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Loneliness and Interoceptive Accuracy in the Elderly Population: Behavioral and Neurophysiological Evidences

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Introduction and Theoretical Background

Loneliness in the Elderly Population

Loneliness is described as a distressing emotion accompanied by the subjective perception that one's needs of social companionship are not being met in light of the quality or quantity of one's actual relationships (Hawkley & Cacioppo, 2010; Peplau & Perlman, 1982). Cacioppo (e.g., 2014) denominates loneliness as perceived social isolation (PSI) and delimits the construct from objective social isolation (OSI). Accordingly, there can be people who have many social contacts (are objectively not lonely) but feel subjectively lonely, whereas there can also be those who lack social companionship and, conversely, not feel lonely.

However, the prevalence of loneliness seems to differ across nations and age (Yang & Victor, 2011). In the German population, loneliness is proposed to form a non-linear trajectory across the lifespan with increased levels of loneliness among the young adults and the oldest old (Luhmann & Hawkley, 2016).

Primary reasons for the occurrence of loneliness among older adults are considered deteriorating health as well as the loss of one's partner (Perlman, 1988).

Baumeister and Leary (1995) argued that the so-called need to belong is a fundamental motivation to form and maintain long-lasting interpersonal relationships. Furthermore, the social control theory (e.g., Umberson, 1987) posits that the impact of the social environment encourages health-promoting behavior and discourages health-impairing behavior. For instance, being married was suggested to promote good health behavior like exercise (Umberson, 1987, 1992). Thus, loneliness is associated with a series of poor health behaviors and might lead to negative consequences such as obesity (Lauder, Mummery, Jones, & Caperchione, 2006), poorer physical health (Cornwell & Waite, 2009), Alzheimer's disease (Wilson et al., 2007) and alcoholism (Akerlind & Hornquist, 1992; Bell, 1956). Therefore, it is often viewed as a risk factor for mortality and morbidity (e.g., Cacioppo et al., 2014; Holt-Lunstad, Smith & Layton, 2010).

Based on a social neuroscience model, social ties helped individuals to reproduce and to survive (Cacioppo et al., 2014). Isolation from others might be a dangerous condition, since no mutual protection is available in case of an assault. As a result, the brain activates a so called "short-term self-preservation mode" (Cacioppo et al., 2014, p. 1467) when being without the assistance of others. The mode evokes multiple effects: (i) implicit hypervigilance for social threats accompanied by elevated hostility, anxiety and social withdrawal; (ii) elevated fragmentation of sleep due to potential predation during sleep; (iii) increased hypothalamicpituitary-adrenal activity, heightened vascular activity, as well as modified immunity and gene expression to cope with possible assaults; (iv) reduced impulse control for the benefit of responses most elevated in the hierarchy of responses (i.e., prepotent responding) resulting in the display of behavior that led to success in past events; (v) increased depressive symptoms signalizing the need for social reconnection and support. Although these effects might serve to ensure short-term survival, they may also carry costs when being exposed to them chronically, resulting in alterations in brain function and structure (Cacioppo et al., 2014).

According to researches like Hawkley and Cacioppo (2010), the aforementioned hypervigilance for social threat generates cognitive biases: Lonely persons perceive social interactions more negative. They also seem to perceive their social environment to be more threatening when compared to non-lonely individuals. Those cognitive biases might lead to negative social expectations, which in turn result in a self-fulfilling prophecy. Since others might display more frequently negative behavior towards lonely people and thereby confirm the expectations imposed to them beforehand, lonely individuals most likely react with social withdrawal, distancing themselves from others. Consequently, a "self-reinforcing loneliness loop" (Hawkley & Cacioppo, 2010, p. 220) is set in motion, creating the belief in lonely people that the reason for their loneliness is due to others and uncontrollable for them (Newall, Chipperfield, Clifton, Perry & Swift, 2009). Therefore, they actively distance themselves from potential social partners (Hawkley & Cacioppo, 2010). Thus, these mechanisms of loneliness seem to be associated with low self-esteem, as well as with feelings of anxiety, stress, pessimism, hostility (Cacioppo et al., 2006), social withdrawal (Cacioppo et al., 2014) and interpersonal distrust (Qualter, Wagner, Quinton & Brown, 2009).

Loneliness and Alexithymia

Alexithymia is considered a three-dimensional personality trait (Preece, Becerra, Allan, Robinson & Dandy, 2017) that is characterized by difficulties identifying one's own feelings, difficulties describing feelings and externally oriented thinking (Bagby, Parker & Taylor, 1994). The dimension externally oriented thinking is defined as "an absence of the capacity to produce fantasies with the result that thought content [is] restricted to a preoccupation with external objects, people, and environmental events" (Nemiah, 1984, p. 127). Nemiah and Sifneos (1970) were the first who implemented the term alexithymia which originates from the Greek and means "lack of words for emotions" (a = lack, lexis = word, thymos = feeling).Thus, individuals with high levels of alexithymia are able to experience physiological arousal associated with emotional states. Nonetheless, they are unable to distinguish between emotions and their physiological concomitants as well as between affective states as such (e.g. between anger and sadness) (Taylor & Bagby, 2004).

Two studies have examined the direct relationship of alexithymia and loneliness (Frye-Cox & Hesse, 2013; Qualter et al., 2009). Both of them found the two constructs to be significantly associated with each other. Qualter and colleagues (2009) utilized the Social and Emotional Scale for Adults (SELSA; DiTommaso & Spinner, 1993) to assess the levels of romantic loneliness (the perceived lack of attachment with a romantic partner), family loneliness (the perceived lack of attachment with family members) and social loneliness (the perceived deficiency of a peer social network) (Weiß, 1973). Results indicated moderate positive correlations between romantic, family and social loneliness and alexithymia (measured with the TAS-20; Bagby, Parker & Taylor, 1994). Furthermore, interpersonal distrust was considered to partly mediate this association. Frye-Cox and Hesse (2013) conducted a study collecting data of married couples. Aim of the study was to investigate the mediating roles of intimate communication and loneliness in the relationship between alexithymia and marital quality. Results showed that increased levels of alexithymia (assessed with the TAS-20; Bagby, Parker & Taylor, 1994) were related to higher levels of loneliness (assessed with the UCLA Loneliness Scale; Russell, 1996), predicting decreased intimate communication, which was associated with lower marital quality. Taken together, both studies suggest a moderate to high correlation between loneliness and alexithymia.

Possible mechanisms explaining the link between loneliness and alexithymia are considered to be deficiencies in the ability to recognize and understand one's own emotions and also those of others' which might result in problems to form intimate and effective interpersonal relationships (Qualter et al., 2009). Thus, the perceived quality of romantic relationships seems to be decreased in individuals with higher levels of alexithymia (Frye-Cox & Hesse, 2013; Holder, Love & Timoney, 2014). According to the neo-Darwinian affection exchange theory (AET; Floyd, 2006) affectionate communication is an adaptive behavior in the sense that it helps us through the formation and maintenance of relationships to reproduce and to survive. Individuals with higher levels of alexithymia displayed decreased abilities to give and experience affection (Hesse & Floyd, 2008) leading to less satisfactory and fewer close relationships (Frye-Cox & Hesse, 2013; Hesse & Floyd, 2011). In addition, prior research also pointed out that highly alexithymic persons felt disconnected from others and reported having poor networks of social support (Hesse & Floyd, 2011; Humphreys et al., 2009). Another theory explaining the link between loneliness and alexithymia is the personality-behavioral approach (e.g. Maragoni & Ickes, 1989), which posits that personality predispositions such as alexithymia might cause higher levels of loneliness due to the incapability of engaging in certain behaviors, for instance intimate communication, which are necessary to maintain interpersonal relationships (Frye-Cox & Hesse, 2013).

Interoceptive Accuracy

Previous studies defined interoception as the perception of the physiological state of the body (Craig, 2002, 2009). Hence, interoception is said to function as a body-to-brain axis (Cameron, 2002; Sherrington, 1948), “connecting the mind and body pathways” (Forrest, Smith, White & Joiner, 2015, p. 754). Whereas former definitions of the term interoception claim that only visceral information (e.g. hunger and heart rate) are supposed to be considered as interoceptive (e.g. Fowler, 2003), definitions that are more recent have been extended by the inclusion of other physiological signals (e.g. tickle and affective touch), which are processed utilizing the same neurological pathways as visceral stimuli (e.g., Murphy, Brewer, Catmur & Bird, 2017a). Hence, according to some recent definitions all bodily signals that are transmitted (i) via small unmyelinated group C nerve fibres or large myelinated group A nerve fibres, the marginal nucleus of the spinal cord (lamina I) and the spinothalamic tract onto the anterior cingulate cortex (ACC) and the insula (Craig, 2002), or (ii) via cranial nerves (glossopharyngeal and vagus) to the nucleus of the solitary tract (NTS) (Critchley & Harrison, 2013; Saper, 2002) are considered to be interoceptive. While some researchers maintain the original and more restrictive meaning to define the term interoception (e.g., Dworkin, 2007), we use the term more broadly to refer to the perception of any physiological condition that is transmitted by the aforementioned neural pathways (e.g., Craig, 2002; Critchley & Harrison, 2013; Murphy et al. 2017a). According to Sherrington (1984), interoception is distinguishable from proprioception, the body position in space, and exteroception, defined as the perception of external stimuli.

