interaction among lonely individuals, and in other words, it is possible that loneliness represents a state of "chronic social hunger (p.406)". Therefore, loneliness could be underlined by a negative interoceptive experience, rather than solely a response to the outer world. The current results therefore further contribute to the understanding about loneliness, and could have implications for the definition of loneliness, which still lacks consensus.

On the other hand, there was more activations in the right supramarginal gyrus and other regions during inclusion (versus exclusion) for the not-lonely group. The supramarginal gyrus has been reported in previous Cyberball studies, and its possible role relates to attentional control or re-orientation (Bolling et al., 2015). In line with this explanation, the supramarginal gyrus was found to be activated during emotion regulation tasks that required the participants to control their attention when distracted with emotional information (Loeffler et al., 2019). Therefore, in addition to studies on issues related to loneliness, it may be of interest for future studies to explore the mechanisms of successful emotion regulation during exclusion among those who are socially connected in daily life.

Building on emerging evidence of the importance of sex effect on social experiences, we also explored sex differences for exclusion versus inclusion. We found that male participants had higher brain activations in the hippocampus, and superior temporal gyrus. One possible explanation is that male participants engaged with more emotional memory processing when confronted with social exclusion, such that the

Table 3
Results of two-sample *t*-tests comparing the 'lonely' and 'not-lonely' groups (contrast: exclusion > inclusion).

Cluster-level		Region-level (only AAL regions included)	Abbrev	Cluster size (voxels)	Peak *T* value	MNI Coordinates (mm)		
Cluster NO.	Voxels					x	y	z
1	147	Left Superior frontal gyrus (medial orbital)	ORBsupmed.L	25	4.91	0	60	−2
		Left Superior frontal gyrus (medial)	SFGmed.L	31	3.60	−4	62	2
		Right Superior frontal gyrus (medial orbital)	ORBsupmed.R	43	5.06	2	60	−2
		Right Superior frontal gyrus (medial)	SFGmed.R	42	3.16	2	62	2
2	184	Left Anterior cingulate and paracingulate gyri	ACG.L	55	3.69	−10	40	12
		Left Middle frontal gyrus	MFG.L	11	3.30	−20	46	16
		Left Superior frontal gyrus (dorsolateral)	SFGdor.L	15	3.00	−22	48	24

Alphasim correction, $p < 0.01$ with a minimum cluster size threshold of 71 voxels.

