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SOCIAL NETWORK SIZE MODERATES THE ASSOCIATION BETWEEN LONELINESS AND CARDIOVASCULAR REACTIVITY TO ACUTE STRESS

Stephen Gallagher[1,2], Ann-Marie Creaven,[1,2] Ruth A. Hackett[3], Daryl B. O'Connor[4]& Siobhán Howard[1,2]*

[1]Department of Psychology, Centre for Social Issues Research, Study of Anxiety, Stress and Health Laboratory, University of Limerick, Limerick, Ireland

[2]Health Research Institute, University of Limerick, Ireland

[3] Health Psychology Section, Institute of Psychiatry, Psychology & Neuroscience, King's College London, London, United Kingdom

[4] School of Psychology, University of Leeds, Leeds, England

[*]**Corresponding author**

Prof Stephen Gallagher

Department of Psychology

University of Limerick

Ireland

Email: stephen.gallagher@ul.ie

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Abstract

Loneliness and objective measures of social isolation (e.g., social network size) have been associated with increased risk of cardiovascular disease (CVD). However, the evidence is mixed and the precise causal mechanisms remain unclear. Cardiovascular reactivity (CVR) to acute stress has been posited as a proposed mechanism. This study aimed to investigate: i) effects of loneliness and social isolation on CVR to stress and, ii) whether the loneliness – CVR relationship was moderated by social network size. Two hundred and six participants from the Pittsburgh Cold Study underwent a modified version of the Trier Social Stress Task. Cardiovascular measures of systolic (SBP) and diastolic blood pressure (DBP) and heart rate (HR) were taken throughout the laboratory stress trial. Hierarchical regression analyses found that social network size was positively associated with DBP reactivity (β = 0.19 95% CI [0.05, .29] p = 0.005), while loneliness was not. In addition, social network size moderated the loneliness - DBP reactivity relationship such that a higher number of outer social network ties were beneficial at lower levels of loneliness but not higher. The current study contributes new evidence linking loneliness and social network size to cardiovascular psychophysiology but raises questions about the loneliness - CVD relationship. The findings confirm the importance of social network size and highlight that the characteristics of the networks may be more important than the number of networks.

Keywords: Blood pressure; Cardiovascular Reactivity; Loneliness; Social Network Size; Stress

1. Introduction

Loneliness is a feeling of distress that arises from perceiving that the quality of one's social relationships is inadequate (Peplau & Perlman, 1982). It has been associated with increased risk of morbidity and mortality (Gallagher & Wetherell, 2020; Hackett et al., 2020; Holt-Lunstad et al., 2015; O'Súilleabháin et al., 2019), including increased risk of cardiovascular disease (CVD) development (Paul et al., 2021; Sorkin et al., 2002; Valtorta et al., 2016). Loneliness is a fundamentally subjective experience and differs from objective social isolation in that a person with few connections may not experience loneliness, and a person with many social connections can still feel lonely. Objective social isolation has also been linked with CVD, with both high loneliness as well as high isolation (indexed by relationship status, living alone, and frequency of participation in a number of social activities) associated with increased risk of CVD in a sample of over 50,000 women (Golaszewski et al., 2022). However, not all studies have found concordant associations between loneliness and indicators of social isolation on later cardiometabolic risk (Hackett et al., 2020; Valtorta et al., 2016).

There are several proposed mechanisms linking both loneliness and social isolation to CVD risk including behavioural (e.g. smoking), psychological (e.g., depression) and biological (e.g., inflammation) pathways (Hackett et al., 2019; Hawkley & Cacioppo, 2010; Paul et al., 2021). However, it remains unclear as to whether subjective feelings of loneliness or objective social isolation/connectedness is more important for CVD (Paul et al., 2021). Studies assessing both constructs are needed, particularly in relation to cardiovascular reactivity (CVR) to acute psychological stress, a biological pathway implicated in the development of CVD (Obrist, 1981).