Garfinkel and colleagues (2015) suggested to distinguish between three different dimensions of interoceptive ability. Correspondingly, they defined objective *interoceptive accuracy* as the extent to which an individual is capable of accurately perceiving physiological signals, subjective *interoceptive sensibility* as the belief about the own interoceptive accuracy and metacognitive *interoceptive awareness* as the degree of the equivalence between objective and subjective interoceptive abilities. However, due to an observed moderation of interoceptive accuracy (assessed using heartbeat detection tasks) on the relationship between interoceptive accuracy, interoceptive sensibility (assessed using confidence judgements) and interoceptive awareness (assessed using confidence-accuracy correlations), interoceptive accuracy was proposed to be the construct underlying the other interoceptive measures. To assess interoceptive accuracy two different kind of measurements, which both rely on heartbeat perception, are applied most frequently, namely heartbeat tracking tasks, originally developed by Schandry (1981), and heartbeat discrimination tasks (Whitehead & Drescher, 1980; Whitehead, Drescher, Heiman & Blackwell, 1977). The first ones require the participants to count their own heartbeats during a specified time interval. Later on, the counted number of heartbeats is compared with the actual number of heartbeats. The latter ones ask the participants to detect whether external stimuli (a series of lights, tones or tactile stimuli) are simultaneous or delayed in comparison to their own heartbeats. The term "heartbeat detection task" serves as an umbrella term to refer to both kind of assessments (e.g. Garfinkel et al., 2015). For the present study, we applied a heartbeat tracking task in order to measure interoceptive accuracy (for more details see section measures).

Accurate interoceptive abilities may be essential for homeostasis and thus for the regulation of the bodily condition and the maintenance of the physiological health (Murphy et al., 2017a; Murphy, Geary, Millgate, Catmur & Bird, 2017b). In addition, poor interoceptive accuracy has been found to contribute to a number of mental disorders, such as schizophrenia (Ardizzi et al., 2016), depression (e.g. Harshaw, 2015), somatic symptom disorders, obsessive compulsive disorders, eating disorders (Brewer et al., 2015; Brewer, Cook & Bird, 2016a,b; Khalsa & Lapidus, 2016; Stern, 2014) and addiction (Naqvi & Bechara, 2010; Verdejo-Garcia et al., 2012). Atypically heightened interoceptive accuracy, on the other hand, has been observed in individuals with anxiety syndromes (Paulus & Stein, 2006) and panic disorders (Ehlers & Breuer, 1992).

Previous neuroimaging studies have associated elevated interoceptive accuracy (as assessed via heartbeat detection tasks) with enhanced activation in the somatosensory cortex, the inferior frontal gyrus (IFG), the precentral gyrus and the anterior insula when paying attention to bodily sensations (Caseras et al., 2011; Critchley et al., 2004; Kuehn et al., 2016; Pollatos, Traut-Mattausch, Schroeder & Schandry, 2007b; Stern et al., 2017). Enhanced processing in these brain regions has shown to entail a more accurate perception of internal signals.

Interoceptive Accuracy and Alexithymia

In several emotion theories, the perception of physiological signals plays a crucial role for the emotional experience (Damasio, 1994; James, 1884; Schachter & Singer, 1962). As James (1884) hypothesized, the interpretation of our bodily changes subsequently following the perception of an exciting incident *is* the emotion that we are feeling. In addition, Damasio's somatic marker hypothesis (Damasio, 1994, 1999) states that bodily signals are integrated in certain brain regions, generating associations that elicit emotional states, which in turn influence cognition. Furthermore, Damasio (1999) argues for the relevance of considering the relatedness of bodily and emotional experiencing when referring to the body as the principal stage of emotions in either a direct way or an indirect way (through bodily representations in somatosensory brain regions). Thus far, a number of studies have shown that bodily sensitivity (interoceptive accuracy) is positively associated with more intense processing of emotion-eliciting stimuli (Herbert, Pollatos & Schandry, 2007; Pollatos, Kirsch & Schandry, 2005). Regions most commonly involved in the processing of non-affective interoceptive states have shown to be the AI and the ACC (Craig, 2002, 2003, 2009; Garfinkel & Critchley, 2013). Interestingly, those brain areas are also proposed to be implicated in the processing of one's own affective states (Bush, Luu & Posner, 2000; Etkin, Egner & Kalisch, 2011; Kober et al., 2008; Lindquist, Wager, Kober, Bliss-Moreau & Barrett, 2012; Phan, Wager, Taylor & Liberzon, 2002).

There is a substantial amount of research demonstrating that alexithymia (emotional blindness) may be associated with impaired interoceptive accuracy. Therefore, many researchers proposed to describe alexithymia by general deficits in interoceptive accuracy rather than by specific deficits in the emotional domain (Brewer et al., 2016a; Gaigg, Cornell & Bird, 2016; Herbert, Herbert & Pollatos, 2011; Longarzo et al., 2015; Näring & Van der Staak, 1995; Shah, Hall, Catmur & Bird, 2016). The underlying idea is that people who have problems identifying their physical state also fail to recognize which emotional state they are in. Brewer and colleagues (2016a), for instance, observed that alexithymia is related to poor affective *and* non-affective interoception. Two other studies (Herbert et al., 2011; Shah et al., 2016) discovered that highly alexithymic individuals were less accurate in detecting their own heartbeat in comparison to a control group of typical participants. On a neural level, alexithymia has been shown to involve atypical function and structure in the ACC and the anterior insular cortex (Goerlich-Dobre, Bruce, Martens, Aleman & Hooker, 2014; Ihme et al., 2013; Moriguchi et al., 2007). These brain areas also appear to be involved in the processing of interoceptive signals (Craig, 2002, 2003, 2009; Garfinkel & Critchley, 2013).

Limitations of Prior Research

In previous research, aging has not only been associated with increased prevalence of loneliness (e.g., Luhmann & Hawkley, 2016), but also with reduced interoceptive accuracy (Khalsa, Rudrauf & Tranel, 2009; Murphy et al., 2017a,b). Nonetheless, only a limited number of studies (Khalsa et al., 2009) has examined cardiac interoceptive accuracy in late adulthood. None of them investigated the cerebral activity during heartbeat detection. Overall, there is a lack of objective tests and longitudinal data, leaving several questions unanswered, including those on whether the observed decline in interoceptive accuracy is just a cohort effect and cannot be traced back to the process of aging or whether the decline is caused by psychological and physiological factors other than aging (e.g. the BMI or the heartrate frequency) (Murphy et al., 2017b). Furthermore, the relationship between loneliness and interoceptive accuracy has not been examined so far.

Aim of the study and hypothesis

The present study aims to investigate the relationship between interoceptive accuracy and loneliness in the elderly population. Because of the negative consequences of atypical (too low or too high) interoceptive accuracy and the negative consequences of loneliness, an investigation of how these two constructs are linked to and might interact with each other is of major relevance. By combining two large areas, the one of loneliness and the one of interoception, which are both of great psychological interest, we intent to close a gap within the current research literature. Results might give us new insights into the perception (interoeptive and exteroceptive) of lonely persons.

Previous studies observed a positive correlation between alexithymia and loneliness (Frye-Cox & Hesse, 2013; Qualter et al., 2009). Due to the association of alexithymia with deficits in interoceptive accuracy (e.g., Brewer et al., 2016a), we hypothesize that the level of interoceptive accuracy is decreased in lonely individuals. On a neural level, increased interoceptive accuracy was observed to involve enhanced activation in the somatosensory cortex, the inferior frontal gyrus (IFG), the precentral gyrus and the anterior insula (Caseras et al., 2011; Critchley et al., 2004; Kuehn et al., 2016; Pollatos et al., 2007b; Stern et al., 2017). Since we expect lonely participants to show reduced interoceptive accuracy, we hypothesize that they will exhibit decreased neural activity within the aforementioned brain areas (the anterior insula, the somatosensory cortex, the IFG and the precentral gyrus) during the heartbeat perception task.

Methods

Participants

Twenty-eight (17 men, 11 women) participants older than 64 years took part in the study. The mean age of men was 72.2 ± 5.6 years and the mean age of women was 70.3 ± 3.8

years. In total, the age ranged from 64 to 84 years. Participants were recruited via advertisements in Facebook groups, clubs for retirees, fairs targeting the elderly population as well as other public places such as medical practices, pharmacies or supermarkets. Potential subjects who took psychopharmalogical medication, had less than nine years of education, had a current diagnosis of psychiatric disorder, studied psychology, took part in a similar study, or did not use a computer at least once a month were excluded. Only interested persons without any health issues concerning their heart or their brain (e.g. heart attack or stroke) were included. Furthermore, possible participants had to fill in a questionnaire, which assures that they are safe for the MRI scanning (MRI Safety Questionnaire). Other exclusion criteria included colour-blindness and a score below 26 in the Minimental-Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975; Kessler, Markowitsch, & Denzler, 2000). The MMSE is a screening measure to detect initial stages of cognitive deficits. Moreover, all participants were ought to be German-speaking, right-handed and heterosexual. Due to technical errors during the scanning session, three participants had to be excluded for the behavioural part of the study.

Measures

Sociodemographic Information. For each participant sociodemographic information on gender, nationality, year of birth, education, handedness, mental illnesses, cardiac problems, last employment, last income, computer usage and sexual orientation were collected. Moreover, possible participants were required to indicate whether they have studied or are currently studying psychology and if they have already participated in a similar research project. The given information were utilized for further analysis or to exclude persons who were not eligible for the study.

Mini-Mental State Examination. The German version of the Mini-Mental State Examination (Kessler et al., 2000) was used as a tool to screen for cognitive impairment among the elderly population. Higher scores correspond to higher cognitive functioning skills (Folstein et al., 1975). The maximum score is 30. Content of the items regard the local and temporal orientation of a person. Participants were required to answer 28 questions concerning five dimensions of cognitive functioning (*Orientation, registration, attention and calculation, recall and language)*. Example items are, “What is the month?” [Welcher Monat ist gerade?] and “In which town are we?“ [In welcher Stadt befinden wir uns?]. The test-retest reliability of MMSE was satisfactory (r_{tt} = .89) (Kessler et al., 2000). The cut-off threshold for the MMSE was set at 26, whereas persons who scored below 26 were excluded for further analysis.