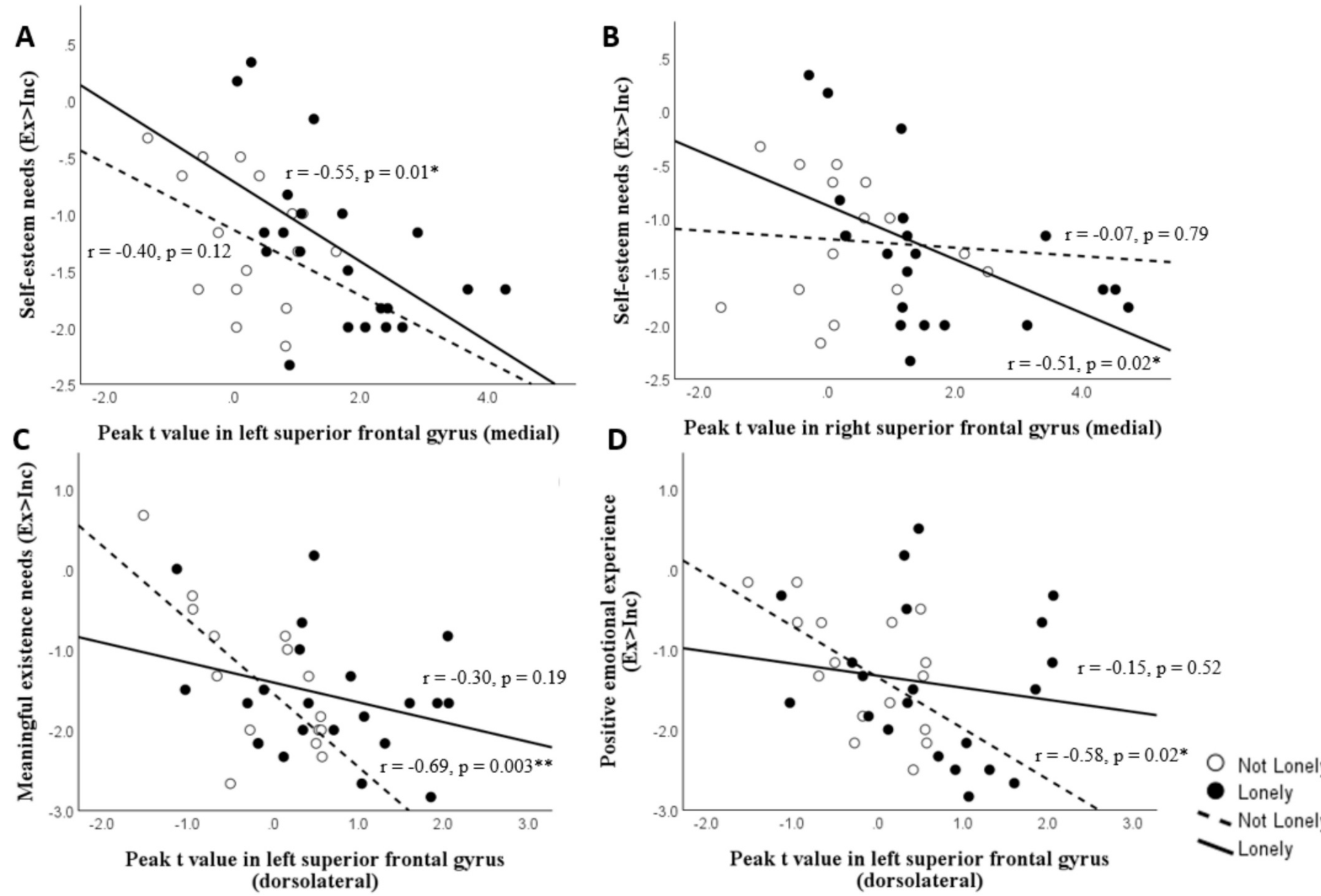

Fig. 3. Scatter plots showing significant correlations in the lonely and non-lonely groups: A) self-esteem needs versus peak *t*-value of activation in the left superior medial frontal gyrus; B) self-esteem needs versus peak *t*-value in the right superior medial frontal gyrus; C) meaningful existence needs versus peak *t*-value in the left superior dorsolateral frontal gyrus; and D) positive emotional experience versus peak *t*-value in the left superior dorsolateral frontal gyrus.

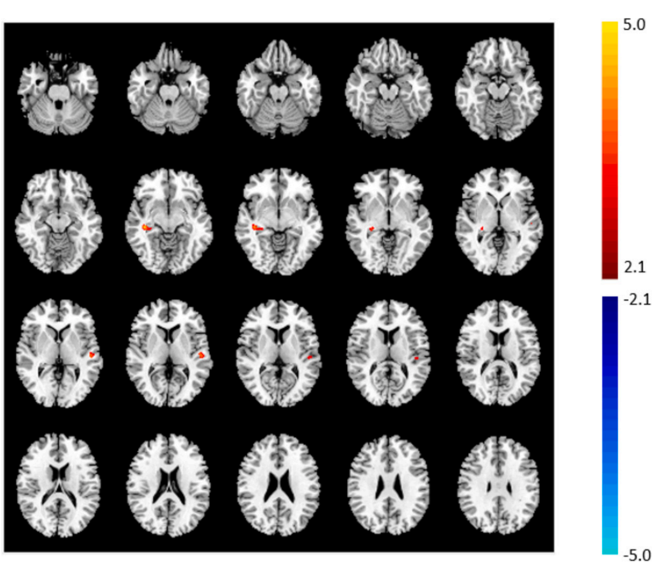

Fig. 4. Interaction of sex with the contrast values of [exclusion-inclusion] in lonely and not-lonely groups. A significant positive coefficient for this interaction was found, which suggests that the difference in outcomes between males and females (male > female) is more pronounced in the lonely group compared to that of the not-lonely group. Alphasim correction, $p < 0.01$ with a minimum cluster size threshold of 71 voxels.