In its original form, the CVR hypothesis posits that exaggerated or prolonged cardiovascular reactions to psychological stress promotes the development of cardiovascular diseases (Obrist, 1981). In fact, a range of longitudinal and prospective studies have found exaggerated cardiovascular stress reactions to predict increases in resting blood pressure (Markovitz et al., 1998; Yuenyongchaiwat et al., 2015) as well as future hypertension (Carroll et al., 2012; Steptoe et al., 2016) and atherosclerosis (Everson et al., 1997; Low et al., 2009). These observations across aggregated cardiovascular events (e.g., hypertension, atherosclerosis, and cardiac events) have also been confirmed by meta-analytic research and reviews (Chida & Steptoe, 2010; O'Connor, Thayer & Vedhara, 2021). As exaggerated reactivity was well-established as being cardiotoxic, by implication, low reactivity was assumed to be benign or health protective. However, recent work has contested this view, with atypically low reactivity also posited to be damaging for CVD outcomes in both healthy and clinical populations (O' Riordan et al., 2022; Steptoe et al., 2014; Whittaker et al., 2021). Further, 'blunted' reactivity has also been associated with a range of indicators of poor coping and health behaviours associated with CVD risk (al'Absi, 2006; Ginty, 2013; Ginty et al., 2020; Ginty et al., 2012; Phillips et al., 2009). As a consequence of this work, the original reactivity hypothesis has been expounded, identifying that cardiovascular reactions to stress that are atypically "high" or atypically "low" relative to the sample mean (Phillips et al., 2013; Whittaker et al., 2021) are predictive of future ill-health and negative outcomes. Moreover, a recent systematic review has identified the cardiovascular thresholds at which blunted cardiovascular reactions to stress are prospectively associated with negative health outcomes (O' Riordan et al., 2022).

While there have been several studies that have investigated the relationship between loneliness and CVR, findings are inconsistent (Brown et al., 2018). Recent work for example, has found no reliable associations between loneliness and CVR to acute stress in older adults (Brown et al., 2022). Elsewhere, studies have found that exaggerated blood pressure responses (Ong et al., 2012), lower heart rate responses (Cacioppo et al., 2000), and lower vascular reactivity (Brown et al., 2019) are all associated with loneliness. Moreover, it appears that these effects may vary across stress tasks with social tasks likely to be more influential for loneliness (Brown et al., 2018); others have found effects only for women, with women who are lonely displaying higher blood pressure reactivity to stress (Steptoe et al., 2004). Taken together these studies suggest that further clarity and replication of these studies are needed.

One variable that may bring clarity to the area is the impact of social network size or variables such as social isolation. A recent theoretical paper (Beller & Wagner, 2022) has argued for such an examination of the potential synergy between loneliness and other social variables. While indicators of social isolation, such as social network size are distinct constructs to loneliness, they are related. For example, in a study of Dutch older adults, having a smaller network size was associated with lower feeling of loneliness over time, and this, in turn, had a negative effect on social networks (Domènech-Abella et al., 2021). Similarly, both proximal and distal aspects of social networks were found to explain the frequency of loneliness in older Korean adults (Kim et al., 2022). Studies have also found that people who have close family ties with few neighbourhood friends as well as those with a restricted support network (i.e., no relatives, few nearby friends, and low levels of community involvement) are more at risk of feeling lonely (Wenger, 1997; Wenger & Tucker, 2002), implying that proximal and distal networks matter for loneliness. Proximal networks tend to be more closely tied to one's social identity to family, and friend for example, while those further removed such as friends of friends may be seen as more distal. Moreover, other have suggest that the reason why proximal networks (e.g., family and friends) lead to better health is they provide a space for more social interaction and communication compared to distal networks (e.g., co-workers) (Graziani et al, 2022). To be clear, a lower number of social interactions does not necessarily mean that people feel lonelier or are less satisfied with their social networks (Delmelle et al., 2013). Nonetheless, given the robust associations between increased social network size and lower levels of loneliness it is plausible they may interact, producing synergistic effects on CVR such that social networks may influence the association between loneliness and CVR. In fact, a study from Japan has recently found support for this notion, with those reporting lower social networks alongside higher feelings of loneliness had greater levels of inflammation (Koyama et al., 2021). Given that few studies have investigated the effects of social isolation on CVR, the current study will examine if loneliness and social network size interact and will examine if both proximal and distal effects have moderating effects.

The current study

Given that loneliness is a recognised a chronic stressor (Epel et al., 2018), we aimed to replicate past studies showing atypical reactivity in response to stress in those with high loneliness. We hypothesise that the association between loneliness and CVR will be moderated by social network size, such that those with greater social networks will report lower feelings of loneliness and this will be associated with a healthy cardiovascular response (O'Riordan et al. 2022). Further we expect that proximal social network to have a stronger effect on CVR.