Loneliness. In order to measure the individual level of loneliness for each participant, the third version of the UCLA (University of California, Los Angeles) Loneliness Scale (Russell, 1996) was applied. The UCLA Loneliness Scale (UCLA-LS) is a self-report questionnaire consisting of 20 items, such as, “How often do you feel that you lack companionship?”, or, “How often do you feel alone?”. The participants were requested to answer all of them on a four-point Likert scale (never, rarely, sometimes and always). The total score can range from 20 to 80, whereat higher scores correspond to higher levels of loneliness. The psychometric properties of the UCLA-LS (Version 3) were also evaluated amongst a sample of elderly individuals, over 65 years of age (Russell, 1996). Results indicate that the UCLA-LS is very reliable, showing a test-retest correlation of .73 (for the elderly population). Internal consistency ranged from Cronbach’s α = .89 to .94 for four different populations (college students, nurses, teachers and elderly). Construct validity was provided by significant correlations of loneliness with other instruments measuring well-being, health and the adequacy of interpersonal relationships in each population. Convergent validity was supported by significant associations with other instruments measuring loneliness. The cut-off threshold for loneliness was set at ≥ 40 by the authors of the UCLA-LS (Russell, 1996). For this study, the threshold was set at 33.6 (mean value of the sample) to achieve a balanced distribution of non-lonely and lonely participants. After conducting a mean split, participants with a score ≥ 34 were assigned to the lonely group.

Anxiety. Due to relations between anxiety and both, loneliness (e.g. Cacioppo et al., 2014) and interoceptive accuracy (e.g., Domschke, Stevens, Pfleiderer & Gerlach, 2010), the German version of the State-Trait-Anxiety Inventory (STAI; Grimm, 2009) was applied to measure anxiety. The STAI was designed by Spielberger and colleagues (1970) who distinguished between two different dimensions: anxiety as a personality trait and anxiety as a state. Trait anxiety is described as the general tendency of perceiving anxiety, whereas state anxiety is defined as the current level of anxiety a person experiences (Grimm, 2009). Since the participants filled in the questionnaire on a different day other than the scanning session took place, only the trait and not the state subscale of the STAI was assessed. The trait version of the STAI includes 20 items and is answered on a four-point Likert scale ranging from 1 (“almost never”) to 4 (“almost always”). It provides a score ranging from 20 to 80, with higher scores corresponding to higher levels of anxiety. An example of an item is, “I am happy” [Ich bin glücklich]. Good internal consistency was found for the original trait version in community-dwelling older adults with Cronbach’s α ranging from .79 to .90 (Himmelfarb & Murrell, 1984; Stanley, Beck & Zebb, 1996).

Depression. In order to measure the level of depression, a German translation of the second version of the Beck-Depression-Inventory (BDI-II; Kühner, Bürger, Keller & Hautzinger, 2007) was handed to the participants. It a self-report questionnaire consisting of 21 items. Each item is answered on a four-point Likert-type scale, ranging from 0 to 3, whereas higher scores correspond to higher levels of depression within the past two weeks. The items measure diagnostically crucial symptoms of depression such as sadness, pessimism, past failure, crying, worthlessness, loss of pleasure, guilty feelings, punishment feelings, suicidal thoughts, concentration difficulty, etc. An example of an item is, "Sadness: 0 ('I am not sad'); 1 ('I am often sad'); 2 ('I am always sad'); 3 ('I am so sad and unhappy that I cannot stand it')" [Traurigkeit: 0 ('Ich bin nicht traurig'); 1 ('Ich bin oft traurig'); 2 ('Ich bin ständig traurig'); 3 ('Ich bin so traurig und unglücklich, dass ich es nicht aushalte')]. Kühner et al. (2007) propose values of the internal consistency ranging from .84 to .94. Scores that range from 0 to 13 denote no or minimal depression, those that range from 14 to 19 denote mild depression, scores of 20 to 28 are indicative for moderate and those of 29 to 63 for severe depressive symptomatology.

Alexithymia. Since previous research suggests an association of alexithymith both, loneliness (Qualter et al., 2009), as well as interoceptive accuracy (e.g., Brewer et al., 2016a), the German version of the 20-item Toronto-Alexithymia-Scale (TAS-20; Bach, Bach, de Zwaan, Serim & Böhmer, 1996) was administered for this study. The TAS-20 measures alexithymia on the basis of self-report and includes three subscales: *Difficulty Identifying Feelings (DIF)*, *Difficulty Describing Feelings (DDF)* and *Externally-Oriented Thinking (EOT)*. An example of an item is, "I am often confused about what emotion I am feeling" [Mir ist oft unklar, welche Gefühle ich gerade habe]. Items were rated on a five-point Likert scale (doesn't apply at all, does rather not apply, partially applies, largely applies and fully applies). Results of Bach and colleagues (1996) showed an adequate internal consistency of the total scale (Cronbach's $\alpha = .70$ for a non-clinical sample). The TAS-20 uses a cut-off scoring: scores less than 51denote no alexithymia, scores from 52 to 60 denote possible alexithymia and scores equal to or above 61 denote alexithymia (Bagby, Taylor & Parker, 1994).

Interoceptive Accuracy. To measure interoceptive accuracy a variant of the *heartbeat tracking task,* originally developed by Schandry (1981), was applied. For this study an fMRI design similar to the one implemented by Wiebking (e.g., Wiebking et al., 2010) was utilized. Wiebkings' design included three different experimental conditions - an interoceptive task (heartbeat counting), an exteroceptive task (tone counting) and rest periods. In the present study, the aforementioned design was modified by replacing the rest periods with a time estimation condition. Anyhow, the time estimation condition was added to the task because both abilities, heartbeat counting, as well as time estimation require an activation of the insular cortex (Wittmann, 2013). Hence, subjective time estimation could be impacted by one's ability to perceive the heartbeat, which might serve as an internal reference (Wittmann, 2013). Since current literature suggests that the tone counting condition is much more common as control task (e.g., Schulz, 2016), only the data of the tone counting condition and not those of the time estimation were analysed. For the sake of completeness, the tone counting condition was nevertheless described within this section.

During the interoceptive task (IT), participants were instructed to count their heartbeat without the help of any external manipulation (e.g. measuring the pulse on the lower forearm or at the throat). Each trial had the same structure: resting period, preparation period, condition and one or two rating periods. At the beginning of the trial a black fixation cross on a white screen was shown to the participant (resting period). Afterwards the preparation period began. Here, the display of a grey symbol (in this case the symbol of a heart) served as a signal for the participant to know which task is next. He/ she had three seconds of time (indicated by dots) to prepare for the task. When the grey heart turned black, the actual condition began and the participant started to count his/ her heartbeat until the black symbol disappeared again. Subsequently, the participant had to rate how many heartbeats he/ she counted (rating period). In case he/ she did not perceive his/ her heartbeat at all, the participant was instructed to answer "0".

The exteroceptive task (ET) had the same structure as the interoceptive task (resting period, preparation period, condition and rating period), with the difference that the symbol to indicate the task type was a musical note. During this task, the participants were instructed to silently count pulsating tones played by the scanner loud speaker. To make the frequency of the tones distinguishable from the scanner noise, it was set to 440 hz. The duration of the tones was set to 200 ms in order to adjust them to the possible duration of a heartbeat. Since each of the three conditions should be comparable in terms of difficulty, the volume of the tones was calibrated individually by each participant so that it was just audible, like the heartbeat (see study procedure). The stimulus frequency was matched to the participant's heart rate with a jitter of 200 ms to avoid habituation effects. After the condition took place, the participant was asked to report the number of counted tones. The exteroceptive task was chosen to control for neural responses to external stimuli compared to internal stimuli and as well for the control of general effects of counting (see Schulz, 2016).

During the time estimation task (TE) the participants were requested to count the elapsed time of an interval in seconds. The structure of the task was the same as in the other two tasks (resting period, preparation period, condition and one or two rating period), with the difference that the symbol to illustrate the type of the task was depicted by a clock. After the condition took place, the participant was asked to rate the number of counted seconds in the same way as in the other two task.

The total experiment consisted of 18 trials so that each of the three tasks was executed six times. As mentioned before, each trial had the same structure (resting period, preparation period, condition and one or two rating periods). The resting period was jittered and had a duration of 5 ± 2 seconds. The preparation period had a fixed duration of 3 seconds. The condition (IT/ ET/ TE) was jittered and had a variable duration of 20 ± 5 seconds. The duration of the rating period was variable as well (depending on the participant's velocity) and took place after each trial. After the middle and the end trials of each of the three tasks there was a confidence rating. On a continuous visual scale ranging from 'not confident at all' on one end to 'very confident' on the other end, the participant was asked to indicate the degree of perceived confidence regarding his/ her rating in the step before. In the middle of the experimental task (after the 9^{th} trial) the participants had a short break of 10 seconds.

fMRI Data Acquisition

The fMRI data was acquired using a Siemens Magnetom Skyra 3-Tesla MRI-system (Siemens Medical, Erlangen, Germany) which was equipped with a 32-channel head coil. It was located at the dental clinic of the University of Vienna. For the MR-scanning, a gradient-recalled echo-planar imaging-system with correction of distortion (echo time = 34 ms, repetition time = 704 ms, voxel size = 1.5 × 1.5 × 5 mm, 32 slices, fractional anisotropy (FA) = 50°) was applied. For the behavioural task and the stimulus presentation (the tones during the sound calibration) MATLAB R2017b (MathWorks) was utilized. Stimuli were presented and recorded using Cogent 2000, a toolbox implemented in MATLAB.

