Characterizing the Dynamics of Loneliness, Depression, and the Role of Social Interactions: An Experience Sampling Study

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Abstract

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Loneliness is becoming increasingly recognized as a problem of clinical and public health significance (Badcock et al., 2023). Although this increase is concerning on its own, given the importance of social relationships and relational well-being to the human experience (Baumeister & Leary, 1995; Bugental, 2000), loneliness is also associated with numerous mental and physical health problems (Courtin & Knapp, 2017; Luanaigh & Lawlor, 2008; Ong et al., 2016; Park et al., 2020), including depression. Despite decades of observational research showing that loneliness is a risk factor for increased depression symptom severity and caseness (Erzen & Çikrikci, 2018; Kuczynski, in prep), however, how loneliness may increase risk for depression is poorly understood. Cacioppo and colleagues' (2006; 2018) evolutionary theory of loneliness suggests that the answer may lie in one's response to feelings of loneliness. Do individuals engage in social interaction and reestablish connection with others or instead withdraw from others in an attempt to avoid social rejection? This study aimed to examine this very idea. Using

ecological momentary assessment with a sample of 102 depressed adults, we explored whether acute (i.e., state) feelings of loneliness were associated with changes in depressed mood throughout the course of the day and whether the quantity and quality of one's social interactions moderated this association. Guided by Kanter and colleagues' (2020) contextual-behavioral formulation of the interpersonal process model (Reis & Shaver, 1988), we hypothesized that the association between loneliness and depressed mood would be weaker when individuals engaged in social interaction characterized by greater self- and other-disclosure and perceived responsiveness following feelings of loneliness and stronger for individuals who experience chronic feelings of loneliness. Results demonstrated that feelings of loneliness throughout the day were associated with changes in depressed mood not only at the same time point, but also 3 and 6 hours later. Individuals varied considerably in the degree to which loneliness was associated with subsequent depressed mood. Contrary to our hypotheses, neither social interaction quantity nor quality moderated this association. Methodological factors such as the timing of momentary assessments, sample demographics, and measurement strategy are considered, and implications for theory and clinical practice are discussed.

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Although it is my name on the face of this dissertation, it is the product of a true collaboration between mentors, colleagues, friends, and family, all to whom I am deeply indebted. I am but the final runner in a decades-long relay race to the doctoral finish line.

This work is dedicated to my grandfather, Ronald "Gramps" Cohen, who believed in me before I was able to believe in myself, who instilled in me the value of education, and who inspires me to be more generous and kind toward others every day. I could not have made it this far if not for the unwavering support of my parents, Robin and Silvio – thank you for always having my back and showing me all of the different ways to love. To my twin sister Jenna, thank you for making me laugh and for reminding me that life is diverse and has much to offer. To my grandmother Elaine, whose love for me is unconditional and patient, and who teaches me the importance of walking a mile in others' shoes. Vovó e vovô, obrigado por me mostrarem o valor do esforço e determinação.

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In memory of Robert J. Kohlenberg, PhD

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Introduction

Loneliness is a problem of increasing public health significance. Although population-level estimates of loneliness are notoriously difficult to obtain (Holt-Lunstad, 2017), recent evidence suggests that mean levels of loneliness are increasing over time, at least in emerging adult populations (Buecker et al., 2021; Xin & Xin, 2016; c.f. Clark et al., 2015). Although perhaps not reaching levels high enough to warrant a "loneliness epidemic" (Buecker et al., 2021), this increase is concerning, especially in light of evidence that the Covid-19 pandemic and associated measures to prevent the spread of the SARS-CoV-2 virus, have recently exacerbated this problem (Ernst et al., 2022).

There are several well-known risk factors for loneliness. Evidence from twin studies suggests that loneliness is heritable across the lifespan (Bartels et al., 2008; Boomsma et al., 2005, 2007), although genome-wide association studies have been unsuccessful in their efforts to identify specific candidate genes (Gao et al., 2017). Lonely individuals are more likely to live alone (Beutel et al., 2017; Hutten et al., 2022), be unmarried (Fokkema et al., 2012; Hajek & König, 2020; Lykes & Kemmelmeier, 2014), have inadequate financial resources (Hawkley et al., 2020; Hutten et al., 2022), and be in adolescence or old age (Victor & Yang, 2012). Socially isolated individuals tend to be lonelier than their socially connected counterparts (Dahlberg et al., 2022; Luhmann & Hawkley, 2016), however loneliness can occur in even the most socially connected individuals. In fact, lonely individuals are more likely to affiliate in groups with other lonely individuals, leading some to suggest that loneliness may spread from one individual to another (J. T. Cacioppo, Fowler, et al., 2009). Although single studies often find gender

differences in loneliness (e.g., Barreto et al., 2021; Hutten et al., 2022), a meta-analysis by Maes and colleagues (2019) observed very small effects that are unlikely to be meaningful in practice.

Cultural factors may also influence feelings of loneliness. Much of this work has focused on cross-national differences in loneliness as a function of individualism (wherein greater value is placed on autonomy and self-reliance) and collectivism (wherein greater value is placed on in-group membership and cohesion; Hofstede, 2001). The literature is mixed with respect to the effect of this cultural dimension on risk for loneliness. For example, in an analysis of 44,492 respondents across 30 countries, Taniguchi and Kaufman (2021) found that individuals in collectivist countries were less likely to report feeling lonely than those in individualistic countries. A similar finding was reported in an analysis of 46,054 respondents across 237 countries (Barreto et al., 2021) and in a cross-national study with respect to individuals' own collectivist versus individualistic ideals (Heu et al., 2019). In contrast, Lykes and Kemmelmeier (2014) surveyed 42,769 respondents and found greater levels of loneliness in European countries characterized by greater collectivism than individualism. As Luhmann and colleagues (2022) point out, this cultural dimension likely interacts with loneliness in complex ways, which could explain the discrepant findings. For example, individuals in collectivist cultures may be less likely to report experiencing loneliness due to increased stigma (Barreto et al., 2022). Socio-cognitive factors may also influence this association. For example, having stronger relationships with others appears to protect against loneliness to a greater degree in individualistic cultures (Lykes & Kemmelmeier, 2014), an effect that may be due to perceived norms about relationships and living with others.

Loneliness is, in turn, a risk factor for several negative health outcomes. Compared to non-lonely individuals, lonely individuals are at greater risk of experiencing cardiovascular

problems (Golaszewski et al., 2022; Hawkley et al., 2003, 2006; Valtorta et al., 2016), impaired immune system functioning (Cole et al., 2007, 2011; Pressman et al., 2005; Stephen et al., 2022), increased hypothalamic-pituitary-adrenal activity (Adam et al., 2006; Steptoe et al., 2004), poor quality sleep (J. T. Cacioppo et al., 2002; Kurina et al., 2011; Peng et al., 2021), and other health problems (Christiansen et al., 2021) that may ultimately contribute to increased risk of mortality (Holt-Lunstad et al., 2015; Rico-Uribe et al., 2018). Loneliness is also associated with increased risk for various common psychiatric conditions such as suicide ideation and attempts (Stickley & Koyanagi, 2016; Stravynski & Boyer, 2001), generalized anxiety (Domènech-Abella et al., 2019), and depression (Erzen & Çikrikci, 2018), and may help identify individuals at risk for more severe cases of psychopathology (Nuyen et al., 2020).

The Association Between Loneliness and Depression

The association between loneliness and depression may be especially important considering the increasing burden of depression worldwide. The World Health Organization (2008) estimated that depression will become the world's leading contributor to disease by 2030. In the United States, roughly 20% of individuals will receive a diagnosis of depression in their lifetime (Hasin et al., 2018), leading to substantial economic costs (Greenberg et al., 2015). Although the availability and efficacy of depression treatments has improved over the last several decades, these improvements have not translated to decreased prevalence. While the reasons for this are likely multifactorial (Jorm et al., 2017; Ormel et al., 2020), Ormel and colleagues (2022) note that poor external validity of existing depression efficacy trials is likely a contributing factor. There is thus a need for externally valid research to identify risk factors for depression in the "real world" with the aim of informing ongoing intervention efforts.

Several converging lines of evidence suggest that loneliness is prospectively associated with depression across the lifespan. For example, average feelings of loneliness measured across 5 days of ecological momentary assessment in a large sample of Belgian women were associated with increased risk of incident major depressive disorder 18 months later (van Winkel et al., 2017). Similar findings were observed in samples of German (Beutel et al., 2017) and Swedish (Sjöberg et al., 2013) older adults across a 5-year time span. In clinically depressed samples, those with high baseline levels of loneliness are less likely to experience remission one (Wardenaar et al., 2015), two (Holvast et al., 2015; Maarsingh et al., 2018), six (Jeuring et al., 2018) and even 17 (Luoma et al., 2015) years later. Loneliness is prospectively associated with increased depression symptom severity in clinical (van Beljouw et al., 2010) and non-clinical (J. T. Cacioppo et al., 2010; Lim et al., 2016; McHugh Power et al., 2018, 2020; Wei et al., 2005) samples, and may be more severe when individuals experience structural changes in their social network (e.g., via retirement; Segel-Karpas et al., 2018). Similar findings have also been observed in child and adolescent populations (Adam et al., 2011; Brière et al., 2018; Goosby et al., 2013; Yang et al., 2018).

Despite a wealth of research establishing an association between loneliness and subsequent changes in depression symptoms, our understanding of this phenomenon remains quite limited. Loneliness, like other socioemotional phenomena, varies in intensity and duration as a function of person, place, time, and other contextual factors. However, existing longitudinal research has largely ignored these time-varying contextual factors and has opted for a measurement strategy that requires individuals to report, in retrospect, how often they felt lonely over a predetermined period of time (see the de Jong-Gierveld Loneliness Scale and UCLA Loneliness Scale; de Jong-Gierveld & Kamphuls, 1985; D. W. Russell, 1996). This approach to

measurement is due in part to the large time intervals between assessments in existing longitudinal research (the majority of which are one year or greater in duration) and has several implications that limit the development of a theoretical model of this association.