2.0 Methods

2.1 Participants

The current research utilises secondary data taken from the Pittsburgh Cold Study (PCS3), a study conducted by the Laboratory for the Study of Stress, Immunity, and Disease at Carnegie Mellon University directed by Sheldon Cohen (grant number NCCIH AT006694). This data is publicly available on https://www.cmu.edu/common-cold-project/pittsburgh-cold-study-3/index.html. In brief, the PCS3 recruited 213 healthy adults; cardiovascular reactivity data were available for 206 of these (119 men, 87 women) aged 18-55 years (*M* =

29.68, *SD* = 10.70) residing in Pittsburgh, Pennsylvania (USA) between 2007 and 2011. Prior to enrolment, participants were medically screened by a physician to ensure good health. Further exclusion criteria included using certain medications (e.g., beta blockers), hospitalisation for a psychiatric condition in the last 5 years, history of chronic illness (e.g., asthma, diabetes mellitus, and cardiovascular disease), current pregnancy, and having cold or flu-like symptoms. Sociodemographic details were gathered for ethnicity (White, Caucasian = 1, Black, African-American, = 2, Native American, Eskimo, Aleut = 3, Asian or Pacific Islander = 4, Hispanic, Latino = 5, or Other = 6), education levels (High School or lower; some college but ≤2 years; ≥ years of college or associate degree; college graduate or above, we also included current smoking status (yes/no) and body mass index (BMI), which tend to be negatively correlated with CVR (al'Absi, 2006; Phillips et al., 2009; Phillips et al., 2013). All participants provided informed consent and received $1000 for participation. The study approved by the Carnegie Mellon University and University of Pittsburgh Institutional Review Boards.

2.2 Design and Procedure

For the testing session, participants were scheduled to attend between 3:00 pm and 9:00 pm at the University of Pittsburgh and were asked to abstain from alcohol for 48 hours, exercise and non-prescription medications for 24 hours, and from eating for 2 hours, and from smoking for 1 hour prior attending the session.

An automated blood pressure (BP) cuff for measurement of systolic BP (SBP), diastolic BP, (DBP) and heart rate (HR) was then fitted. This session included a 20-minute habituation/baseline session where cardiovascular indices of SBP, DBP and HR were taken 4-times during the last 6-minutes (averaged for baseline values), this was followed by a 15-minute stressor phase that had a speech preparation phase with 9 cardiovascular readings taken (averaged for reactivity), and then 50-minute recovery phase with somewhat similar cardiovascular monitoring throughout. The present study will only focus on the cardiovascular stress reactivity data (stress minus baseline values) and not the recovery data. It is worth noting that these variables tend to be stable across short periods of time (Morgan et al., 1997; Mund et al., 2019).

2.3 Measures

2.3.1 Loneliness

The 3-item short loneliness scale (Hughes et al., 2004) was used to assess the degree of loneliness typically felt by participants. This scale was adapted from the Revised UCLA Loneliness Scale (Russell et al., 1980) and includes the following three item; "How often do you feel that you lack companionship?", "How often do you feel left out?" and "How often do you feel isolated from others?". Participants respond on a 4-point rating scale, from 1 = Never, 2 = Once in a while, 3 = Fairly often, 4 = Very often. The scores are summed to give a total score. Hughes et al. (2004) reported a Cronbach α of 0.72 and in the present study this was 0.79.

2.3.2 Social network size

Measurement of social network size was captured by the social convoy circles model (Antonucci & Akiyama, 1987) which itself is based on sound theoretical underpinnings in health research (Antonucci et al., 2014). In the scale, participants are presented with a diagram of three concentric circles (inner; middle; outer) with the following set of instructions: "in relation to your social network members with whom you are in contact at least once a month; using first name and last initial, place these people in the circle. Members in your innermost circle are those who are close and important to you, and without whom life would be difficult to imagine. The remaining two circles are for people who you would see as being less close”.

Participants are asked to list no more than 20 network members. Scores can be a total number within all the circles (Circles 1, 2, and 3) or total number of individuals listed in each respective circle: Inner Circle Count, Middle Circle Count, Outer Circle Count. Given that other studies find that the other characteristics of the network are equally important for CVR (Uchino et al., 2001; Uchino et al., 2016) we examined both the total and individual components to see if these particular qualities are important.