Study procedure

The *heartbeat tracking task* was conducted within the context of a larger fMRI research project. Therefore, participants were required to execute two further tasks in the MR-scanner (an economic game and a social touch task). Since those tasks are irrelevant for the present research question, they will not be mentioned in the subsequent description of the study procedure.

As a first step, potential subjects, who expressed their interest in participating in the study, were asked to fill out three online questionnaires containing sociodemographic information, the MRI Safety Questionnaire, as well as the UCLA-LS. If they were eligible for the study, they needed to orally confirm during a personal phone call that they had no risk factors regarding MRI scanning (e.g. wearing permanent make-up or having unremovable metal parts such as implants in the body). Next, they were invited to a screening appointment, during which they were asked to fill out several instruments including the STAI, the BDI-II and the TAS-20. Additionally, they were requested to perform the MMSE. After arranging an appointment for the scanning session, they received an e-mail with the informed consent, a document designed to teach about the rights and responsibilities of study participants. On arrival, the MRI Safety Questionnaire and the informed consent were handed to the participant in order to check again for MRI-related risks and to give the subject the opportunity to clarify remaining questions. It was only proceeded with the experiment if the participant signed the two beforementioned forms. Subsequently, the participant was invited to enter the scanning area where the test administrator explained the structure of the experiment. To obtain more detailed instructions and to practice each task, the participant underwent a short computer training (outside of the MR-scanner). Since the stimulus frequency of tones during the exteroceptive condition was individually adapted to each participant's heartrate, the pulse was measured prior to the interoception training. Moreover, before the interoception training a short heartbeat perception training was performed, during which the participant should lean back, relax and try to focus on his/ her heartbeat without manually measuring it. In case the participant couldn't perceive his/ her heartbeat, he/ she was instructed to concentrate on his/ her breath and to try it again. If he/ she couldn't feel his/ her heartbeat at all he/ she should answer "0" in the rating of counted heartbeats. The interoception training consisted of six practice trails (two per condition) that were presented to the participant in a pseudorandomized sequence. Before entering the MR-scanner for the execution of the experimental tasks, the test administrator made sure that the participant did not carry any metal objects with him/ her. In the MR-scanner a head coil was placed over the participant's face. Above, a mirror was installed with which the participant was able to see the instructions of the task on a monitor behind him/ her. Furthermore, the response box, a remote control that enabled the participant to perform the task, was fixated upon his/ her right side. Another device, the pulsemeter, served to measure the participant's heartrate.

Inside the MR-scanner, prior to the actual conduction of the *heartbeat tracking task*, the subjects were requested to complete the following steps:

Sound calibration. The individual adaption of the volume of tones for the exteroceptive task was conducted by means of the sound calibration. During the sound calibration pulsating tones with increasing or decreasing volume were presented via the scanner loud speaker to the participant. The participant was instructed to press a bottom as soon as he hears the tones (increasing volume) or does not hear the tones any longer (decreasing volume). In total, there were four trials (two with increasing and two with decreasing volume). Thus, the final volume for the exteroceptive condition was the average of all four trials.

Heartbeat Perception Training. Similar to the heartbeat perception training outside the MR-scanner, there was also a heartbeat perception training inside the scanner. Several participants reported that they had difficulties perceiving their heartbeat due to the MR-scanner noise. Hence, they had the opportunity to focus on their heartbeat for one minute with the MR-scanner turned on before the actual task started.

Subsequently, the *heartbeat tracking task* was conducted. In total, the task comprised 18 trials in a pseudorandomized order and had a duration of approximately 15 minutes. The participant could communicate via intercom with the qualified user of the MR-scanner. (To ensure the participant's comfort, frequent communication was preferred.) In case of emergency, the participant could press the alarm bottom and leave the MR-scanner immediately. After the conduction of the three experimental tasks, the structural image (T1) and the resting state were acquired. Later on, the participant left the scanner and orally answered several feedback questions about the experiment. He/ she was asked whether he/ she wanted to sign a contact form for subsequent studies. As incentive the participant received an image of his/ her brain (via e-mail or via mail) and a payment of 40 € plus a maximum of 5 € (the amount of money he/ she gained in the economic game).

Data Analysis

Behavioral and Statistical analysis. Acquisition and analysis of the behavioral data (the perception scores) was conducted using MATLAB R2017b (MathWorks). Further statistical analyses of the perception scores and the questionnaire data was done applying IBM SPSS Statistics Software (SPSS 20).

To analyse interoceptive (ITacc) and exteroceptive accuracy (ETacc), two perception scores were calculated for each participant (see Schandry, 1981; Shah et al., 2016; Herbert et al., 2011, Kuehn et al, 2016):

ITacc score = 1/6 ∑ (1 – (|actual heartbeats − counted heartbeats|)/actual heartbeats)

ETacc score = 1/6 ∑ (1 – (|actual number of tones – counted number of tones|/actual number of tones)

The perception score is determined by the use of the mean score of all intervals (in total there were six intervals for each condition). It varies from 0 to 1, whereas a higher number indicates a higher level of perceptive accuracy.

Concerning the ITacc scores, winsorization was implemented in order to deal with outliers (e.g. those participants who couldn’t perceive their heartbeat and answered “0”).

In order to test for associations between sociodemographic, questionnaire and behavioral data, several Pearson’s Product-Moment Correlations were performed on all measures (Sociodemographic data, MMSE, UCLA-LS, STAI-T, BDI-II, TAS-20, ITacc and ETacc,).

To define a threshold for the non-lonely and the lonely group, we performed a mean split. Afterwards, we conducted several Welch’s t-tests (due to unequal variances) to observe whether the two groups differ significantly from each other in terms of loneliness (UCLA-LS score), age and cognitive functioning (MMSE score). Moreover, several independent-samples t-tests of the loneliness groups with other variables (Education, STAI-T, BDI-II, TAS-20, ITacc and ETacc) were conducted to assess differences between the two groups.

Furthermore, we conducted a two-way (2 × 2) mixed ANOVA with the within-subject factor condition (IT vs. ET) and the between-subject-factor loneliness (non-lonely vs. lonely) to test for differences of IT and ET depending on the loneliness group. Another reason for the conduction of the two-way (2 × 2) mixed ANOVA was to observe differences in the task difficulty.

In order to test whether there were more participants who couldn’t perceive their heartbeat in the lonely group than in the non-lonely group, a Fisher’s Exact Test was used. Since the sampling distribution of the test statistic was too deviant from a chi-square distribution, the assumptions for the more commonly used chi-square test were not met.

fMRI analysis. For the fMRI data analysis the 12th version of the software package Statistical Parametric Mapping (SPM 12, Wellcome Trust Center of Neuroimaging) implemented in MATLAB was applied. The preprocessing included the following procedures: realignment, unwarping, coregistration of the structural to the functional data, segmentation of tissue classes in anatomical scans, normalization and smoothing of the functional images. Only spatial preprocessing was conducted. For the subject-level analysis, four regressors were created: one for the interoceptive condition, one for the exteroceptive condition, one for the time estimation condition and one for the preparation period. For the model specification, not only onset and duration of the three conditions (IT, ET and TE) were modelled, but also onset and duration of the preparation period, the rating period and the text (containing the onset and duration of the break and the ending screen). The realignment parameter was added to the model specification as an additional regressor. Convolution of the regressors with the canonical hemodynamic response function (HRF) was used to predict the blood-oxygen-level dependent (BOLD) response. For the group-level analysis, a full factorial analysis of variance containing two factors, namely the between-subject factor group (lonely versus non-lonely) and the within-subject factor condition (IT and ET), was computed.

Results

Behavioral results

Descriptive Statistics. Descriptive statistics were performed on each measure. Table 1 therefore illustrates sample sizes, means, standard deviations and ranges of sociodemographic, behavioral and questionnaire data.

Table 1

Sample Sizes, Means, Standard Deviations and Ranges for Sociodemographic Data and Scores on the MMSE, UCLA-LS, STAI-T, BDI-II, TAS-20, ITacc and ETacc

Variable	n	*M*	*SD*	Min	Max
Age	25	71.40	5.30	64	84
Education[1]	24	12.96	2.10	9	17
MMSE	25	29.16	0.90	27	30
UCLA-LS	25	33.60	10.64	22	67
STAI-T	21	30.57	7.18	20	51
BDI-II	24	3.79	3.78	0	12
TAS-20	24	44.79	10.79	28	70
ITacc	25	0.44	0.29	0.10	0.95
ETacc	24	0.94	0.15	0.31	1

Note. Min = Minimum; Max = Maximum; MMSE = Minimental-Mental Examination Test; UCLA-LS = University of California, Los Angeles – Loneliness Scale; STAI-T = State-Trait-Anxiety Inventory-Trait Version; BDI-II = Beck Depression Inventory-II; TAS-20 = 20-item Toronto-Alexithymia-Scale; ITacc = interoceptive accuracy; ETacc = exteroceptive accuracy. * indicates p < .05. ** indicates p < .01.