The use of large time intervals between assessments broadly, and measurement strategies that require participants to report frequency of loneliness across these intervals more specifically, may obscure the effect of heterogenous patterns of loneliness across time. For example, one individual may report 'often' feeling lonely in response to daily transient experiences of loneliness while another may similarly report 'often' feeling lonely in response to more intense experiences of loneliness across fewer days. These various patterns of loneliness may result in different risk profiles for conditions such as depression and require different prevention and intervention strategies. Indeed, individuals with depression exhibit different patterns of negative affectivity throughout the day than those without depression (Kuppens et al., 2010; Thompson et al., 2012; c.f., Bos et al., 2019). It is therefore possible that varied momentary experiences of loneliness confer differential risk for depression, however this has not been specifically examined.

Another implication of the use of large time spans between assessments in existing longitudinal research on this topic concerns the distinction between transient and chronic feelings of loneliness. Whereas transient feelings of loneliness are temporary and likely occur in response to changes in one's psychosocial context, chronic feelings of loneliness are more permanent and impervious to change. Cacioppo and colleagues' (2006; 2018) evolutionary theory suggests that loneliness evolved to motivate social reconnection when an individual perceives their relationships as impoverished. However, because impoverished social relationships, according to this theory, often resulted from the presence of adversarial (rather than altruistic or mutually

beneficial) relationships, loneliness also evolved to motivate withdrawal and reappraisal of one's social environment prior to reconnection. These seemingly antagonistic motivations may help explain the association between loneliness and adverse health conditions such as depression insofar as they precipitate biopsychosocial changes (e.g., social isolation versus connection) that increase risk or resilience factors. Research delineating the temporal sequence of these cognitive-behavioral responses to loneliness, however, is limited.

Evidence suggests that chronic forms of loneliness are associated with biological and behavioral changes consistent with the social withdrawal and reappraisal hypothesis. For example, chronically lonely individuals show greater resting state functional connectivity in cortical regions implicated in social cognition and attention to social threat (Brilliant T. et al., 2022; Layden et al., 2017; Tian et al., 2014), greater attention to negative social versus non-social stimuli (J. T. Cacioppo, Norris, et al., 2009; S. Cacioppo et al., 2015, 2016), and higher social threat sensitivity (Bangee et al., 2014; Gardner et al., 2005; Nowland et al., 2018). Moreover, these biological changes appear to have meaningful effects on social behavior such as decreased likelihood of accepting invitations for social inclusion (Vanhalst et al., 2018) and actual social disengagement (McHugh Power et al., 2018). Research on the effects of transient loneliness, on the other hand, is sparse, however some evidence suggests that it is similarly associated with an acute stress response (Adam et al., 2006; Doane & Adam, 2010). Emerging evidence suggests that transient feelings of loneliness may not, contrary to Cacioppo and colleagues' evolutionary theory, promote actual engagement in social interaction (Kuczynski, Piccirillo, et al., 2022; Tran et al., 2023).

Given that the prospective association between loneliness and depression has been established predominantly across large time intervals, this literature has arguably provided a

basis for understanding the association between chronic, but not transient, forms of loneliness and depression. Studying the effect of transient feelings of loneliness on depression is important for several reasons. First, if one's behavioral response to transient feelings of loneliness differ from its (perhaps more pernicious) chronic form, we might observe different effects on depression. To our knowledge, this has not been examined in existing research. Second, research suggests that etiological factors for depression likely operate by producing momentary (i.e., micro-level) changes in depression symptomatology (in addition to macro-level changes) as people navigate their natural 'everyday' environments (Nelson et al., 2017; Wichers, 2014). This is, in many respects, the level at which evidence-based psychological interventions operate. It is therefore important to understand whether micro-level (i.e., transient) changes in loneliness are associated with micro-level changes in depression, as this could be an important intervention target for some individuals. Lastly, differentiating the effects of transient and chronic feelings of loneliness will aid mental health clinicians and policymakers in understanding which populations are at greatest risk and thus where to allocate time and resources.

Another problem lies in the existing literature's reliance on retrospective methods of data collection. Retrospective reports of affect are subject to systematic recall biases that may obscure a true and clinically useful understanding of the association between loneliness and depression as it occurs on a momentary basis (Conner & Barrett, 2012). Research indicates that people tend to overestimate the intensity and duration of both positive and negative affective experiences (e.g., Ben-Zeev et al., 2009; Miron-Shatz et al., 2009; c.f., Barrett, 1997). Contextual factors during recall such as one's current mood (Faul & LaBar, 2022) and cognitive factors such as the personal salience of affective events (Gaddy & Ingram, 2014; Ottenstein & Lischetzke, 2020) can further impact retrospective self-report of affect. Furthermore, clinical samples, including

individuals with depression, exhibit recall biases characterized by greater attention toward negative affective experiences (Ebner-Priemer et al., 2006; Gaddy & Ingram, 2014; Mitte, 2008; Solhan et al., 2009). For example, using experience sampling methodology, Ben-Zeev and colleagues (2009) collected self-reports of momentary positive and negative affect every 1.5 hours for 7 days in a sample of depressed individuals and non-depressed controls. All participants were then invited to retrospectively report on their experience of positive and negative affect at the end of the week. Depressed individuals overestimated their experience of negative affect to a greater extent throughout the previous week than non-depressed controls. It is therefore possible that retrospective reports of both loneliness and depression were inflated in existing research with depressed samples and, if so, that the association is weaker or non-existent when momentary reports of affect (e.g., via experience sampling methods, ecological momentary assessment) are obtained.

Psychological Mechanisms Underlying the Association Between Loneliness and Depression

Existing research has focused primarily on establishing the association between loneliness and depression across various contexts, developmental stages, and geographies. Although this form of conceptual replication is important in establishing that this finding is robust to variations in sampling strategy, research design, and data-analytic methods, there has been lesser focus on understanding the mechanism through which loneliness and depression are associated.

Consistent with research indicating that depressed individuals are more resistant to change in negative affective states than non-depressed individuals (i.e., exhibit greater emotional inertia; Brose et al., 2015; Koval et al., 2012, 2016; c.f., Bos et al., 2019), van Winkel and

colleagues (2017) observed greater loneliness autocorrelation in a group of Belgian women who developed major depressive disorder 18 months after completing a 10-day experience sampling protocol compared to those who did not develop the disorder. Chronicity of loneliness was also found to mediate its association with depression 12-16 weeks later in adults (Lim et al., 2016) and 8 years later in a sample of school-aged children (Qualter et al., 2010).

The context in which one experiences loneliness may also exert influence on this association. Two large-scale studies with middle-aged adults from the United States (Segel-Karpas et al., 2018) and older adults from Europe (Conde-Sala et al., 2019) examined the association between loneliness and depression across a two-year period. In the US sample, this association was stronger for individuals who transitioned out of the workforce and into retirement during this period (Segel-Karpas et al., 2018), suggesting that feelings of loneliness may be particularly harmful when experienced in situations where social contact is less available. It is also possible that the effects of loneliness on mental health are stronger in cultures with more restrictive norms about social embeddedness (e.g., collectivist cultures; Heu et al., 2021). Consistent with this hypothesis, Conde-Sala and colleagues (2019) observed a stronger association between loneliness and depression for individuals living in southern European countries compared to those in other regions of the continent where a lesser emphasis is placed on familial relationships.

Collectively, this research suggests that not all experiences of loneliness confer equal risk for depression. The way in which one responds to the experience of loneliness, the social opportunities available to them, and sociocultural factors that influence social cognition may be responsible for any negative downstream effects it may produce. For example, individuals who engage in more active coping strategies and respond to the experience of loneliness by increasing

social engagement may not experience the same negative effects as those who engage in passive coping and who decrease social engagement (Glass et al., 2006; Kivelä et al., 2022; Vanhalst, Luyckx, et al., 2012). Loneliness may also impact the perceived quality of one's interactions, for example through attentional biases toward social threat and away from cues of safety and acceptance. Indeed, the degree to which one perceives their interaction partners as understanding and caring is associated with daily levels of depressed mood (Kuczynski, Halvorson, et al., 2022). If one's response to momentary experiences of loneliness moderate is association with negative outcomes such as depression, interventions focusing on teaching adaptive responses may prevent these negative downstream effects from occurring.

What does an adaptive response to loneliness look like? Turning to Cacioppo and colleagues' (2006; 2018) evolutionary theory of loneliness may provide an answer to this question. The theory suggests that, similar to seeking water upon feeling thirsty or nutrition upon the experience of hunger, seeking social connection upon feeling lonely may protect against negative outcomes. However, not all forms of social interaction were made equal, and Cacioppo and colleagues do not make explicit the specific characteristics of social interactions that may be beneficial. With whom should one interact when feeling lonely? What features of an interaction ought to be present? How important is the quantity of one's social interactions versus the quality? Just as all liquids are not the same in quenching thirst and preventing dehydration, not all interactions may be the same in "quenching" loneliness and preventing negative mental health consequences. The current study aims to begin providing answers to these questions.

The Interpersonal Process Model of Intimacy

According to Reis and Shaver's (1988) Interpersonal Process Model of Intimacy, relational intimacy (c.f., sexual or romantic intimacy) is a dyadic momentary process wherein individuals engage in an exchange of vulnerable, self-revealing self-disclosure and the provision of understanding, care, and validation in response. The basic tenets of this model have replicated across various samples and research designs, including a daily diary study with married couples (Laurenceau et al., 2005), experimental research with college students (Haworth et al., 2015; Manbeck et al., 2020), behavioral observational research with breast cancer patients and their partners (Manne et al., 2004), and longitudinal research within intra- and interracial friendships (Shelton et al., 2010).