2.3.3. Control variables

A recent study using this dataset (John-Henderson et al., 2019) found that social integration, an index of high social roles, to be important to consider when testing these social relationship and CVR associations. In fact, it could be that our main predictor variables loneliness and social network may be related to social integration, and as such could be a potential confound, therefore we included this as a covariate in our analyses.. Social integration measures the number of different types of high contact social roles (e.g., parent or friend) a person will engage with others with on a regular basis such as once every two weeks. In line with the previous study, we extracted the social integration data, which was computed as the sum of all high contact roles (Cohen et al., 1997; John-Henderson et al., 2019).

2.4. Cardiovascular Monitoring

Cardiovascular parameters were recorded using a Critikon DINAMAP Vital Signs Monitor 1846SX (GE Healthcare, US). This monitor uses an oscillometric technique to determine BP values. An automated BP cuff was attached to the upper arm of the non-dominant arm, allowing non-invasive measurement recording.

2.5 Acute Stress Task

A modified version of the Trier Social Stress Task (Kirschbaum et al., 1993), a validated and reliable method to elicit physiological stress responses was employed. This stress task incorporated both a speech and mental arithmetic component. For the public-speaking element of the task, participants were asked to prepare a speech to defend themselves against an alleged transgression (a traffic violation or shoplifting). This aspect included an anticipation phase where they were given 5 minutes to prepare their speech. Participants then had to deliver their speech for 5 minutes while being video recorded. After the speech task, the experimenter then entered the room and provided instructions for the mental arithmetic task. Participants were asked to serially subtract 13 from 1022 as quickly and accurately as possible for 5 minutes. The experimenter remained in the room and corrected participants when they made an error, instructing participants to start the task again from the beginning.

2.6 Statistical Analysis

Prior to analysis, a statistical analyses plan was pre-registered on the Open Science Framework (https://osf.io/nte7v). Mean levels of SBP, DBP, and HR during baseline and completion of the task phases were created, and reactivity for each variable was identified by subtracting baseline levels from task levels (delta scores). Prior to analyses data were screened for normality and assumptions of fit. Data for all our CVR indices were normally distributed. However, we identified several indices of HR reactivity that had Z scores ≥ 3. We ran our analysis with and without these participants and there were no differences in study findings; thus, we used our full sample for our analyses. In our initial analyses, tests of differences and correlations checked for age, sex, and other socio-demographics, smoking, and BMI and differences/associations with our outcome variables. This was followed up with repeated measures analysis of variance (ANOVA) to confirm whether our task was physiologically stressful. A series of hierarchal linear regressions were used to test our main replication hypotheses with our CVR indices (SBP, DBP and HR) being our dependent variables, potential covariates including baseline cardiovascular indices were entered at Step 1, followed by the predictor variables (loneliness and social network size) separately at Step 2. When testing our synergistic effects, we conducted a moderation analysis using Model 1, from PROCESS (Hayes, 2013). Partial Eta-squared (η^2), adjusted R^2 were used as an indicators of effect size. All analyses were conducted using SPSS version 28 (IBM Corp, USA).

3. Results

3.1 Descriptive Statistics

The majority of the sample were categorised at White (77%) and in terms of education, 23.3% reported having a high school education, 25.7% had ≤ 2 years of college, 24.8% ≥ 2 years of college and 26.2% were college graduates. The mean BMI was 27.26kg/m^2 (*SD* = 6.44). Descriptive statistics for social network size, loneliness and cardiovascular variables are reported in Table 1.

[Insert Table 1 About Here]

3.2 Manipulation check

A series of repeated-measures (baseline, task) ANOVAs confirmed that the stress task increased cardiovascular levels for: SBP, $F(1, 205) = 418.35$, $p < .001$, $\eta^2_p = .67$; DBP, $F(1, 205) = 567.84$, $p < .001$, $\eta^2_p = .74$; HR, $F(1,205) = 356.35$, $p < .001$, $\eta^2_p = .64$. There were no differences in CVR across stress tasks; however, participants rated the mental arithmetic task as more stressful than the speech task; mean (*SD*), 4.57 (1.26) vs 4.13 (1.46), $F(1, 168) = 12.38$, $p < .001$, $\eta^2_p = .07$, with no significant differences in terms of how engaging they found the task.