Correlational Analysis.[2] Correlational analysis showed that age correlated significantly with depression (BDI-II score; r = .43, *p* = .037) and alexithymia (TAS-20 score; r = .46, *p* = .024). Education and cognitive functioning (MMSE score) were not found to correlate with any other variable. Loneliness (UCLA-LS score) was associated significantly with depression (r = .68, *p* < .001) and alexithymia (r = .82, *p* < .001). Anxiety only correlated significantly with depression (r = .54, *p* = .011). Depression correlated significantly with several other constructs, namely age, loneliness, anxiety, alexithymia (r = .76, *p* < .001) and interoceptive accuracy (r = -.49, *p* = .016). Alexithymia was associated significantly with age,

[1] Indicated in years.
[2] Previous literature suggested that interoceptive accuracy is associated significantly with age (e.g., Murphy et al., 2017b) and the BMI (e.g., Rouse, Jones & Jones, 1988). Since we couldn't find such associations in our data, we didn't control for age and the BMI during data analysis.

loneliness, depression and interoceptive accuracy (r = -.42, *p* = .41). Interoceptive accuracy was associated significantly with depression and alexithymia. Exteroceptive accuracy showed no significant correlation to any construct included in the analysis (see Table 2).

Table 2

Means, Standard Deviations and Correlations for Sociodemographic Data and Scores on the MMSE, UCLA-LS, STAI-T, BDI-II, TAS-20, ITacc and ETacc

Measure	*M*	*SD*	1	2	3	4	5	6	7	8	9
1. Age	71.40	5.30	−	-.11	-.28	.24	-.17	.43*	.46*	-.21	-.32
2. Education	12.96	2.10	-.11	−	.16	-.02	-.07	-.28	-.11	.30	-.07
3. MMSE	29.16	0.90	-.28	.16	−	.08	.04	.09	.21	.02	.15
4. UCLA-LS	33.60	10.64	.24	-.02	.08	−	.34	.68**	.82**	-.31	-.11
5. STAI-T	30.57	7.18	-.17	-.07	.04	.34	−	.54*	.39	-.28	.09
6. BDI-II	3.79	3.78	.43*	-.28	.09	.68**	.54*	−	.76**	-.49*	.17
7. TAS-20	44.79	10.79	.46*	-.11	.21	.82**	.39	.76**	−	-.42*	-.16
8. ITacc	.44	.29	-.21	.30	.02	-.31	-.28	-.49*	-.42*	−	.06
9. ETacc	.94	.15	-.32	-.07	.15	-.11	.09	.17	-.16	.06	−

Note. MMSE = Minimental-Mental State Examination; UCLA-LS = University of California, Los Angeles – Loneliness Scale; STAI-T = State-Trait-Anxiety Inventory-Trait Version; BDI-II = Beck Depression Inventory-II; TAS-20 = 20-item Toronto-Alexithymia-Scale; ITacc = interoceptive accuracy; ETacc = exteroceptive accuracy. * indicates *p* < .05. ** indicates *p* < .01.

Analysis of Variance. After conducting a mean split, the 13 participants with higher scores were assigned to the lonely group (*M* = 41.08 ± 9.74), while the 12 participants with lower scores were assigned to the non-lonely group (*M* = 25.50 ± 2.43). The independent Welch's t-tests revealed that the two groups significantly differed in loneliness (*t*(13.61) = -5.58, *p* = .000) but not in age (*t*(17.14) = -1.32, *p* = .204) and cognitive functioning (*t*(16.15) = -0.40, *p* = .699). Subsequently, several indepenent-samples t-tests were implemented to test for differences between the loneliness groups with regard to sociodemographic, behavioral and questionnaire data. Further results revealed that the loneliness groups differed significantly in depression (*t*(22) = - 2.64, *p* = .015) and alexithymia (*t*(22) = - 3.66, *p* = .001), indicating that participants of the lonely group showed increased levels of depression and alexithymia. On average, no significant difference between lonely and non-lonely participants was observed in education (*t*(22) = -0.30, *p* = .770), anxiety (*t*(19) = - 1.75, *p* = .096), ITacc (*t*(23) = 1.37, *p* = .18) and ETacc (*t*(22) = .57, *p* = .58) (see Table 3).

Table 3

Results of t-tests and Descriptive Statistics for Sociodemographic Data and Scores on the MMSE, UCLA-LS, STAI-T, BDI-II, TAS-20, ITacc and ETacc by lonely group

	Lonely group						95% CI for Mean Difference		
	Non-lonely			Lonely					
	M	*SD*	n	*M*	*SD*	n		*t*	*df*
Age	70	3.05	12	72.70	6.63	13	-6.99, 1.60	-1.32	17.14
Education	12.82	2.36	11	13.08	1.94	13	-2.08, 1.56	-0.30	22
MMSE	29.08	1.17	12	29.23	0.60	13	-0.94, 0.65	-0.39	16.15
UCLA-LS	25.50	2.43	12	41.08	9.74	13	-21.58, -9.57	-5.58**	13.61
STAI-T	27.56	6.23	9	32.83	7.25	12	-11.59, 1.03	-1.75	19
BDI-II	1.82	2.79	11	5.46	3.78	13	-6.50, -.79	-2.64*	22
TAS-20	37.73	7.50	11	50.77	9.58	13	-20.43, -5.66	-3.66**	22
ITacc	.52	.25	12	.36	.31	13	-.08, .39	1.37	23
ETacc	.96	.08	12	.92	.20	12	-.10, .17	.57	22

Note. MMSE = Minimental-Mental State Examination; UCLA-LS = University of California, Los Angeles – Loneliness Scale; STAI-T = State-Trait-Anxiety Inventory-Trait Version; BDI-II = Beck Depression Inventory-II; TAS-20 = 20-item Toronto-Alexithymia-Scale; ITacc = interoceptive accuracy; ETacc = exteroceptive accuracy.* indicates p < .05. ** indicates p < .01.

Do lonely individuals show decreased levels of interoceptive accuracy as predicted in the first hypothesis? To assess the levels of ITacc and ETacc in the two loneliness groups and to compare the difficulty of the two conditions (IT and ET), a two-way (2 × 2) mixed ANOVA was conducted. There was no significant interaction between condition and loneliness group (F(1,22) = 1.44, p =.243, η_{p2} = .243). Due to the non-significant interaction, the two main effects can be interpreted without any restrictions. The main effect of condition (IT vs. ET) was significant (F(1,22) = 64.147, p =.000, η_{p2} = .745). Bonferroni *post hoc* tests revealed that the perception scores of the interoceptive condition were significantly lower compared to those of the exteroceptive condition (p < .01). Thus, the interoceptive condition appeared to be the more difficult condition. There was a non-significant main effect of the loneliness groups on the two conditions (F(1,22) = 2.96, p = .099, η_{p2} = .119). Although this main effect was not significant, there was the tendency (p = .099) that participants of the lonely group (M = .63, SE = .046) achieved lower perception scores than those of the non-lonely group (M = .74, SE = .046). Due to the medium effect size (η_{p2} = .119), a significant main effect might be expected when considering a bigger sample size. Figure 1 displays means and standard deviations of the two loneliness groups on ITacc and ETacc.

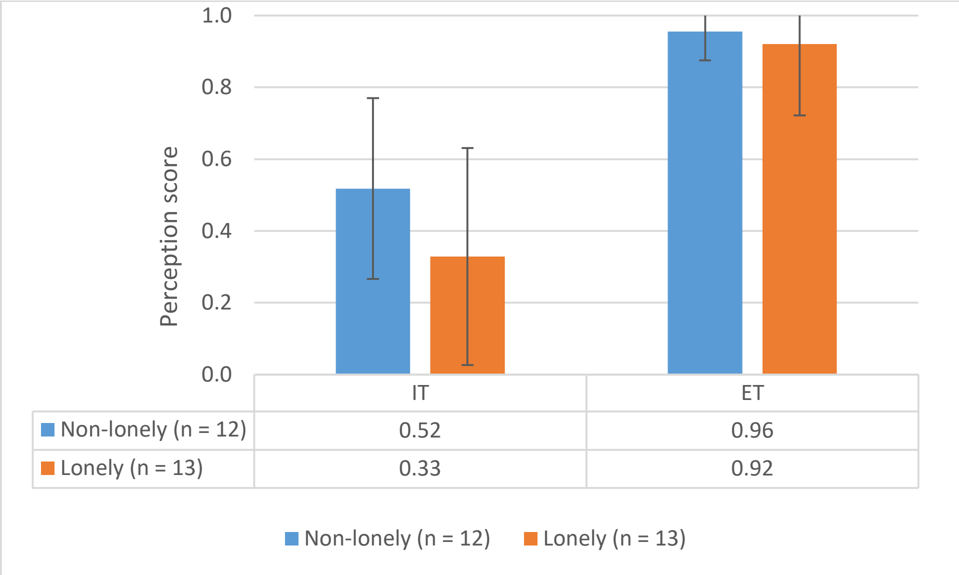

Figure 1. Mean perception scores for the loneliness groups. Error bars indicate one standard deviations (± 1 SD) around the mean. IT = Interoceptive task; ET = Exteroceptive task.

Analysis of Frequency. To assess whether or not there were more participants who couldn't perceive their own heartbeat in the lonely group, we conducted a Fisher's Exact Test. The test revealed that there was a non-significant association between the loneliness group and whether or not the participants would perceive their own heartbeat (p = .160).

fMRI results

For all contrasts, which are listed below, no masking was applied. The threshold of the significance level was used uncorrected and it was set at p = .001. Furthermore, a cluster-extent threshold of $k \geq 10$ voxels that are significantly active was utilized. The Automated Anatomical Labeling (AAL) running on MRIcron was applied in order to report the brain areas. The subsequent analysis was conducted considering the whole brain. Only main and interaction effects regarding the hypothesis are presented below.