Kanter and colleagues (2020) have since expanded upon this model by integrating relevant findings from throughout the social psychology and clinical science literatures to identify core sets of functional relations within intimate dyadic interactions. In their expanded model, they highlight the role of non-verbal expression of emotion (met with the provision of safety), verbal engagement in self-revealing self-disclosure (met with the provision of validation), advocating for one's needs within the interaction (met with the provision of, or negotiation around, those needs), and a reciprocal exchange of caring and closeness. Research has supported the importance of each component highlighted within this model, with particular emphasis on the mediating role that perceived responsiveness may play within intimate interactions (Laurenceau et al., 1998; Reis, 2007)

The Current Study

The overarching aim of this study was to characterize the momentary association between feelings of loneliness and depressed mood and identify whether engagement in social interaction may moderate this association. Drawing on research indicating an effect of affect variability on health outcomes such as depression (Jenkins et al., 2020), we examined variance-level (i.e., 'scale') associations among affective and social constructs in addition to mean-level (i.e., 'location') associations. An ethnically diverse sample of adults in the United States with elevated depression symptoms was recruited to ensure variation in depressed mood throughout the duration of the study and improve generalizability of our findings.

To our knowledge, this research is the first to study the momentary association between loneliness and depressed mood. However, emerging research conducted during the Covid-19 pandemic suggests that momentary loneliness, at least in the pandemic context, is associated with negative affect and other constructs related to depression. For example, in a sample of 80 college students recruited in the first month of the pandemic, Fried et al. (2022) found that feelings of loneliness were contemporaneously associated with anhedonia and concerns about one's future and predicted increases in these constructs just a few hours later. The current study expands upon this and other research discussed above. Using Cacioppo and colleagues' (2006; 2018) evolutionary theory of loneliness and Reis and Shaver's (1988) interpersonal process model as our guiding frameworks, we developed the following hypotheses: state loneliness will be associated with depressed mood at the same (H1a) and next (H1b) time points, and these associations will be stronger for individuals who are lonelier on average (H1c, H1d). We will also explore the effect of varying time lags within day (i.e., two, three, and four time points after

the experience of loneliness) to help delineate the time scale at which this association unfolds, an important yet largely ignored metric in the theoretical and empirical literature guiding this work (Hopwood et al., 2022). In addition, we will explore whether gender moderates the contemporaneous and lagged associations as well as other dynamic measures of this association, including the effect of loneliness inertia (i.e., autocorrelation; the degree to which individuals get 'stuck' in experiences of loneliness) and stability (i.e., mean squared successive difference; the degree to which one's experience of loneliness fluctuates when it does), and the effect of state and trait loneliness on the degree to which one varies in depressed affect throughout the course of the day.

As discussed above, we also aim to identify whether specific characteristics of interactions (or lack thereof) moderate the association between loneliness and depressed mood, and have the following hypotheses: the association between loneliness and depressed mood at the next time point will be weaker when an individual is more satisfied with their interactions since reporting feeling lonely (H2a), perceives their interactions as characterized by greater responsiveness (i.e., communicating understanding, validation, and care; H2b), vulnerable self- (H2c) and other-disclosure (H2d), and engages in more frequent social interaction since feeling lonely (H2e). We also expect that the contemporaneous association between state loneliness and depressed mood will be stronger when individuals report being alone (i.e., state solitude) at the same time as this self-report (H2f).

Consistent with our preregistered hypotheses on the Open Science Foundation (https://osf.io/7rkfm and https://osf.io/nhs7z), main effects ranging from 0 to 0.10 will be considered "null", those ranging from 0.10 (our smallest effect size of interest; SESOI; Anvari & Lakens, 2021) to 0.25 will be considered "meaningful", and those larger than 0.25 will be

considered “large” effects. Estimates of interaction effects will be interpreted with respect to these values by identifying individuals for whom the main effect is null, meaningful, or large.

Method

Participants

Participants were 102 adults (M_{age} = 31.94, SD_{age} = 11.56) recruited through advertisements on the online social media platforms Facebook and Instagram. Our sample was balanced across race/ethnicity within the following five groups: Asian or Pacific Islander (N = 20), Black or African American (N = 19), Hispanic or Latino (N = 20), White or European American (N = 20), and multiracial/other (N = 23). Most participants (N = 83) were women, with 19 individuals identifying as men and 4 as gender non-conforming. Roughly half our sample was partnered (N = 52) and the majority lived with others (N = 77). Most participants (N = 58) self-reported a diagnosis of at least one mental health disorder from a medical professional in their lifetime: 36 with Major Depressive Disorder (MDD) or Persistent Depressive Disorder (PDD), 34 with Generalized Anxiety Disorder (GAD), 10 with Social Anxiety Disorder (SAD), 16 with Posttraumatic Stress Disorder (PTSD), and 20 with another psychiatric disorder not listed. Slightly less than half (*n* = 48) of our participants reported receiving mental health services at the time of the study. A more detailed overview of our sample’s sociodemographic characteristics can be found in Table 1.

Procedure

Advertisements on social media directed prospective participants to the study’s webpage where they could learn more about participating. If they were interested in participating at this

point, they were directed to our online screening survey to determine eligibility. Participants were eligible to participate if they were between 18-64 years of age, lived in the United States or its territories, owned a smartphone, reported having at least one social interaction on an average day, and scored 10 or higher on the Patient Health Questionnaire – 9 (PHQ-9; including 1+ on items 1 [depressed mood] or 2 [anhedonia]; Kroenke et al., 2001). Participants were excluded from participating if they were unwilling to provide identification during the baseline visit, provided a VoIP (voice over internet protocol) phone number (e.g., Google Voice), reported a geographic location that was inconsistent with their geotagged location (based on IP address), or whose responses indicated careless responding (e.g., Not at all on "Hearing voices when you are alone" and Nearly every day on "Hearing voices talking to each other when you are alone"). Participants who were eligible after taking our online screening survey received a phone call from a member of the study team to confirm eligibility criteria, describe the study in more detail, and schedule their baseline study visit.

Baseline visits were conducted using online telecommunications software and lasted roughly one hour. Participants provided informed consent to participate, took a baseline survey, and discussed the protocol for the experience sampling period, including a brief description of each item they would be asked to respond to. The baseline survey contained questions about participants' demographics, medical history (including mental health), and several self-report psychological questionnaires, a subset of which is reported on in the current study. The 14-day experience sampling period began the following day.

The experience sampling period used an anchor test planned missingness (Silvia et al., 2014) random-interval design with 5 surveys per day for 14 days. Surveys were sent randomly within five 150-minute (2.5 hours) blocks of time with a minimum of 120 minutes (2 hours)

between each. A maximum of 4 reminders (every 15 minutes) for each survey were sent if participants did not complete the survey within 15 minutes of receiving the notification. Participants had 90 minutes (1.5 hours) to complete each survey. Surveys were sent to most participants within the following five intervals: 0900-1130, 1130-1400, 1400-1630, 1630-1900, 1900-2130. These intervals were shifted up and down for a minority of participants to accommodate their wake/sleep schedules. All survey notifications were sent by text message (i.e., SMS) using Pingr (https://pingr.co).

Participants were compensated USD$25 for completing the baseline study visit, USD$1 for each completed experience sampling survey, and an additional USD$30 if they completed 90% or more (63+) of the experience sampling surveys. Thus, participants could earn up to USD$125 for participation in this study. All procedures were approved by the University of Washington's institutional review board.

Measures

State Depressed Mood

State depressed mood was measured using 11 items adapted from the PHQ-9 (Kroenke et al., 2001) for use in the experience sampling paradigm. Using a slider ranging from 0 (*Not at all*) to 100 (*Very much so*), participants were asked to rate the following items with respect to their state as they were taking the survey: "I feel depressed," "I feel hopeless," "I feel down", "I feel worthless," "I feel discouraged," "I feel sad," "I feel like a failure," "I feel disappointed in myself," "I have little interest in doing things right now," "I have found little pleasure in the things I did since the last prompt," and "I am enjoying myself right now." A random subset of 7 of these items were asked at each assessment, however "I feel depressed" and "I have little

interest in doing things right now" were both asked at each assessment. A total score was computed by taking the mean across all 11 items. These items demonstrated strong reliability at the between-person (ω_b = .96) and within-person (ω_w = .89) levels.

State Loneliness

State loneliness was measured using 12 items adapted from the UCLA Loneliness Scale (version 3; D. W. Russell, 1996) for use in the experience sampling paradigm. Using a slider ranging from 0 (*Not at all*) to 100 (*Very much so*), participants were asked to rate the following items with respect to how they felt as they were taking the survey: "I feel lonely," "I feel 'in tune' with those around me," "I feel part of a group of friends," "I feel included by others," "I feel close to people," "I feel that there are people I can talk to," "I feel that I lack companionship," "I feel alone," "I do not feel close to others," "I feel like I don't belong," "I feel isolated from others," and "I feel left out." A random subset of 5 of these items were asked at each assessment, however "I feel lonely" was asked at each assessment. A total score was computed by taking the mean across all 12 items after reverse scoring the positively valenced items. These items demonstrated strong reliability at the between-person (ω_b = .95) and within-person (ω_w = .86) levels.

State Social Interaction Quantity

At each assessment, participants reported the number of social interactions they engaged in since the previous assessment ("how many social interactions have you had since the last prompt?"). Following previous research (Nauta et al., 2020; J. J. Russell et al., 2007), participants were instructed to include all interactions toward this total that were 5 minutes or longer in duration and with an individual who was 7 years old or older. All forms of interaction,

whether in-person or virtual, were included. Response options ranged from ‘0’ to ‘25 or more’ interactions.

Social Interaction Characteristics

Participants who indicated engaging in 1+ interactions since the previous survey were asked follow-up questions regarding those interactions. To prevent inadvertently reinforcing fewer social interactions by presenting fewer items at each assessment, participants who reported no interactions since the previous survey were instructed to select “not applicable” for these items, resulting in the same itemset regardless of their social interaction behavior.