activation reflected the effort of downregulation of negative experiences (Látalová et al., 2023). Alternatively, it might be that men were more inclined to comprehend the reason behind the social exclusion, based on a previous study that interpreted activations of the middle and superior temporal gyri as reflecting theory of mind during Cyberball (Wudarczyk et al., 2015). More studies are needed to better understand the experience of social exclusion among older men, which appears to be a neglected research gap in the literature so far. More importantly, it may offer additional insights to guide interventions in the future.

We believe that this is the first study to examine how loneliness affects the response towards social exclusion among community-dwelling non-clinical older people. The results further showed the negative consequences of loneliness in terms of being more reactive towards social exclusion. Practitioners working with older adults could consider such a finding when designing interventions. For example, providing tailored psychoeducational information to older adults for better self-understanding and identification of triggers of emotional or social problems in their daily life.

The results should be interpreted in light of some limitations of the current study. First, it is acknowledged that there were more males than females in the study. Therefore, further study with a balanced sex ratio is needed to explore possible sex effects further. Second, due to the fMRI methodology, and the more difficult to reach target population of lonely older adults, we were limited to a relatively small sample size, which may have hindered the power for detecting group differences at both the behavioral and neural levels. Third, the study's interpretability would be strengthened by including a comparison group of younger adults, which would help determine whether the observed activation patterns are

Table 4
Areas of significant brain activation reflecting a sex × loneliness interaction for the contrast (exclusion > inclusion).

Cluster-level		Region-level (only AAL regions included)	Abbrev	Cluster size(voxels)	Peak *T* value	MNI Coordinates (mm)		
Cluster NO.	Voxels					x	y	z
1	97	Right Hippocampus	HIP.R	27	3.85	38	−24	−8
2	87	Left Superior temporal gyrus	STG.L	70	3.84	−54	−18	6
		Left Heschl gyrus	HES.L	10	3.11	−52	−14	8

Alphasim correction ($p < 0.01$) with a minimum cluster size threshold of 71 voxels.

specific to older adults or reflect a more general neural response to social exclusion. Fourth, we used the Alphasim correction method, which may not be sufficiently stringent. Given our small sample size, this approach represented a practical compromise between sensitivity and specificity. Additionally, the design of the Cyberball task introduced some methodological challenges. The relatively long block durations and lack of breaks likely increased low-frequency noise in the signal, complicating the modelling of condition-specific effects. Future studies with improved task design and shorter, better-balanced blocks could help mitigate these issues. Finally, the 6-item De Jong Gierveld Loneliness Scale measures subjective feelings of loneliness without capturing objective social isolation, raising the possibility of circular reasoning or self-selection bias. It is possible that the results reflect a general sensitivity to isolation rather than loneliness itself.

In conclusion, we found that among older adults, those who self-reported loneliness had more neural activation in regions of the default mode network and the pain network when confronted with social exclusion. Further research is needed to better understand the experience of social exclusion among older adults, especially among men.

CRediT authorship contribution statement

Yuan Cao: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Hui Zhang:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis. **A.W.T. Fung:** Supervision, Methodology, Funding acquisition, Conceptualization. **David H.K. Shum:** Writing – review & editing, Visualization, Validation, Supervision, Funding acquisition.

Disclosure statement

All studies, measures, manipulations, and data/participant exclusions are reported in the manuscript or its Supplementary Material.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2026.106723.

Data availability

Data will be made available on request.

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