Main effect of condition. The main effect of the interoceptive compared to the exteroceptive condition revealed significant activation within the left posterior cingulate gyrus, the left and right precuneus, the right rolandic operculum, the right supramarginal gyrus, the left middle temporal gyrus, the left angular gyrus, the right middle frontal gyrus, the left and right posterior insula, the right middle insula, the left superior frontal gyrus, the right cerebellum exterior and the left superior temporal gyrus (see Table 4 and Figure 2). Only the activation in the left posterior cingulate gyrus and the left precuneus remained significant after the correction of the family-wise error.

Table 4

Main effect of condition (interoceptive > exteroceptive)

Anatomical Region	H	cluster K	T	Z score	x, y, z
Posterior cingulate gyrus	L	583	5.38	4.77	-4, -48, 30
Precuneus	L		5.29	4.71	-8, -54, 34
Precuneus	R		4.14	3.83	4, -58, 26
Rolandic operculum	R	150	4.73	4.30	50, -20, 18
Rolandic operculum	R		4.44	4.07	40, -20, 18
Rolandic operculum	R	86	4.29	3.95	50, -4, 8
Supramarginal gyrus	R		3.95	3.68	54, -28, 30
Supramarginal gyrus	R	24	3.98	3.70	60, -18, 28
Supramarginal gyrus	L	11	3.72	2.48	-58, -28, 24
Middle temporal gyrus	L	46	4.22	3.89	-54, -64, 22
Middle temporal gyrus	L	4	3.59	3.37	-52, 2, -18
Middle temporal gyrus	L	5	3.47	3.27	-52, -58, 4
Middle temporal gyrus	L	4	3.46	3.26	-44, -58, 16
Middle temporal gyrus	L	1	3.37	3.19	-56, -10, -8
Middle temporal gyrus	L	1	3.31	3.14	-58, -64, 4
Angular gyrus	L		3.43	3.24	-52, -58, 28
Middle frontal gyrus	R	14	3.92	3.65	36, 20, 36
Posterior insula	R	20	3.93	3.66	38, -18, 6
Posterior insula	L	2	3.57	3.36	-42, -8, 6
Middle insula	R	5	3.73	3.49	36, 6, 10
Superior frontal gyrus	L	11	3.66	3.44	-16, 56, 28
Cerebellum exterior	R	1	3.49	3.29	26, -68, -30
Superior temporal gyrus	L	1	3.37	3.19	-56, -10, -8

Note. H = hemisphere; R = right; L = left. Coordinates are given in mm. p = .001 (uncorrected).

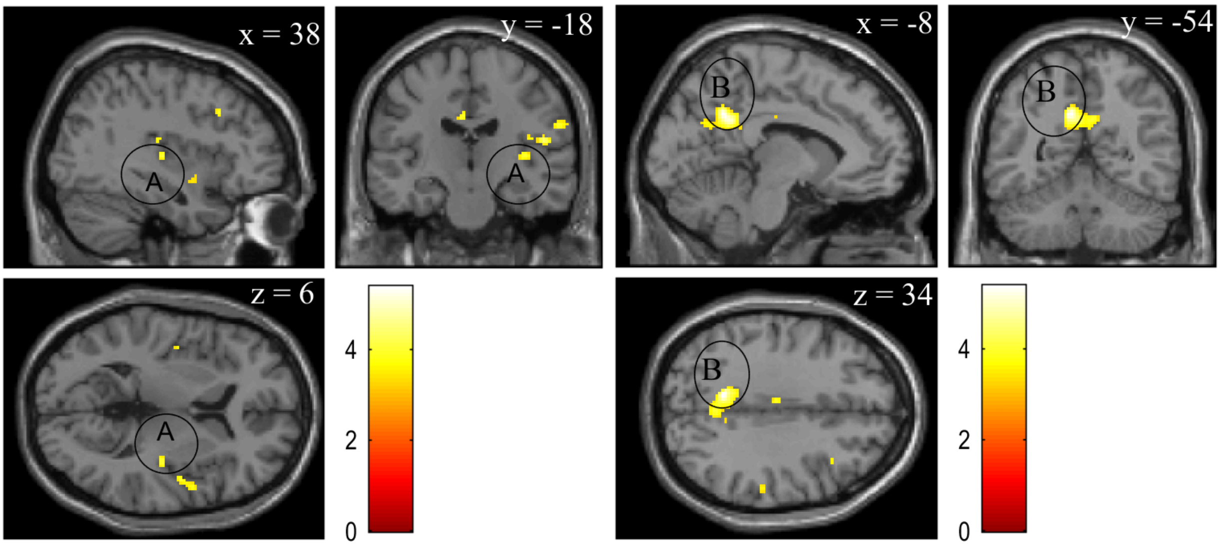

Figure 2. Increased activations for the main effect of condition (*interoceptive* > *exteroceptive*) were found i.a. in the right posterior insula (A) and the left precuneus (B). The sample size was n = 28.

Interaction loneliness x condition. *Do lonely participants exhibit decreased neural activity within the anterior insula, the somatosensory cortex (postcentral gyrus), the inferior frontal gyrus and the precentral gyrus during the heartbeat perception task?* This hypothesis could be supported. The interaction between loneliness and condition (non-lonely (interoceptive > exteroceptive) > lonely (interoceptive > exteroceptive)) showed significantly greater activation of the non-lonely when compared to the lonely in the following areas: the left precentral gyrus, the right rolandic operculum, the left and right caudate, the bilateral triangular part as well as the right opercular part of the inferior frontal gyrus, the left lingual gyrus, the right supplementary motor area, the left and right supramarginal gyrus, the left superior temporal gyrus, the right anterior insula, the left and right middle insula, the right superior parietal gyrus, the left and right superior frontal gyrus, the right postcentral gyrus, the right middle frontal gyrus and the right angular gyrus (see Table 5 and Figure 3). No activation remained significant after the correction of the family-wise error.

For the opposite contrast, when comparing the lonely group with the non-lonely one with regard to the difference in interoceptive versus exteroceptive accuracy (lonely (interoceptive > exteroceptive) > non-lonely (interoceptive > exteroceptive)), no significant activation could be found. In other words, the lonely group showed in no brain area greater activation than the non-lonely group during the interoceptive condition when contrasted with exteroceptive condition.

Table 5

Interaction effect of loneliness x condition: non-lonely (interoceptive > exteroceptive) > lonely (interoceptive > exteroceptive)

Anatomical Region	H	cluster K	T	Z score	x, y, z
Precentral gyrus	L	58	4.77	4.32	-38, 2, 60
Precentral gyrus	L	1	3.32	3.14	-50, 12, 42
Rolandic operculum	R	52	4.68	4.26	44, -20, 20
Rolandic operculum	R	3	3.44	3.25	50, 6, 12
Caudate	L		3.50	3.30	-20, -16, 26
Caudate	R		3.50	3.30	20, -10, 22
Caudate	L	14	3.53	3.33	-20, 0, 22
Caudate	R	2	3.36	3.18	18, 6, 24
Inferior frontal gyrus (triangular)	L	51	4.09	3.79	-48, 16, 30
Inferior frontal gyrus (triangular)	L	12	3.64	3.42	-38, 26, 8
Inferior frontal gyrus (triangular)	R	10	3.70	3.47	40, 30, 6
Inferior frontal gyrus (opercular)	R	53	3.86	3.60	58, 14, 32
Inferior frontal gyrus (opercular)	R		3.65	3.43	58, 10, 24
Inferior frontal gyrus (opercular)	R	8	3.46	3.26	52, 16, 18
Inferior frontal gyrus (opercular)	R	2	3.37	3.19	58, 20, 20
Lingual gyrus	L	11	3.81	3.57	-22, -64, -2
Supplementary motor area	R		3.69	3.46	14, -2, 52
Supplementary motor area	R	50	4.08	3.78	8, 2, 56
Supramarginal gyrus	R	106	3.99	3.71	48, -32, 46
Supramarginal gyrus	L	41	3.71	3.48	-58, -46, 24
Superior temporal gyrus	L		3.57	3.36	-62, -38, 24

(continuous)

Table 6

Interaction effect of loneliness x condition: non-lonely (interoceptive > exteroceptive) > lonely (interoceptive > exteroceptive)

Anatomical Region	H	cluster K	T	Z score	x, y, z
Anterior insula	R	18	3.67	3.45	38, 16, 6
Anterior insula	R	6	3.49	3.29	42, 22, 0
Anterior insula	R	5	3.49	3.29	32, 30, 10
Middle insula	R	43	4.16	3.85	34, 2, 16
Middle insula	R	11	3.80	3.55	48, 6, -4
Middle insula	L	24	3.59	3.38	-46, 0, 6
Middle insula	R	9	3.49	3.29	46, 4, 6
Middle insula	L	2	3.30	3.13	-32, 4, 16
Superior parietal gyrus	R	21	3.62	3.40	18, -74, 56
Superior parietal gyrus	R		3.42	3.23	26, -68, 56
Superior frontal gyrus	L	16	4.51	4.13	-14, 8, 72
Superior frontal gyrus	R	6	3.56	3.35	26, 0, 64
Postcentral gyrus	R	2	3.37	3.19	44, -38, 62
Middle frontal gyrus	R	4	3.51	3.31	30, 14, 58
Middle frontal gyrus	R	4	3.44	3.25	32, 50, 30
Middle frontal gyrus	R	2	3.38	3.20	38, 50, 20
Middle frontal gyrus	R	1	3.34	3.16	34, 44, 34
Middle frontal gyrus	R	1	3.33	3.16	42, 2, 58
Angular gyrus	R	2	3.36	3.18	32, -56, 48

Note. H = hemisphere; R = right; L = left. Coordinates are given in mm. p = .001 (uncorrected).