As can be seen in Table 2, age, gender, ethnicity, education, BMI and smoking status were statistically correlated with our cardiovascular measures. Those who were older had lower DBP and HR reactivity, women had lower DBP reactivity, (8.77 (6.52) compared to men, 11.97 (5.90); $F(1, 204) = 11.90$, $p < .001$, $\eta_p^2 = .06$). Further, White participants had higher reactivity than participants from other ethnic groups for SBP, (19.37 [10.37] versus 9.76 [10.26]), $F(1, 205) = 36.39$, $p < .001$, $\eta_p^2 = .15$; DBP, (11.90 [6.18] versus 7.69 [5.68]), $F(1, 205) = 22.24$, $p < .001$, $\eta_p^2 = .09$; and HR, (11.92 [8.86] versus 8.21 [5.67]), $F(1, 205) = 9.89$, $p = .002$, $\eta_p^2 = .05$, respectively. Those who had higher educational attainment also had higher SBP and HR reactivity. While compared to non-smokers, those who smoked had lower SBP, (17.48 [11.15] versus 13.38 [10.86]), $F(1, 205) = 6.64$, $p = .01$ $\eta_p^2 = .03$ and HR reactivity, (12.02 [8.96] versus 8.48 [5.93)), $F(1, 205) = 69.50$, $p = .002$, $\eta_p^2 = .05$. BMI was also negatively correlated with SBP, DBP and HR responses to the task. Moreover, our covariate variable. i.e. social integration, was statistically negatively correlated with loneliness and positively with social network index. In addition, BMI and smoking status were also statistically correlated with reduced social network size and social integration was also positively correlated with both SDP and DBP, reactivity. Thus, given the associations of age, gender, smoking, ethnicity, education, BMI, and social integration with our cardiovascular indices, these confounding factors were controlled for in relevant analyses.

[Insert Table 2 about here]

3.3 Associations between loneliness, social network size and CVR

A series of hierarchical linear regressions, with covariates including, social integration and the relevant baseline cardiovascular index added at Step 1 and loneliness and social network size entered individually at Step 2, were conducted. The outcome variables were SBP, DBP, and HR reactivity. After controlling for the covariates, there were no associations between loneliness and SBP, $\beta = .00$, 95% CI [-0.78, 0.84, $t = .07$, $p = 0.94$; DBP, $\beta = -0.06$, 95% CI [-0.63, 0.25], t = -0.82, p = 0.41; or HR, β = -0.01, 95% CI [-0.63, 0.54], t = -0.18, p = 0.85, reactivity. However, total social network size was not significantly associated with SBP, β = 0.14, 95% CI [-.05, .44], t = 1.92, p = 0.06, or HR reactivity, β = 0.09, 95% CI [-0.06, 0.27], t = 1.25, p = 0.29, but was positively associated with DBP, β = 0.19 95% CI [0.05, 0.30], t = 2.76, p = 0.006, reactivity. Those reporting higher numbers of close ties in their networks showed higher levels of DBP reactivity (see Figure 1, for illustration). This added an additional 2% variance in explaining DBP reactivity.

[Insert Figure 1 About Here]

In subscale analysis of the social network size interactions over the previous month, we found for DBP, it was both proximal levels at the inner, β =13. 95% CI [.003, .43], t = 2.00 p = .046, and middle, β =17. 95% CI [.06, .50], t = 2.51 p = .01 social network circles, that were associated with reactivity. There was no association between the distal or outer circle and DBP reactivity.

3.4 Moderation Analysis

Given that only DBP was significantly related to social network size, we focused on these indices in moderation analyses. After controlling for covariates, there was evidence of moderation for total network size on loneliness for DBP reactivity, R^2-chng, 0.017, F(1, 195) =4.70, p = .03. Further analysis of conditional effects using the social network subscale, revealed that this was only evident at higher distal levels, i.e. outer network, but not the proximal/inner or medium circle, β = -0.87, 95% CI [-1.65, 0.11], t = -2.23, p =0.02. Specifically, the findings for DBP moderation found that higher number of distal social network ties are beneficial at lower levels of loneliness but not higher (see Figure 2). In fact, for those high in loneliness and reporting larger numbers of distal social ties, the DBP response equated to that identified in a recent review to be predictive of negative health outcomes (O'Riordan et al., 2022). Given the cross-sectional nature of the data, we also checked the alternative model (i.e., moderation of social network size by loneliness). This model was not supported. Moreover, we also checked to see if the effect of the distal social network would still be evident after controlling for both proximal social ties. In this post-hoc analysis we found that the moderation effect was abolished on the inclusion of the inner social circle (more proximal) but not at the middle level (less proximal), implying that having a larger number of distal social ties is likely to have a negative effect on DBP reactivity in during high feelings of loneliness.