Participants indicated how satisfied they were with their interactions (**social interaction satisfaction**; “how satisfied did you feel with these interactions?”) using a slider ranging from 0 (*Not at all satisfied*) to 100 (*Very satisfied*).

State vulnerable self-disclosure was measured using 4 items derived from the interpersonal process model of intimate relationships (Kanter et al., 2020; Reis & Shaver, 1988). Using a slider scale ranging from 0 (*Not at all*) to 100 (*Very much so*), participants responded to the following items with respect to their interactions since the previous survey: “I let others see how I was feeling non-verbally,” “I expressed closeness with others,” “I shared how I felt with others,” and “I shared personal information with others.” Three of these items (the first two plus a random selection from the latter two) were presented at each assessment. A total score was computed by taking the mean across all 4 items. These items demonstrated strong reliability at the between-person (ω_b = .93) and within-person (ω_w = .79) levels.

State vulnerable other-disclosure was measured using 4 items that were similarly derived from writings by Reis et al. (1988) and Kanter et al. (2020). Using a slider scale ranging from 0 (*Not at all*) to 100 (*Very much so*), participants responded to the following items with

respect to their interactions since the previous survey: “Others let me see how they were feeling non-verbally,” “Others expressed closeness with me,” “Others shared how they felt with me,” and “Others shared personal information with me.” Three of these items (the first two plus a random selection from the latter two) were presented at each assessment. A total score was computed by taking the mean across all 4 items. These items demonstrated strong reliability at the between-person (ω_b = .93) and within-person (ω_w = .79) levels.

State responsiveness was measured using 6 items derived as well from Reis et al. (1988) and Kanter et al. (2020). Using a slider scale ranging from 0 (*Not at all*) to 100 (*Very much so*), participants responded to the following items with respect to their interactions since the previous survey: “I felt understood by others,” “I felt cared about by others,” “I felt validated by others,” “I felt that others were not interested in me,” “I felt criticized by others,” and “I felt rejected by others.” Four of these items were randomly presented at each assessment. A total score was computed by taking the mean across all 6 items after reverse scoring the negatively valenced items. These items demonstrated strong reliability at the between-person (ω_b = .88) and within-person (ω_w = .75) levels.

State solitude (i.e., aloneness) was measured using the single item “Are you alone or with others right now?” Participants were instructed to select “with others” if they were engaged in virtual social interaction at the time of the survey (e.g., phone call, video chat). Participants were instructed to select “alone” if they were at their residence with others but in a separate room.

Trait Loneliness

Trait loneliness was measured using the UCLA Loneliness Scale (version 3; D. W. Russell, 1996), a 20-item measure that asks participants to indicate how often they experience

certain feelings that pertain to loneliness from 1 (*never*) to 4 (*often*). Although the UCLA Loneliness Scale was designed as a unidimensional measure, some evidence suggests that it measures 2 (Wilson et al., 1992; Zakahi & Duran, 1982) or 3 (Hawkley et al., 2005) distinct subtypes of loneliness in various samples. Despite this, the vast majority of literature in this area has adhered to the unidimensional approach, which is the approach we take in this study. A total score was computed by taking the sum across all 20 items after reverse scoring the positively valenced items. Reliability was strong in the current sample ($\omega = .91$).

Analytic Approach

Missing Data

We used an anchor test planned missingness design (Silvia et al., 2014) to reduce participant burden at each assessment while maintaining multiple indicators for each of our measured variables. A random subset of items for each construct was presented to participants in addition to 1+ items per construct that were displayed at each assessment. Excluding data that were missing by design and those due to completely missed assessments (8%), missing data were rare (around 1% for each variable) and were thus primarily missing completely at random (MCAR).

We used fully conditional specification implemented in Blimp (version 3; Enders et al., 2020) to impute missing data at the item-level for all state variables. Although no missingness was observed at baseline, we included person-level variables in our imputation model to improve prediction. Each imputation was conducted with 10 chains each with 20,000 iterations to create 20 imputed datasets. Maximum potential scale reduction factors ($\hat{R}$) near 1.00 and density plots

of the imputed versus fully-observed values indicated that the imputation process converged on stable estimates.

Models

Bayesian mixed effects location scale models (MELSM) were used to address our primary hypotheses and exploratory aims. Mixed effects models account for non-independence (i.e., clustering, nesting) of observations by modeling person-level differences in parameter estimates (i.e., intercepts, slopes) as random variables. Although there are many ways to correct for the presence of dependent observations, the ability of mixed effects models to estimate random effects has the added advantage of characterizing the degree of heterogeneity around the fixed effects (McNeish et al., 2017).

Traditional 'location-only' mixed effects models are used to answer questions that pertain to conditional means (i.e., location). Although these models are well-equipped to address our primary hypotheses, they have several shortcomings. First, they make the critical and likely untenable assumption that error variances are stable across time and constant across all individuals (McNeish, 2021). Although violations of this assumption are unlikely to bias parameter estimates, they may downwardly bias standard errors (Pugach et al., 2014) and lead to erroneous conclusions about the precision of our effects. Second, and perhaps more importantly, is the fact that traditional mixed effects models preclude modeling variation as an outcome in its own right (for a discussion, see McNeish, 2021). A wealth of evidence suggests that emotion variability is related to psychological well-being (Houben et al., 2015) and may even serve as a marker of the transition from non-depressed to depressed states (van de Leemput et al., 2014). Thus, it is important to understand whether loneliness is associated with variation in addition to mean levels of depressed mood.

Mixed effects location scale models are similar to traditional mixed effects models, but they allow for an additional model on the within-person residual variance (the scale submodel). Unlike alternative "two-step" approaches that use the residuals from a location model as the outcome in a scale model, the location scale model takes a joint modeling approach that estimates uncertainty in the variability estimates and can model the covariance between the random location and random scale effects.

Separate location scale models were used to address our primary hypotheses. In each of these models, state loneliness was centered around each participant's mean, which enables estimating the within-person effect of loneliness on depressed mood separate from any between-person effects that may exist (Wang & Maxwell, 2015). Random intercepts were estimated in the location and scale submodels. In addition, random slopes of the contemporaneous (Hypothesis 1a) and lagged (Hypotheses 1c) effects of state loneliness were included in each submodel, which represent person-level heterogeneity, or dissimilarity, in these effects. In addition, the random effects in each submodel were allowed to covary, allowing us to identify, for example, whether individuals who experience a stronger association between loneliness and depressed mood also show differences in variation as a function of loneliness. This is important insofar as both mean levels and variability in depressed mood are associated with psychological well-being. A log-linear scale submodel was used to ensure that estimates of within-person variation remain positive. A first-order autoregressive structure was placed on the within-person residuals to account for autocorrelated error caused by the repeated measures nature of the data.

Weakly informative priors were chosen in line with recommendations by Gelman et al. (2017). With a sufficiently large sample, these priors function to regularize parameters while yielding minimal influence on the final estimates. The following priors were used:

$$\beta_0 \sim N(50, 10)$$

$$\beta_{state\ loneliness\ (t)} \sim N(0, 0.50)$$

$$\beta_{state\ loneliness\ (t-1)} \sim N(0, 0.30)$$

All models were estimated using the brms package (version 2.17.0; Bürkner, 2021) for R (version 4.1.1; R Core Team, 2021), which uses the probabilistic programming language Stan (Carpenter et al., 2017) as its computational engine. R code for all analyses can be found on this project's OSF page.

Results

A total of 6,568 surveys were completed by participants (M = 64.39 [91.99%], Mdn = 68, SD = 11.63). Most participants (83.33%) completed 90% or more of the surveys, and nearly everyone (96.08%) completed at least half (see Figure 1). 44% of all surveys were completed within five minutes of being sent to participants, and 90% of all prompts were completed within 45 minutes of the original send time.

Markov Chain Monte Carlo (MCMC) Convergence and Model Diagnostics

To aid in model convergence, it was necessary to deviate slightly from our preregistered data-analytic plan. Specifically, we increased the number of 'burn-in' iterations (samples from the posterior which are discarded prior to recording the draws) in the MCMC sampler to 2,000 and the number of total iterations (including burn-in) to 4,000, enabling a more complete traversal of the posterior distribution and a greater chance of starting this traversal in a high-probability region of the distribution. Related, we also set the initial starting value of each parameter to 0 rather than using the defaults set by the brms package, which can also aid the

sampler in more effectively traversing the posterior. Lastly, we changed the default priors from brms to the following weakly informative priors to aid in model convergence:

$$\sigma_0, \sigma_\beta, \sigma_{0\epsilon}, \sigma_{\beta\epsilon} \sim exponential(1)^*$$

$$\rho \sim LKJ(2)^\dagger$$

With these minor modifications, our models converged without warnings. Trace and density plots indicated that each chain of the MCMC sampler arrived at similar values for the posterior distribution (see Appendix A for combination trace and density plots for our primary parameters of interest). The $\hat{R}$ statistic, a ratio of between- and within-chain variability for all model parameters, also indicated that our chains mixed well; all $\hat{R}$ values were less than 1.01 in this study. Finally, we examined the effective sample size (ESS) metric, which is an indicator of how effectively the MCMC sampler traversed the entire posterior distribution versus getting 'stuck' in particular regions. (Gelman et al., 2003) suggest a rule of thumb that ESS values should be larger than 100 times the number of chains, which in the current study is ≥ 400. ESS values for the middle 90% (bulk ESS) and the lower 5% and upper 95% (tail ESS) of the posterior distributions for all parameters were above this value.