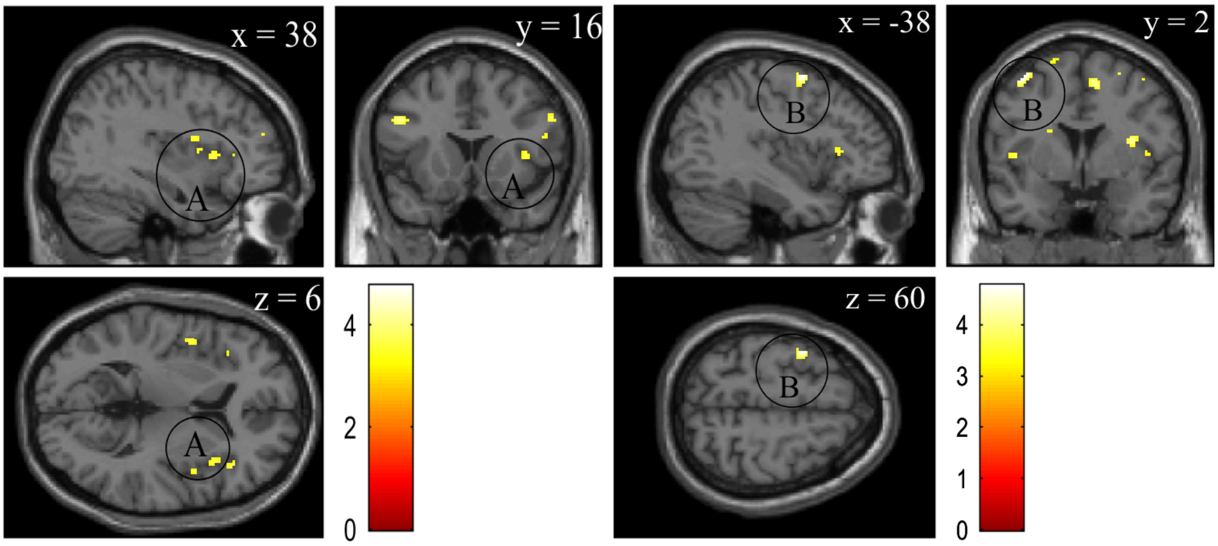

Figure 3. Increased activations for the interaction effect loneliness x condition *(non-lonely (interoceptive > exteroceptive) > lonely (interoceptive > exteroceptive*) were discovered i.a. in the right anterior and middle insula (A) and the left precentral gyrus (B). The sample size was n = 28.

Discussion

Our research examined, whether the level of interoceptive accuracy is decreased in lonely individuals when compared to non-lonely persons. In particular, we investigated whether the interoceptive accuracy scores on a *heartbeat tracking task* (originally developed by Schandry, 1981) were significantly lower in the lonely group (participants who scored above 33.6 on the UCLA-LS). Prior research discovered that the level of alexithymia (emotional blindness) was enhanced in individuals reporting greater loneliness (Frye-Cox & Hesse, 2013; Qualter et al., 2009). Other studies, which aimed to investigate the link between alexithymia and interoceptive accuracy, observed that highly alexithymic individuals displayed significantly lower levels of both, affective *and* non-affective interoceptive accuracy (Brewer et al., 2016a). Thus, several researchers proposed that alexithymia should rather be described by general deficits in interoceptive accuracy, rather than by impairments specific to the affective domain (e.g., Herbert et al., 2011; Shah et al., 2016). However, due to the associations mentioned above, we hypothesized that if lonely individuals may display elevated levels of alexithymia, they might consequently show decreased levels of interoceptive accuracy. Our second hypothesis stated that lonely participants exhibit decreased neural activity within certain brain areas (the anterior insula, the somatosensory cortex, the inferior frontal gyrus and the precentral gyrus) that have been associated with interoceptive accuracy in prior studies (Caseras et al., 2011; Critchley et al., 2004; Kuehn et al., 2016; Pollatos et al., 2007b; Stern et al., 2017). Our results indicated no significant difference of interoceptive accuracy between the two loneliness groups on a behavioral level. However, we could find a tendency that participants in the lonely group showed less accurate perceptive abilities in comparison to participants in the non-lonely group. Due to the medium effect size observed for this main effect, significant results are to be expected when considering a larger sample. In terms of the second hypothesis, we found evidence to be able to support it completely. In line with other studies, significant activation was observed inter alia within the anterior insula (e.g., Critchley et al., 2004), the middle insula (Kelly et al., 2012; Kurth, Zilles, Fox, Laird & Eickhoff, 2010), the precentral gyrus (e.g., Simmons et al., 2013), the opercular and triangular part of the inferior frontal gyrus (Critchley et al., 2004) and the postcentral gyrus (somatosensory cortex) (Simmons et al., 2013) during the *heartbeat tracking task.*

Our findings strongly support the view that the insula may be involved in the processing of heartbeat-focused interoceptive attentiveness, presumably including facets of interoceptive accuracy (Schulz, 2016). Associated with the perception of visceral stimuli, it was conceptualized as the interoceptive cortex (Craig, 2002). Apparently, it is also supposed to be activated during interoceptive processing other than cardiac attentiveness, for instance pain, temperature, touch, distention of bladder, rectum or stomach, as well as itching after a histamine injection (Craig, 2002; 2009). The insula cortex, which is also connected to the limbic system, is considered a multisensory region, integrating visceral, tactile, nociceptive and vestibular sensations (Aghion & Cosgrove, 2014). Two studies (Critchley et al., 2004; Pollatos, Schandry, Auer, Kaufmann, 2007a) measuring interoceptive accuracy with variations of the *heartbeat tracking task* (Schandry, 1981) found the strongest associations of ITacc specifically within the right anterior insula, which was also shown to be activated in our study. The right precentral gyrus, also known as the opercular part of the inferior frontal gyrus (Schulz, 2016), is located at the border of the insula and is considered important for music perception, as well as syntactic and phonological processing (Brown, Martinez & Parsons, 2006). Additionally, this region has been associated with language accentuation, verbal understanding, emotional processing, generating melodies, as well as monitoring and inhibitioning of behavior (Craig, 2002), specifically concerning selective response suppression (go/ no go tasks) (Forstmann, van den Wildenberg & Ridderinkhof, 2008). According to Schulz (2016) applying a tone detection task as control condition might lead to a significantly increased activation within the precentral gyrus during the interoceptive task indicating that subjects might have used auditory strategies in both conditions. Hence, also in the present study, participants might have utilized auditory strategies for the performance in the interoceptive condition. Moreover, participants might have selectively suppressed specific responses to events other than the heartbeat (for instance scanner vibration and noise). The postcentral gyrus was associated with the perception of tactile and nociceptive stimuli (Aghion & Cosgrove, 2014). Furthermore, the interaction between loneliness and condition also revealed significant neural activity within the bilateral middle frontal gyrus and parietal operculum (secondary somatosensory cortex). The right middle frontal gyrus in particular has been associated with a shift of attention from exogenous to endogenous attentional control (Japee, Holiday, Satyshur, Mukai & Ungerleider, 2015). Other authors (Petrides, 2016) have attributed damages to the dorsolateral prefrontal areas of the middle and superior frontal gyrus with impairments in attentional control and in specific aspects of the working memory. Inside the parietal operculum lies the secondary somatosensory cortex (S2), which was also activated during cardioceptive accuracy. This area is considered relevant for the recognition of the nature of a nociceptive (painful) stimulus. Damages in this area might lead, for instance, to difficulties in distinguishing between heat and mechanical pain (Coen, Hobson & Aziz, 2012).

In the comparison of interoception vs. exteroception, we have replicated previous studies indicating a crucial role of somatosensory areas (the postcentral gyrus) and the insula. Anyhow, we only found significant activation within the middle and posterior insula but not within the anterior insula, perhaps because in the small sample of this study, half of the participants who displayed higher levels of loneliness could have dampened the cerebral activity within this area. However, a bilateral activation within the posterior insula may be indicative for cardioceptive awareness (e.g., Schulz, 2016). Importantly, we found increased activation within the left posterior cingulate gyrus and the left precuneus that remained significant even after the correction of the family-wise error. The posterior cingulate and precuneal cortices have been associated with self-reflection and conscious awareness (Vogt & Laureys, 2005). The precuneus in particular has recently found to play an important role in memory representation, contributing to the recall and recognition of already existing memory tracks (Brodt et al., 2016). Craig (2009) concluded that the posteromedial cortex (including the precuneus and the cingulate) might provide the fundament for self-awareness. This area appears to contribute to self-reflective episodic memory retrieval. Activation within this region is inversely correlated with activity in the anterior insular cortex that relates to task-relevant attention and awareness. Our results are in line with previous studies that also found significant activation within the precuneus (e.g., Simmons et al., 2012).

Furthermore, we administered and analysed several questionnaires (STAI-T, BDI-II and TAS-20) to see whether distinct constructs (trait anxiety, depression or alexithymia) might have an impact on loneliness and interoceptive accuracy. As we argued in the section of the theoretical background, alexithymia showed highly significant correlations with both, loneliness, as well as interoceptive accuracy. This observation is in line with previous research (e.g., Brewer et al., 2016a; Qualter et al., 2009). Not surprisingly, depression also seemed to be highly correlated with both, loneliness, as well as interoceptive accuracy. Results of other studies (e.g., Cacioppo, Hawkley & Thisted, 2010; Golden et al., 2009; Paulus & Stein, 2010; Pollatos et al., 2009) have also discovered significant associations regarding the constructs mentioned before. Astonishingly, anxiety did neither significantly correlate with loneliness, nor with interoceptive accuracy. Contrary to our results, prior studies have found significant associations of anxiety with both, loneliness (e.g., Cacioppo et al., 2014; Lim, Rodebaugh, Zyphur & Gleeson, 2016), as well as interoceptive accuracy (e.g., Domschke et al., 2010; Pollatos et al., 2009).