4.0 Discussion

This study sought to build on previous research on loneliness and social network size and CVR to acute psychological stress. Our findings show that while there were no independent associations between loneliness and CVR, social network size was positively associated with CVR, as indexed by DBP. In particular, we found that those reporting being in close contact with a larger number of people over the previous month had higher reactivity to the stress task. However, in subscale analysis it became evident that these effects were driven by those proximal ties as indicated by the significant associations with inner and middle social networks, with no direct effect seen for distal ties. In contrast, our moderation analysis found that it was the distal networks, but not the proximal networks, that was a moderator of the loneliness-CVR relationship. Here, we found that when loneliness was high, having a larger distal network was associated with a blunted DBP response. This CVR response was equivalent to that already identified as being of clinical relevance in a systematic review and meta-analysis of prospective studies of blunted CVR to stress and future cognitive, behavioral, and health outcomes (O'Riordan et al., 2022). These effects remained significant after controlling for several confounding factors including, age, gender, ethnicity, education, smoking, BMI, social integration and baseline blood pressure.

Our findings for social network size are a replication of earlier work showing that higher social network size is associated with higher reactivity (Levit, 2006). Other studies have found that it is not just the number in the network that is important for CVR, but that the characteristics are equally important (Uchino et al., 2001; Uchino et al., 2016). Likewise, our study found network characteristics to be important. While a higher total network size was positively associated with both SBP and DBP reactivity, in subscale analysis it was larger number of close contacts over the previous month in the larger social networks in proximal ties (inner and middle) that were important. Moreover, like other social support and CVR studies, including support in real life, we found that a larger network was associated with higher CVR reactivity (Lee et al., 2015; McMahon et al., 2020; Roy et al., 1998). In fact, our DBP mean reactivity levels in the present study are equivalent to those found recently for the positive association between receiving social support (Gallagher, O'Súilleabháin, et al., 2021) and reactivity but also for positive correlation between gratitude and CVR in other cross-sectional studies (Gallagher, Creaven, et al., 2021).

In terms of loneliness and CVR, the majority of research has tended to find patterns of atypical responses (Brown et al., 2019; Brown et al., 2018; Cacioppo et al., 2000; Ong et al., 2012); however, our study did not replicate these findings. Here, loneliness was not independently associated with CVR which is somewhat similar to one recent study in older adults (Brown et al., 2022). In that study, there was no clear association with either a 20-item or 3-item psychometric measures of loneliness in older adults (aged 55-88 years). This study replicates that finding in a younger sample (aged 18 – 55 years). Recent work has highlighted methodological issues such as variation in loneliness measurement as one area for consideration in relation to mixed findings (Brown et al., 2022). However, perhaps CVR to stress is not the psychosomatic pathway (Hackett et al., 2019) through which loneliness is associated with increased risk of CVD. Although loneliness is stable over short periods of time, as this construct can be a transient phenomenon (e.g., Zhong, Chen, & Conwell, 2016), it may be the case that loneliness does not show consistent associations with reactivity. The conflicting findings in the literature must acknowledge this possibility.

Nonetheless, this study does identify another reason why loneliness shows inconsistent associations with CVR stress; failing to consider social network size, and importantly, characteristics of that social network. Recent theoretical work (Belle & Wagner, 2022) has suggested examining these synergistic interactions with other psychosocial factors is where some of our research efforts should focus. We found that there was a moderating effect on the loneliness-DBP reactivity association by social network size, particularly by distal close ties. Those experiencing higher levels of loneliness and who reported higher numbers of social contacts with distal, but not proximal ties, over the month displayed a more blunted DBP reactivity profile; this pattern was not evident at lower levels of loneliness where reactivity tended more toward a healthier reactivity profile. The distinction between the blunted and healthy reactivity profile arises from findings reported by O'Riordan et al. (2022) that identify that ranges from -2.4mmHg to 5.00mmHg are reflective of DBP reactivity levels predictive of future ill-health. In addition, in our post-hoc analyses we found that the moderation effect was strongly evident in the less proximal connections, implying that having a larger number of distal social ties is likely to have a negative effect on DBP reactivity in during high feelings of loneliness. Thus, despite having larger networks at these distal networks, you may not feel connected to them and experiencing higher levels of loneliness during a period of stress is not good for one's health.