To assess model fit, we conducted posterior predictive checks, which compare simulated values of the outcome (depressed mood) from the joint posterior distribution with observed values. Across models, simulated values closely resembled the distribution of the observed

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* The exponential(1) prior was applied to all intercepts and slopes in the location (σ_0 and σ_β) and scale ($\sigma_{0\epsilon}$ and $\sigma_{\beta\epsilon}$) submodels.

† The Lewandowski-Kurowicka-Joe(2) prior was applied to all correlations among random slopes and intercepts within and across the location and scale submodels.

depressed mood scores, indicating that our models fit the data well (see posterior predictive plots for all models in Appendix A).

Scale Submodel Simplification

Estimates of the scale submodel parameters across all models indicated little evidence of an effect of time, seasonality within day or by week/weekend, state and trait loneliness, and their interaction (see Table 2 example scale submodel results). This indicates that the degree to which participants deviated from their conditional mean depressed mood score was relatively stable, on average, across time of day and study day. This also indicates that variation in depressed mood was not related to how lonely an individual was feeling in any given moment nor how lonely they are on average. Thus, knowing this information about an individual does not appear to aid the researcher nor the clinician in understanding how accurately loneliness can predict one's concurrent or subsequent level of depressed mood.

The intercept in the scale submodel is interpreted similarly to the value of the intercept in the location submodel; it represents the expected value of variation in depressed mood when the values of all covariates in the model are at zero. Thus, $\hat{\sigma}_0$ in this scale submodel represents the expected variation in depressed mood on an averagely lonely participant's first day in the study in the morning (when that observation lands on a weekday) when they are at their own average level of loneliness. As is, the intercept is not a particularly interesting or useful metric. However, when the scale submodel is constrained to an empty random intercept-only model, the intercept is more interpretable, as it represents the average level of variation in depressed mood and participant-level deviations around that mean. Given scant evidence of effects in our scale submodel, we re-ran all models with a random intercept-only scale submodel, allowing us to

better characterize participant-level variation in variation. All results found below derive from these simplified models.

General Findings

Study day, ping number (i.e., which survey per day; 1-5), and a dummy code indicating whether the observation was collected on a weekend or weekday were included in each model to account for potential time trends and seasonality in the data. As previously mentioned, a random-intercept only scale submodel was also included in our analysis to relax the assumption that error variances were identical across participants. Results across all models were consistent with respect to these effects, thus estimates from the model pertaining to H1a and H1c are presented herein.

There was no evidence of an effect of study day (Figure 2a; b = 0.02, SE = 0.05, 95% CI = -0.07 to 0.12) on depressed mood, suggesting that participants' depressed mood scores, in the aggregate, did not change across the 14-day study period. Similarly, no evidence of an effect of ping number (Figure 2b; b = -0.05, SE = 0.10, 95% CI = -0.25 to 0.14) on depressed mood was observed in this study. We found a small effect of weekend on depressed mood (b = -1.06, SE = 0.41, 95% CI = -1.86 to - 0.26) such that participants were, on average, 1.06 points less depressed on weekends than weekdays. Notably, this represents just over 1% of the entire range of depressed mood and is thus likely not clinically meaningful.

The posterior distribution of the intercept of the scale submodel ($\hat{\sigma}_{0\epsilon}$) suggests that, on average, participants varied around their predicted value of depressed mood $\pm$10 points (95% CI = 9.84 to 11.78). As expected, random intercept variation around this value indicated that some participants varied around their mean depressed mood to a greater extent than other participants,

with 68% of values lying between 9.66 and 11.83. Figure 3 illustrates such variation in variation with two exemplar participants from this study with low and high levels of variation.

Momentary Effect of Loneliness on Depressed Mood

Table 3 presents a summary of the main findings for the effect of loneliness on depressed mood. Separate models were fit for the contemporaneous (H1a) and lagged (H1b) effects of loneliness on depressed mood and are presented together in this table.

Higher levels of state loneliness were associated with greater levels of depressed mood at the same time point (b = 0.50, SE = 0.02, 95% CI = 0.45 to 0.54) such that, on average, depressed mood is expected to increase 5 units (of 100 total; 5%) for every 10 units increase above one's average level of loneliness. Nearly the entire area of the posterior distribution lied above both our smallest effect size of interest (SESOI; 0.10) and preregistered "large" effect of 0.25, suggesting with a great deal of certainty that the population-level effect is large (Figure 4a-b). Random effects estimates show meaningful variation around this average effect, with the middle 68% lying between 0.35 and 0.63 (Figure 4c). This effect is thus stronger for some participants than for others. There was a positive correlation between random slopes for the effect of loneliness (t) on depressed mood and the intercept of the scale submodel (r = 0.66, SE = 0.09, 95% CI = .47 to .81). This means that, for participants for whom loneliness was more strongly associated with depressed mood at the same time point, those participants also varied more around their average level of depressed mood.

Higher levels of state loneliness were also associated with greater levels of depressed mood at the next time point (b = 0.12, SE = 0.02, 95% CI = 0.09 to 0.15) such that, on average, depressed mood is expected to increase 1.2 units (1.2%) for every 10 units increase above one's

average level of loneliness. The majority (86%) of the posterior distribution lied above our preregistered 'medium' effect size range (0.10 to 0.25), which provides relatively strong evidence in favor of H1b (Figure 4a-b). Controlling for the contemporaneous effect of loneliness, feeling lonely predicts moderate increases in depressed mood roughly 3 hours later in the day. Random effects estimates show meaningful variation around this average effect, with the middle 68% lying between 0.07 and 0.16 (Figure 5c).

Evidence that trait loneliness moderated the contemporaneous (H1c; Figure 6a) and lag-1 (H1d; Figure 6b) association between loneliness and depressed mood was not observed in these data. Nearly the entire area of both posterior distributions lied between -0.1 and 0.1, providing strong evidence in favor of our null hypothesized effect (Figure 6a-b).

Our next aim was to identify whether engagement in social interaction, and characteristics of those interactions, moderated the association between state loneliness and subsequent depressed mood. Our primary estimates of interest from these models can be found in Table 4.

Evidence that state social interaction satisfaction moderated the association between state loneliness (*t*-1) and depressed mood (H2a) was not observed in these data (b = -0.001, SE = 0.0005, 95% CI = -0.002 to .00007). Although the association between state loneliness (*t*-1) and depressed mood appears to be weaker when individuals are more satisfied with their interactions (Figure 7), as we hypothesized, this effect is characterized by a great deal of error such that the predicted values at each level of social interaction satisfaction are not statistically distinguishable (e.g., at 50 pts above one's mean state loneliness score, 95% CI at +1 SD social interaction satisfaction: 31.14 to 38.92; -1 SD social interaction satisfaction: 37.03 to 44.82).

Similarly, there was no evidence that state perceived responsiveness moderated the association between state loneliness (*t*-1) and depressed mood (H2b; *b* = -0.002, SE = 0.0008, 95% CI = -0.003 to 0.00002). Although the association between state loneliness (*t*-1) and depressed mood appears to be weaker when individuals perceive greater responsiveness (Figure 8), as we hypothesized, this effect is characterized by a great deal of error such that the predicted values at each level of perceived responsiveness are not statistically distinguishable (e.g., at 50 pts above one's mean state loneliness score, 95% CI at +1 SD social interaction satisfaction: 31.20 to 39.13; -1 SD social interaction satisfaction: 36.96 to 44.86).

No evidence was found for a moderating effect of self-disclosure (Figure 9a; H2c; *b* = -0.0005, SE = 0.0006, 95% CI = -0.002 to 0.0006) or other-disclosure (Figure 9b; H2d; *b* = -0.01, SE = 0.0001, 95% CI = -0.002 to 0.001) on the association between loneliness (*t*-1) and depressed mood. Participants who scored 50 points above their mean state loneliness had nearly identical depressed mood, on average, regardless of their level of self-disclosure (+1 SD: 37.69. -1 SD: 38.56) or other-disclosure (+1 SD: 37.38. -1 SD: 38.84).

Evidence that social interaction quantity moderated the association between state loneliness (*t*-1) and depressed mood (H2e) was not observed in these data (*b* = -0.001, SE = 0.0005, 95% CI = -0.002 to 0.00007). Although the association between state loneliness (*t*-1) and depressed mood appears to be weaker when individuals engage in more social interaction (Figure 10), as we hypothesized, this effect is characterized by a great deal of error such that the predicted values at each level of social interaction quantity are not statistically distinguishable (e.g., at 50 points above one's mean state loneliness score, 95% CI at +1 SD social interaction quantity: 31.20 to 38.94; -1 SD social interaction quantity: 37.10 to 44.85).

No evidence was found for a moderating effect of state solitude on the association between loneliness (*t*-1) and depressed mood (H2f; b = 0.02, SE = 0.02, 95% CI = -0.03 to 0.07). As shown in Figure 11, as state loneliness (*t*-1) increases, the difference between those who were alone versus not alone during the assessment becomes larger. However, this difference is quite small, only apparent at very high levels of state loneliness (50 points above participants' mean), and is quantified with a relatively high level of error. Therefore, it is unlikely this effect exists in the population or is clinically meaningful.

We next evaluated our exploratory aims. As shown in Figure 12, no evidence was found that gender moderated either the contemporaneous (Figure 12a; *b* = 0.005, SE = 0.05, 95% CI = -0.10 to 0.11) nor lag-1 (Figure 12b; *b* = 0.03, SE = 0.04, 95% CI = -0.05 to 0.12) association between state loneliness and depressed mood.

A small effect of state loneliness at *t*-2 was found (Figure 13; *b* = 0.07, SE = 0.03, 95% CI = 0.01 to 0.13) controlling for its lag-1 and contemporaneous effects such that, as a participant moves the entire range of the loneliness scale (0-100), depressed mood is expected to change 7 points on average due to only this effect. Notably, the 95% credible interval was large, and spans effects we consider to be negligible to effects we deemed, *a priori*, small but meaningful ($\geq$ 0.10). No evidence of an effect was found for state loneliness at *t*-3 (*b* = 0.03, SE = 0.03, 95% CI = -0.03 to 0.09) nor *t*-4 (*b* = -0.01, SE = 0.03, 95% CI = -0.07 to 0.04).