It has been suggested by a number of researchers (e.g., Brewer et al., 2016a; Caspi et al., 2014; Murphy et al., 2017a) that one factor, the so-called psychopathology factor (‘p factor’; Caspi et al., 2014) may underlie a variety of psychiatric illnesses. Similar to the g factor, the factor of the general intelligence, which is proposed to function as a latent dimension, having an impact on all kind of distinct mental abilities, Caspi and colleagues (2014) postulated that the p factor might be associated with the propensity of developing all types of psychopathologies. Therefore, the p factor may act as a fundamental dimension of common psychopathologies including the following elven disorders/ symptoms: dependence on hard drugs, alcohol dependence, tobacco dependence, cannabis dependence, fears/ phobias, generalized anxiety disorder, major depression, conduct disorder, positive and negative schizophrenia symptoms, mania and obsessive-compulsive disorder. Whilst the authors of the fifth edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5; American Psychiatric Association, 2013), the current nosology in psychiatry and clinical psychology, assume a discrete classification of the aforementioned disorders into distinct categories, recent research identified a substantial overlap between these categories. Previous investigations (e.g., Krueger et al., 1998) discovered two core dimensions summarizing the structure of psychopathology: the internalizing factor (as found in anxiety disorders and depression) and the externalizing factor (as observed in substance-use and anti-social disorders). By demonstrating that the two factors load onto one single factor, the p factor subsumes the two-factor structure of mental disorders. Recently, Brewer and co-workers (2016a,b) proposed that interoception itself may be the p factor accounting for similarities between symptoms of externalizing disorders such as addiction (Naqvi and Bechara, 2010; Verdejo-Garcia et al., 2012) and internalizing disorders such as panic and anxiety disorders (Ehlers & Breuer, 1992; Paulus & Stein, 2006). Further rationales for this assumption are given in the dependence of decision-making and learning (Furman, Waugh, Bhattacharjee, Thompson & Gotlib, 2013), emotion processing (Bird & Viding, 2014; Gergely & Watson, 1996; Wiens, Mezzacappa & Katkin, 2000), social ability (Bird & Cook, 2013; Brewer, Cook, Cardi, Treasure & Bird, 2015; Cook, Brewer, Shah & Bird, 2013; Grynberg et al., 2012) and cognitive control (Sueyoshi, Sugimoto, Katayama & Fukushima, 2014) from interoceptive abilities. It seems plausible, for instance, that atypical interoception might promote substance abuse due to declined perception of reward cues or anxiety due to impaired interpretation of respiration and heart rate (Brewer et al., 2016a). However, so far little is known about whether or not interoception might also have a contribution on the development and maintenance of loneliness.

Our study has several limitations. First, given the explorative nature of this research, it would have been more informative to investigate the relation between loneliness and interoceptive accuracy across a larger range of age. Atypical interoceptive accuracy has previously been found in individuals of older age (e.g., Khalsa et al., 2009; Murphy et al., 2017b). Since we only tested participants above 65 years of age, it is unknown whether altered interoceptive accuracy might occur due to age or other factors such as loneliness. Second, prior research (Knapp-Kline & Kline, 2005) found an association between the extent of cardiovascular activation and interoceptive accuracy, linking lower resting heart rate to enhanced interoceptive accuracy. In our research, the baseline heart rate was assessed. Yet we did not consider it when analysing the data and consequently did not control for it. Third, in order to be able to compare the interoceptive with the exteroceptive condition, we aimed to create two tasks with similar difficulty. Unfortunately, our analysis revealed that the interoceptive condition seemed to be much more difficult than the exteroceptive condition. Fourth, as the experiment took place in a MRI-scanner, several participants reported difficulties perceiving their heartbeat due to the disturbing noise of the MRI-scanner. Fifth, the cut-off threshold for loneliness was set at ≥ 40 by the authors of the UCLA-LS (Russell, 1996). Given the relatively low scores on the UCLA-LS in the present sample, the threshold for loneliness was lowered to 33.6. However, a broader range of scores on loneliness would have led to a more representative sample. Sixth, the last and perhaps most relevant limitation to mention is the small sample size. Although we found no significant effect of loneliness on interoceptive accuracy, there was a medium effect size (η_{p2} = 0.119), indicating a possible effect when considering a larger sample size.

Future research might attempt to clarify the relationship between loneliness and interoception. By conducting moderation and mediation analysis, the influences of other variables (e.g., alexithymia, anxiety and depression) on this relationship should be examined. Furthermore, future studies assessing the association between loneliness and interoception should also consider and distinguish between distinct dimensions of interoceptive processing, namely baseline heart rate, interoceptive accuracy, interoceptive sensibility and interoceptive awareness (see Forkmann et al., 2016). Further investigations with a larger sample size are required in order to shed more light on the observed results within this study.

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Appendix

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Abstract

Loneliness is described as an unpleasant feeling of deficits in quantity or quality of social ties. Prior studies observed that lonely individuals displayed higher levels of alexithymia (emotional blindness). Furthermore, research in the field of interoception (the perception of the bodily state) discovered atypically low interoceptive abilities within highly alexithyimic individuals. Based on previous findings, we expected lonely individuals to show decreased levels of accurate interoceptive abilities together with reduced neural activity within the anterior insula, the somatosensory cortex (postcentral gyrus), the inferior frontal gyrus and the precentral gyrus. Brain areas previously associated with accurate interoceptive abilities. The data for the present fMRI study were collected within a sample of 28 participants older than 64 years. The extent to which a participant is capable of perceiving his/ her own bodily sensations (interoceptive accuracy) was measured via a *heartbeat tracking task*, during which the subject was required to perceive his/ her own heart rate and report the counted number of heartbeats. Additionally, several questionnaires, assessing loneliness, trait anxiety, depression and alexithymia, were administered and analysed. Results indicated that lonely individuals showed increased levels of depression and alexithymia. Nevertheless, they did not display reduced levels of interoceptive accuracy. Although this observation is not in line with our hypothesis, we found a medium effect size, indicating the possibility of a significant effect when considering a larger sample size. Moreover, enhanced neural activity was observed inter alia within the anterior and middle insula, the somatosensory cortex, the inferior frontal gyrus, as well as the precental gyrus of non-lonely when compared to lonely individuals, which is in line with our hypothesis and with prior research. Future research should consider replicating this study with larger sample sizes.

Keywords: Interoceptive Accuracy, Loneliness, Alexithymia, fMRI, Seniors

German Abstract

Einsamkeit wird als ein unangenehmes Gefühl definiert, welches geprägt ist von Defiziten hinsichtlich der Quantität oder Qualität sozialer Beziehungen. Frühere Studien beobachteten, dass einsame Individuen höhere Werte in Alexithymie (sogenannte Gefühlsblindheit) aufwiesen. Darüber hinaus entdeckte die Forschung auf dem Gebiet der Interozeption (der Wahrnehmung des Körperzustandes) atypisch niedrige interozeptive Fähigkeiten innerhalb sehr alexithymer Individuen. Basierend auf vorherigen Forschungsergebnissen stellten wir die Hypothese auf, dass einsamere Individuen verringerte Werte an interozeptiven Fähigkeiten aufzeigen. Außerdem erwarteten wir, dass einsame VersuchsteilnehmerInnen reduzierte neuronale Aktivität in der anterioren Insula, dem somatosensorischen Kortex, dem inferioren frontalen Gyrus und dem präzentralen Gyrus zeigen würden. Hirnareale, die zuvor mit akkuraten interozeptiven Fähigkeiten in Zusammenhang gebracht wurden. Die Daten für die vorliegende fMRI-Studie wurden innerhalb einer Stichprobe von 28 Teilnehmern, die älter als 64 Jahre waren, erhoben. Das Ausmass, in dem eine Person fähig ist, ihre eigenen Körperempfindungen wahrzunehmen, wird in der Forschungsliteratur als interoceptive accuracy bezeichnet. Jenes Konstrukt wurde mithilfe einer *Heartbeat Tracking Task* gemessen, bei der die Versuchsperson seine eigene Herzfrequenz wahrnehmen und die gezählte Anzahl an Herzschlägen angeben soll. Zusätzlich wurden mehrere Fragebögen, welche Einsamkeit, Angst, Depression und Alexithymie messen, erhoben und analysiert. Die Ergebnisse zeigten, dass einsamere Personen erhöhte Werte in Depression und Alexithymie aufwiesen. Dennoch zeigten Einsame keine verringerten Werte in interoceptive accuracy. Obwohl diese Beobachtung nicht mit unserer Hypothese übereinstimmt, haben wir eine mittlere Effektgröße gefunden, die auf die Möglichkeit eines signifikanten Effekts bei Betrachtung einer größeren Stichprobengröße hinweist. Des Weiteren wurde eine erhöhte neuronale Aktivität unter anderem in der anterioren und mittleren Insula, dem somatosensorischen Kortex, dem Gyrus frontalis inferior, sowie dem Gyrus praecentralis von nicht-einsamen im Vergleich zu einsamen Individuen beobachtet, was mit unserer Hypothese und mit früheren Untersuchungsergebnissen übereinstimmt. Zukünftige Forschung sollte in Betracht ziehen, diese Studie unter Heranziehung einer größeren Stichprobe zu replizieren.

Schlagwörter: Interoceptive Accuracy, Einsamkeit, Alexithymie, fMRT, Senioren