Despite this, we are unsure as to why proximal social networks were important for CVR directly but not for the indirect association with loneliness. Here we speculate on one possible explanation, and this may lie in how loneliness is perceived and constructed in relation to social networks. Loneliness, while a subjective experience, is composed of subjective experiences and objective disconnections (Bahr et al., 2006). Further, objective social disconnections are categorized across different levels, from proximal to distal levels (Kim et al., 2022). Studies have found that we have greater relational connectedness (e.g. stronger feelings of familiarity, closeness and support) to closer social ties, whereas we tend to have a collective connectedness (e.g., wider connection to groups and neighbourhood and less familiar) to more distal ties (Hawkley et al., 2005); thus, it may be that those distal social connections trigger a social alarm system (Cacioppo et al., 2015) whereby social networks become important when dealing with stress whereas those proximal do not trigger the system in the same way. In fact, recent research suggests that neighbourhood connections are equally if not more important than individual level factors for health (Diez Roux, 2016). For example, a recent study showing that neighbourhood cohesion was a key driver of the influence of loneliness on immunity, measured as the antibody response to a covid-19 vaccine (Gallagher et al., 2022). While we acknowledge this is speculative and there may be alternative explanations, our findings demonstrate that further work is needed, and that examining synergistic pathways is an important avenue for a greater understanding of the loneliness and CVR association.

These findings are limited by the cross-sectional observational design employed, meaning causation cannot be inferred. A further limitation is that the study relied on self-report measures of both loneliness and social network size; while this is preferable for loneliness given it is a subjective experience, the limitations of self-report measures are acknowledged. Moreover, it is also possible that the number of ties that were able to be listed on our social network index may have altered network size or apportioning of individuals to different circles. Thus, other measures of social network ties and the importance of those ties may be worthy of investigation. In addition, loneliness was measured using a three-item scale and so could not have captured all elements of this latent construct; however, this scale was developed for use in large-scale studies and has shown good construct validity (Hughes et al., 2004). Of course, our findings require replication, in particular with respect to social networks' interaction with loneliness.

The present study adds to evidence linking both loneliness and social network to cardiovascular psychophysiology, but questions that loneliness is associated with CVD development through repeated and consistent atypical cardiovascular responses to stress. In particular, we have found that loneliness was not directly associated with CVR whereas having contact with a larger number of social network ties over the last month was positively associated with both SBP and DBP reactivity. These effects for social networks were driven by those proximal social networks which suggests that the characteristics of the networks are more important rather than the numbers *per se*. More interestingly, we have confirmed as predicted, that social network size was a moderator of the loneliness and CVR association, but that, in this case, it was only the outer or more distal social networks contact that were important for DBP reactivity. Future research incorporating both loneliness and objective network measures will help clarify how these constructs relate to cardiovascular morbidity and mortality.

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Table 1

Descriptive statistics of social network size, loneliness and cardiovascular reactivity variables

Variables	Range	Mean	Standard Deviation
Social Network Size Total	0.00 – 43.00	12.73	7.05
Inner Circle Size	0.00- 20.00	5.43	3.80
Middle Circle Size	0.00 – 20.00	4.70	3.82
Outer Circle Size	0.00 – 20.00	2.63	2.93
Loneliness	3.00 – 12.00	5.39	1.91
Social Integration	1.00 -10.00	5.15	1.88
Baseline SBP (mmHg)	85.00 - 151.75	114.86	12.57
Baseline DBP (mmHg)	44.25 – 91.00	67.45	8.28
Baseline HR (bpm)	44.0 – 107.25	69.23	10.51
Task SBP (mmHg)	87.67- 166.56	130.41	14.52
Task DBP (mmHg)	59.67 – 101.11	77.91	8.11
Task HR (bpm)	44.89 – 120.89	80.02	12.58
Reactivity SBP (mmHg)	-20.28 – 56.86	15.95	11.19
Reactivity DBP (mmHg)	-6.94 – 38.08	10.51	6.33
Reactivity HR (bpm)	-4.64 – 52.31	10.70	8.13

Abbreviations: SBP = systolic blood pressure; DBP = diastolic blood pressure; HR = heart rate; mmHg = millimetres of mercury