To test whether loneliness inertia (i.e., the degree to which individuals become "stuck" in feelings of loneliness) is related to depressed mood, we estimated the effect of individuals' lag-1 loneliness autocorrelation on depression. Although there was a negative effect observed in the data such that, individuals who more often became stuck in feelings of loneliness were less depressed on average, this effect was characterized by a great deal of error (see Figure 14; *b* = -

0.14, SE = 9.31, 95% CI = -31.71 to 4.72). It is thus not possible to conclude from these data that loneliness autocorrelation is related to depressed mood.

The mean squared successive difference, the average change in loneliness between each assessment, was also not associated with depressed mood (*b* = -0.01, SE = 0.01, 95% CI = -0.03 to 0.01).

Discussion

Loneliness is becoming increasingly recognized as a problem of clinical and public health significance (Badcock et al., 2023). Although this increase is concerning on its own, given the importance of social relationships and relational well-being to the human experience (Baumeister & Leary, 1995; Bugental, 2000), loneliness is also associated with a host of mental and physical health problems (Courtin & Knapp, 2017; Luanaigh & Lawlor, 2008; Ong et al., 2016; Park et al., 2020), including depression. Despite decades observational research showing that loneliness is a risk factor for increased depression symptom severity and caseness (Erzen & Çikrikci, 2018), however, how loneliness may increase risk for depression is poorly understood. Using ecological momentary assessment with a sample of 102 depressed adults, this study investigated whether acute (i.e., state) feelings of loneliness were associated with changes in depressed mood throughout the course of the day, whether loneliness variation and temporal autocorrelation predicted additional variation in depressed mood, and whether one's interactions with others following bouts of loneliness moderated this association.

This study is the first to our knowledge to demonstrate that feelings of loneliness throughout the day were associated with changes in depressed mood not only at the same time point (i.e., contemporaneously), but also 3 and 6 hours later. These findings are important from a

practical perspective, as momentary (i.e., transient; micro-level) changes in depression symptoms are implicated in the pathogenesis of clinical depression (Nelson et al., 2017; Wichers, 2014), and identifying ecologically valid (i.e., "real world") predictors of depressed mood may help ease the growing economic (Greenberg et al., 2015) and global disease (World Health Organization, 2008) burden of depression (Ormel et al., 2022).

These findings are also the first to demonstrate independent within- and between-person effects of loneliness on depressed mood within an experience sampling paradigm. Not only were lonelier participants more likely to experience depressed mood than their less lonely counterparts, but when an individual felt lonelier than they usually do, regardless of their average level of loneliness, they were more likely to experience depressed mood concurrently and later in the day. Although differentiating between these sources of variation is not sufficient for establishing causality (Rohrer & Murayama, 2023), it lends credence to this possibility and suggests that the experience of momentary loneliness may produce sequela that contribute to increased experiences of depressed mood. These findings also suggest that interventions targeting loneliness at both levels of analysis may help reduce risk of depression. For example, population-based interventions aimed at improving opportunities for social connection and reducing chronic feelings of loneliness (Hsueh et al., 2022) as well as interventions aimed at improving an individual's ability to cope with feelings of loneliness when they do occur (Bessaha et al., 2020; Cohen-Mansfield & Perach, 2015; Hickin et al., 2021) may both work to decrease risk for subsequent depressed mood.

The intensive repeated measures design used in this study allowed us to characterize participant-level variation around the average (i.e., fixed) effects of loneliness at *t* (i.e., contemporaneous) and *t*-1 (i.e., lag-1) on depressed mood (i.e., random slopes) as well as around

their conditional-average variation of depressed mood (i.e., random intercept of the scale submodel). Not surprisingly, our data showed substantial variation around the average effects, with stronger effects for some individuals and weaker effects for others. In other words, there are some individuals for whom loneliness is more strongly associated with subsequent depressed mood, and other individuals for whom loneliness exerts lesser of a toll. It is important to identify the distinguishing characteristics of individuals who exhibit a strong association, as this information can help focus public health interventions on those with the greatest need and perhaps save costs compared to a population-wide approach to intervention. Future research should focus on identifying participant-level characteristics (i.e., between-person variables) that may help distinguish between these individuals.

We also found that individuals for whom the effect of loneliness (*t*) on depressed mood was stronger varied more around their conditional-average depressed mood (i.e., a correlation between random slopes in the location submodel and random intercepts in the scale submodel). This is not surprising, as greater changes in depressed mood are expected with smaller fluctuations in loneliness for these individuals. Nevertheless, this finding suggests that efforts to weaken the association between loneliness and depressed mood may, if a causal association exists, work to decrease instability as well as mean levels of depressed mood.

On the one hand, these results were hypothesized and thus expected; findings from longitudinal observational research establishing increased risk for depression following experiences of loneliness abound (Kuczynski, in prep). On the other hand, loneliness theory suggests that loneliness evolved as an aversive stimulus to warn about threats to our relational well-being and motivate us to repair or replace dysfunctional relationships (J. T. Cacioppo et al., 2006; J. T. Cacioppo & Cacioppo, 2018). If it is true that loneliness promotes social

(re)affiliative behavior, which is itself protective against depression (Santini et al., 2015), then we would not expect loneliness to predict increased depression over time, but instead to be harmless, at minimum, and perhaps even protect against depression (via its effect on social reaffiliation) at best (akin to the distinction between transient experiences of hunger and its more chronic and pernicious form, starvation).

Cacioppo and Cacioppo (2018) attempt to reconcile this discrepancy by suggesting that loneliness causes two seemly paradoxical or contradictory cognitive-behavioral responses; in addition to motivating social affiliation, they suggest that feelings of loneliness also promote neurobiological changes that increase vigilance toward social threat and ultimately protect the individual from re-experiencing the social events that prompted loneliness in the first place (e.g., social exclusion). It is thus possible that loneliness is associated with negative outcomes such as depressed mood when followed by hypervigilance to threat and social withdrawal and not when it promotes behavior associated with increased social connection.

Indeed, research suggests that transient forms of loneliness are associated with an acute stress response that may be indicative of the social threat hypothesis (Adam et al., 2006; Doane & Adam, 2010). It is thus possible that loneliness prompts immediate increases in social withdrawal, reappraisal of one's relationships, and increased attention to social threat, followed later by what Qualter and colleagues (2015) call the reaffiliation motive – the desire to reach out and connect with others. Although this idea would help explain the findings in this study, existing research has found an association between loneliness and depressed mood across various time intervals, including days (Hawkley et al., 2010) weeks (Lim et al., 2016), months (Lapierre et al., 2019; Nielsen Forman et al., 2000), and years (Beutel et al., 2018; Conde-Sala et al., 2019). To gain a more comprehensive understanding of the association between loneliness and

depression, future research should focus on systematically examining the temporal structure of this association.

Although the current study was not a direct test of the reaffiliation motive, findings from this study do not support our hypothesis that the reaffiliation motive may protect against negative mental health consequences of loneliness. Using Reis and Shaver's (1988) interpersonal process model as a guiding framework, we hypothesized that, following experiences of loneliness, individuals who engage in more frequent social interaction, or interactions characterized by greater self-disclosure, other-disclosure, and perceived responsiveness (the perception of understanding, validation, and care from one's interaction partner), would protect against depressed mood. This hypothesis was not supported by the data. Although the effect of loneliness on depressed mood was smaller, on average, for individuals who engaged in more social interaction, who reported greater satisfaction with their social interactions, and who perceived greater responsiveness from their interaction partners, these effects were small and characterized by a relatively large amount of error. These findings are in contrast to other experience sampling research which has found a positive association between social interaction quantity and affect (Liu et al., 2019), however notably these effects were small.

These findings were surprising and in contrast to existing research on the protective effects of social interactions on depressed mood. For example, a recent study by Kuczynski and colleagues (2022) found that social interaction quantity and state perceived responsiveness were associated with lower depressed mood at the daily level, regardless of one's average level of sociability and perception that others understand, validate, and care for them. Although we hypothesized a moderating role of social interactions in this study, and not a main effect as described by Kuczynski and colleagues (2022), other lines of research suggest that social factors

(e.g., social support) do indeed buffer risk of depression across the lifespan (Gariépy et al., 2016).

It may be the case the loneliness does not prompt actual engagement in social interaction, but instead prompts desire in the absence of actual behavior. For example, Kuczynski and colleagues (2022) found a daily association between feelings of loneliness and the desire to connect with others that same day, without evidence of changes in actual engagement in social interaction. These same findings were observed by Tran et al. (2023) in a 7-day experience sampling study. Notably, the effects found in these studies were quite small. It is thus possible that, while loneliness may increase one's motivation to affiliate with others, this motivation is weak and perhaps even attenuated by other consequences of loneliness such as increased perception of social threat. Future research would benefit from examining this possibility, as it could provide a potentially fruitful intervention target for cognitive behavioral therapies.

It is also possible that transient feelings of loneliness exert differential effects on depression as a function of whether the individual experiences chronic feelings of loneliness. Although the evolutionary theory of loneliness highlights two competing motivations (that of withdrawal/reappraisal and social reaffiliation), the temporal structure of these sequela was not well-delineated in Cacioppo and colleagues' (2006; 2018) original theoretical account. Empirical research on this topic suggests that increased attention to social threat may be more likely for individuals who experience chronic forms of loneliness (Vanhalst et al., 2018). Thus, momentary, within-person changes in loneliness may have distinct effects on chronically lonely individuals as opposed to those who are not chronically lonely. We did not find support for this hypothesis in the current study; the effect of loneliness on depressed mood was similar for those higher versus lower in trait loneliness.