Table 2. Correlations among study variables

	Variables	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Age	-													
2	Gender	.03	-												
3	Race/Ethnicity	.07	.02	-											
4	Education	-.03	.09	-.06	-										
5	Smoking	.10	-.11	-.02	-.32**	-									
6	BMI	.32**	.17*	.18*	-.17*	-.05	-								
7	Social Network Size	-.24**	.18**	-.06	.27**	-.19**	-.16*	-							
8	Loneliness	.12	-.02	.17*	.06	-.04	-.07	-.12	-						
9	Social Integration	-.04	.11	.00	.17*	-.07	-.04	.34*	-.25**	-					
10.	Baseline SBP	.18**	-.26**	.14*	-.12	.09	.41**	-.27**	.00	-.13	-				
11.	Baseline DBP	.32**	.06	.22**	-.02	.02	.25**	-.24**	.05	-.13	.54**	-			
12	Baseline HR	-.03	.10	.03	-.02	.08	.24**	-.09	-.06	-.04	.15*	.13	-		
13	Reactivity SBP	-.12	-.12	-.26**	.24**	-.17*	-.16*	.24**	-.04	.16*	-.23**	-.14*	-.13	-	
14	Reactivity DBP	-.21**	-.24**	-.19**	.12	-.08	-.20**	.26**	-.06	.14*	-.15*	-.40**	-.18**	.68**	-
15	Reactivity HR	-.29**	-.02	-.15*	.17*	-.21**	-.22**	.21**	-.03	.11	-.15*	-.17*	-.11	.57**	.42**

Correlation is significant at the 0.01 level (2-tailed).**

Correlation is significant at the 0.05 level (2-tailed).*

Abbreviations: BMI = body mass index; SBP = systolic blood pressure; DBP = diastolic blood pressure; HR = heart rate;:

Figure 1. Associations between total social network size and diastolic blood pressure reactivity, controlling for covariates. Error bars are standard error bars and reactivity mean scores for low, medium and high social network sizes. The high and low networks reflect the top 33% (16+ number of close ties; *n* =72) and bottom 33% (0-8 close ties; *n* =63) of the sample and medium represents the remaining middle 33% of the distribution (9-15 close ties; *n* = 71). * = $p < 0.05$

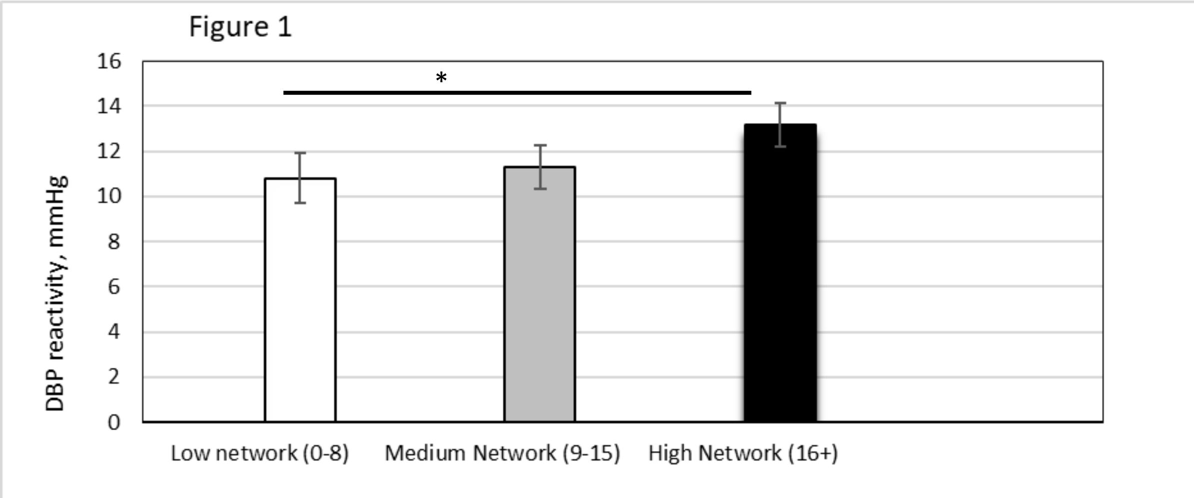

Figure 2. Social network, loneliness and diastolic blood pressure reactivity by distal social network size. Please note, the moderation was only significant at the higher level of the outer social network size.