Methodological factors may explain the discrepant findings between the current study and existing research on the moderating role of chronic loneliness. Most existing longitudinal research has sampled individuals across much larger time spans than the current study, and thus define chronicity of loneliness differently than we were able in this study (elevated loneliness across our 14-day study period versus 1+ years). It may be the case that maladaptive social cognitions (e.g., hypervigilance to social threat) take months or even years to develop, which we might not have captured given our research design. Another possibility is that our sample, recruited because they experienced elevated depression symptoms in the last 2+ weeks, were more likely to be chronically lonely, and that we did not have enough between-person variation in loneliness to test this hypothesis. Indeed, cross-sectional research suggests that depressed individuals are more likely to experience chronic forms of loneliness (Erzen & Çikrikci, 2018). Had we sampled individuals across the entire range of (average) loneliness, it is possible that we may have found a moderating role of chronic loneliness on the experience of momentary loneliness and its association with depressed mood. Future research should investigate this possibility.

We also did not find evidence of an effect of more complex temporal dynamics in the current study. Neither the degree to which loneliness changed, on average, for participants from assessment to assessment (i.e., the mean squared successive difference) nor the degree to which loneliness carried over from one assessment to the next (i.e., autocorrelation) were associated with depressed mood. We also did not observe an association between loneliness and the degree to which individuals varied around their on mean depression score (i.e., main effects of loneliness in the scale submodel). These findings are in contrast with other existing research which suggests that such dynamics may be critical to the pathogenesis of depression. For

example, greater autocorrelation and temporal variation have been observed in depressed individuals (Koval et al., 2012; Kuppens et al., 2010; Thompson et al., 2012), healthy individuals prior to onset of a depressive episode (van de Leemput et al., 2014), and are associated with depression symptom severity in healthy samples (Brose et al., 2015; Koval et al., 2016). It is possible that the null results obtained in the current study are specific to the assessment of loneliness rather than negative affect more generally. Indeed, while solitude inertia (the degree to which an individual becomes stuck in social isolation) is associated with increased risk for depression (Elmer et al., 2020), this study is the first to our knowledge to look specifically at the effect of loneliness inertia. Research in other domains (e.g., substance use; Dora et al., 2023) has observed similarly differential effects of negative affectivity as a function of which specific emotion item was assessed.

Another possible explanation for these findings is that previous research has yielded false positive results with respect to the effect of emotion dynamics on depressed mood. Indeed, in their meta-analysis of 15 experience sampling studies on this exact topic, Dejonckheere and colleagues (2019) found little evidence for an effect of affect dynamics above the effect of mean levels of positive and negative affect.

Collectively, the pattern of results observed in this study suggest that the association between loneliness and depression may be a function of changes in one's cognition rather than overt behavior. Indeed, recent research suggests that loneliness is more strongly associated with one's perceptions of their relationships than actual relationship dynamics (Mund et al., 2022). It is possible, as Cacioppo and colleagues (2006; 2018) propose, that loneliness causes changes in one's social cognition such as increase hostility toward ambiguously motivated social exclusion (Qualter et al., 2013), decreased social self-efficacy (Tsai et al., 2017; Wei et al., 2005), and

increased visual attention to socially threatening stimuli (Bangee et al., 2014), and that these styles of thinking about oneself and others are depressogenic. Indeed, decades of research suggests that the attributions one makes about their (social) circumstances are related to symptoms of depression (Weightman et al., 2014), and cognitive behavioral therapy for depression is based on this very idea (Beck, 1991). Although existing research provides support for the hypothesis that loneliness causes changes in one's social cognition, it appears equally plausible that changes in social cognition (e.g., the belief that one is alone or not loved by others) are responsible for feelings of loneliness. If true, this suggests that the association between momentary feelings of loneliness and depressed mood observed in the current study is confounded by depressogenic and loneliness-inducing social cognition (i.e., changes in one's social cognitions cause both loneliness and depressed mood). Future research can disentangle these effects by measuring (in observational designs) and/or manipulating (in experimental paradigms) negative social cognitions and observing any changes in loneliness and depression that might occur.

Strengths, Limitations, and Future Directions

There are many strengths of the current study that promote confidence in our findings and contribute to the methodological and substantive work in this area of research. Importantly, we recruited a racially and ethnically diverse sample of participants from across the United States. While there is no research suggesting differences in the effects of loneliness by race, most research in this area, and psychological science more broadly (Arnett, 2008; Thalmayer et al., 2021), has recruited samples that do not represent the racial demographics of the populations from which they sample and wish to generalize to. In developing a more thorough understanding

of the effects of loneliness on mental health, it is critical not to assume, as Roberts and Mortenson (2022) and Cheon and colleagues (2020) argue, that data from predominantly White samples are broadly reflective of the human experience and thus generalizable to non-White individuals. Nevertheless, the demographic characteristics of our sample remain unique in many ways, and it is important to exercise caution when generalizing to other populations (e.g., individuals from non-western or low/middle-income countries).

Another strength of this study was our inclusion of individuals with elevated depression symptoms (≥ 10 on the PHQ-9). Although we did not necessarily recruit a clinical/diagnostic sample, scores of 10+ on the PHQ-9 have been shown to maximize sensitivity and specificity to detect major depression with respect to structured clinical interviews (Levis et al., 2019; Moriarty et al., 2015). Indeed 47% of our sample indicated that they are currently receiving some form of mental health treatment, and 35% self-reported a diagnosis of major depressive disorder and/or persistent depressive disorder from a mental health professional. This is an important population to study, as elevated depression symptoms have been shown to impact functioning across a variety of domains (Gotlib et al., 1995; Lerner & Henke, 2008) and thus identifying momentary risk factors for depressive symptomatology in this group may help alleviate the burden of depression. On the other hand, restricting our sample to individuals who presented with depressive symptomatology at the time of study enrollment limits our ability to answer questions related to whether this association differs as a function of depressive symptom severity across the spectrum and whether loneliness is implicated in the etiology of major depression. It is also possible that social interaction confers different effects for depressed versus non-depressed individuals. For example, depressed individuals are characterized by reward processing abnormalities (Ng et al., 2019) that may extend to the social domain (Nezlek et al., 1994). Future

research would benefit by including individuals across the range of depression symptom severity to identify whether this association and our hypothesized mediators differ as a function of depression symptom severity.

The anchor-test planned missingness design used in the current study allowed us to minimize participant burden and thus maximize retention (Rolstad et al., 2011) as we assessed a range of mental health and social phenomena within an intensive longitudinal design. Indeed, our survey completion rate (91.22%) was higher than the average across other experience sampling studies (Wrzus & Neubauer, 2023). Reducing participant burden arguably resulted in higher-quality responses that more accurately reflected the momentary experiences of our participants (e.g., Galesic & Bosnjak, 2009). Moreover, by increasing adherence to the study protocol and thus minimizing day-level missingness, this design allowed us to make the critical assumption that (most of) our data were missing completely at random and use state-of-the-art Bayesian multiple imputation techniques (Enders et al., 2020) to maximize power to detect our hypothesized effects.

Our anchor test planned missingness design also enabled us to include multi-item measures of loneliness, depressed mood, and social interaction characteristics. While single-item measures are not inherently invalid or unreliable (Allen et al., 2022), they pose several risks to both internal and external validity. Indeed, studies have shown that multi-item measures tend to outperform single-item measures of the same construct (Diamantopoulos et al., 2012). For example, research indicates that gender differences are more likely to be observed when face-valid, single-item measures of loneliness (e.g., “I feel lonely”) are used (Barreto et al., 2022). By including this item among several others in our assessment of loneliness, we are more confident that our results generalize across genders and capture participants’ actual momentary

experiences. Using multi-item measures also allowed us to characterize the degree of within- and between-person reliability observed in the current study, which would not be possible had we used single-item measures only. Despite these strengths, more work is needed to evaluate the psychometric characteristics (e.g., validity and reliability at the within- and between-subjects levels of analysis, invariance across time and population) of these measures, and caution should be exercised until sound psychometric qualities have been established.

Our measurement strategy differed in other ways compared to existing research on the association between loneliness and depression. Whereas most research has required participants to indicate the *frequency* of feelings of loneliness (e.g., "I never feel this way" and "I often feel this way" as in the UCLA Loneliness Scale; D. W. Russell, 1996) across long periods of time, we asked participants to indicate the *intensity* across much shorter intervals. Although it is not clear how exactly this may have affected our results, some areas of research (e.g., substance use; Heckley et al., 2017) show a meaningful distinction in this regard. It is possible that one's perception of how frequently they are lonely, or their retrospective account of experiences of loneliness, are more closely related to our hypothesized effects than are momentary accounts of loneliness intensity. On the other hand, frequency and intensity of psychological phenomena are often correlated (Zimmerman & Kerr, 2019) and thus may not provide unique information. Future research should clarify whether this distinction is important with respect to the effects of loneliness on depression, as this would provide useful information to guide public mental health intervention.

The intensive longitudinal design used in the current study allowed us to circumvent issues related to retrospective recall of psychological phenomena (Conner & Barrett, 2012) and thus increases our confidence that these findings accurately reflect within-person momentary

processes. Nevertheless, it is possible that our operationalization of the momentary processes measured in this study did not sufficiently capture the phenomena in which we were interested. For example, to measure social interaction quantity, we instructed participants to include social interactions with individuals 7 years or older that lasted 5 minutes or longer. Although this is consistent with past research (Liu et al., 2019), this strategy may be misaligned with the reaffiliation motive hypothesis, as it may include interactions sought out by participants due either to obligation (e.g., consultation with colleagues at work) or desire (e.g., reaching out to a loved one). It may also be the case that individual social interactions are not the appropriate level of analysis in which to test these hypotheses. Although the evolutionary theory of loneliness is not specific in this regard, it is possible that the duration of one's interactions, who one interacts with, or the degree to which one seeks out new relationships is more closely tied to the experience of loneliness than the sheer number of interactions one has.

The timing of our assessments may also have impacted our findings. It is possible that the effects of loneliness on social interaction unfold over several days, weeks, or even months, which would not have been possible to measure with our 14-day intensive longitudinal design. On the other hand, it is also possible that we did not sample behavior frequently enough. Perhaps the association between loneliness and depressed mood is mediated by cognitive or behavioral processes that unfold across a matter of minutes or even seconds. For example, in the presence of opportunities for social interaction, it may be the case that immediate engagement following feelings of loneliness may protect against subsequent depressed mood just seconds or minutes later. Future research can employ various methodologies (e.g., measurement burst designs) to examine this possibility further.

It is also possible that the outcomes observed in this study were a function of shared method variance rather than a genuine effect (Podsakoff et al., 2012). All of our constructs of interest were measured via self-report, largely with a visual analog scale format. Our measure of loneliness, depressed mood, and social interaction characteristics (satisfaction, self- and other-disclosure, and perceived responsiveness) were additionally worded such that they referred to participants' feelings rather than overt behavior. It is thus possible that our estimate of the effects of loneliness on depressed mood are inflated by virtue of the fact that we measured a feeling-feeling association (rather than feeling-behavior, feeling-biological process) or due to the similar response formats. While loneliness and depressed mood are necessarily subjective experiences, emerging research indicates that passive sensor data collected from smartphones may provide a proxy for these feelings (Yim et al., 2020). Future research should employ multiple methods of measurement, including passive forms of data collection from smartphone sensors, to disentangle true effects from methodological artifacts.

Results from this study may also be unique to the Covid-19 pandemic context. In line with policy efforts aimed at limiting the spread of the SARS-CoV-2 virus, evidence suggests that individuals had fewer social interactions relative to their pre-pandemic levels (Buecker & Horstmann, 2021), with some individuals (e.g., those who live alone) exhibiting larger decreases than others (Rudert & Janke, 2023). The evolutionary theory of loneliness rests on the assumption that opportunities for social interaction abound and thus, with sufficient desire, actual engagement in social interaction would follow. This was not necessarily the case during the months in which data were collected for the current study (August 2021 through February 2022). Given the threat of contracting SARS-CoV-2, it is possible that individuals who felt lonely did not engage in the same forms of interaction they would have otherwise (e.g., technology-

mediated vs. in-person), or with the same individuals. Indeed, in-person forms of interaction have been shown to promote greater feelings of connectedness than technology-mediated forms (video chat, phone, etc.; Sherman et al., 2013), and one's choice of interaction partner also matters in this regard (van Roekel et al., 2015). Future studies should investigate the possibility that not all forms of social interaction are created equal with respect to buffering the association between momentary feelings of loneliness and depressed mood.

Lastly, the observational design used in the current study also prevents us from establishing causality. While it is possible that our findings reflect a casual process, these effects may be confounded by unmeasured between-person (e.g., personality traits such as neuroticism; Buecker et al., 2020; Kotov et al., 2010; c.f., Vanhalst, Klimstra, et al., 2012) or within-person (e.g., changes in social cognition; Bourke et al., 2010; Lim et al., 2016) variables. Future research may consider employing experimental or quasi-experimental designs (Marinescu et al., 2018) or perhaps conducting studies with monozygotic twins (McGue et al., 2010) to get closer to establishing causal associations than we were able to in this study.

Conclusion

In summary, results from the current study provide evidence that loneliness is associated with changes in depression throughout the course of the day, that individuals vary considerably in this effect, and that, on average, this effect persists regardless of one's average level of loneliness. While this finding suggests that treatments targeting within-person fluctuations in loneliness (e.g., cognitive-behavioral interventions) may exert downstream effects on depressed mood, the observational design used in the current study prevent us from drawing causal conclusions. Nevertheless, characterizing the dynamic association between loneliness and

depressed mood remains an important goal for public health, as evidence suggests that both loneliness (Buecker et al., 2021) and depression (Moreno-Agostino et al., 2021) are becoming increasingly prevalent over time. Our hypotheses, informed by the evolutionary theory of loneliness (J. T. Cacioppo et al., 2006; J. T. Cacioppo & Cacioppo, 2018) and the interpersonal process model of intimacy (Reis & Shaver, 1988), that social interaction quantity and quality would buffer the association between loneliness and depressed mood were not supported by the data. Methodological (e.g., frequency of repeated assessments) and substantive (e.g., behavioral vs. cognitive effects of loneliness) factors may explain the lack of findings in this regard, and future research should attempt to systematically investigate these possibilities.

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Table 1

Sample Sociodemographic Characteristics

Characteristic	n	%
Gender		
Cisgender Woman	83	82.18
Cisgender Man	14	13.86
Gender Variant/Non-conforming	4	3.96
Age		
18-24	32	32.37
25-34	37	36.27
35-44	17	16.667
45-54	11	10.78
54-64	5	4.90
Race		
Asian or Pacific Islander	20	19.61
Black or African American	19	18.63
Hispanic or Latino	20	19.61
White or European American	20	22.55
Not listed	23	19.61
Relationship Status		
Married	18	17.65
In a relationship	34	33.33
Single	40	39.22
Divorced/Annulled	5	4.90
Separated	2	1.96
Widowed	3	2.94
Sexual Identity		
Straight	72	70.59
Gay/Lesbian	6	5.88
Bisexual	17	16.67
Not listed	7	6.86
Employment Status*		
Full time (21+ hrs/week)	43	42.16
Part time (1-20 hrs/week)	30	29.41
Full-time student	28	27.45
Part-time student	7	6.86
Retired	1	0.98
Disabled/unable to work	1	0.98
Unemployed	13	12.75
Parent		
No	75	73.53
Yes	27	26.47
Living Arrangement		
Yes	77	75.49
No	25	24.51
Birth Country		
United States	84	82.35
Not United States	18	17.65

Mental Health Treatment		
Yes, current/past treatment	74	72.55
No, current/past treatment	28	27.45
Psychiatric Diagnoses		
Major Depressive Disorder	30	29.41
Persistent Depressive Disorder	6	5.88
Social Anxiety Disorder	10	9.80
Post-traumatic Stress Disorder	16	15.69
Generalized Anxiety Disorder	34	33.33
Comorbid diagnoses	34	33.33

*Participants were instructed to select as many employment statuses as apply to them.

Table 2

Scale Submodel Parameter Estimates from H1a and H1b Mixed Effects Location Scale Model

Parameter	b	SE	95% CI
$\hat{\sigma}_0$	2.38	0.04	2.30 to 2.47
$\hat{\sigma}_{study\ day}$	-0.01	0.003	-0.01 to -.0003
$\hat{\sigma}_{ping\ number}$	0.004	0.008	-0.01 to 0.02
$\hat{\sigma}_{weekend}$	-0.03	0.02	-0.07 to 0.02
$\hat{\sigma}_{state\ loneliness}$	0.01	0.001	0.004 to .009
$\hat{\sigma}_{trait\ loneliness}$	0.009	0.003	0.003 to 0.01
$\hat{\sigma}_{state \times trait\ loneliness}$	-0.0003	0.0001	-0.0005 to .0000009

Note. The scale submodel was modeled as log-linear to ensure positive parameter estimates. Values presented herein are on the log-linear scale.

Table 3

Effect of State Loneliness at t and t-1 on Depressed Mood

Parameter	*b*	SE	95% CI
Within-person effects			
State Loneliness (*t*)	0.52	0.03	0.47 to 0.60
State Loneliness (*t*-1)	0.12	0.02	0.09 to 0.15
Between-person effects			
Trait Loneliness	0.89	0.40	0.11 to 1.66
Cross-level Interactions			
Trait loneliness × State Loneliness (*t*)	0.0004	0.005	-0.009 to 0.01
Trait loneliness × State Loneliness (*t*-1)	0.001	0.004	-0.007 to 0.008
Variance components			
SD: b_0	15.99	1.05	14.07 to 18.21
SD: $b_{0\varepsilon}$	0.29	0.02	0.2 to 0.34
SD: State Loneliness (*t*)	0.20	0.02	0.16 to 0.24
SD: State Loneliness (*t*-1)	0.07	0.02	0.03 to 0.11
Cor: b_0, $b_{0\varepsilon}$	0.22	0.09	0.03 to 0.40
Cor: State Loneliness (*t*), b_0	0.18	0.10	-0.03 to 0.37
Cor: State Loneliness (*t*), $b_{0\varepsilon}$	0.66	0.09	0.47 to 0.81
Cor: State Loneliness (*t*-1), b_0	0.17	0.17	-0.17 to 0.50
Cor: State Loneliness (*t*-1), $b_{0\varepsilon}$	0.27	0.20	-0.13 to 0.66

Table 4

Effects of Social Interaction Quantity and Quality and Their Interaction with State Loneliness at t-1 on Depressed Mood

Parameter	b	SE	95% CI
Main effects			
Social Interaction Satisfaction	-0.09	0.01	-0.11 to -.07
Perceived Responsiveness	-0.11	0.02	-0.14 to -0.07
Self-disclosure	0.003	0.01	-0.02 to 0.02
Other-disclosure	-0.001	0.01	-0.02 to 0.02
Social Interaction Quantity	-0.09	0.01	-0.11 to -0.07
Solitude	1.20	0.41	0.43 to 2.04
Interactions			
Social Interaction Satisfaction	-0.001	0.0005	-0.002 to 0.00007
Perceived Responsiveness	-0.002	0.0008	-0.003 to 0.00002
Self-disclosure	-0.0005	0.0006	-0.002 to 0.0006
Other-disclosure	-0.001	0.0001	-0.002 to 0.001
Social Interaction Quantity	-0.001	0.0005	-0.002 to 0.00007
Solitude	0.02	0.02	-0.03 to 0.07

Figure 1

Distribution of Reminders and Survey Response Times

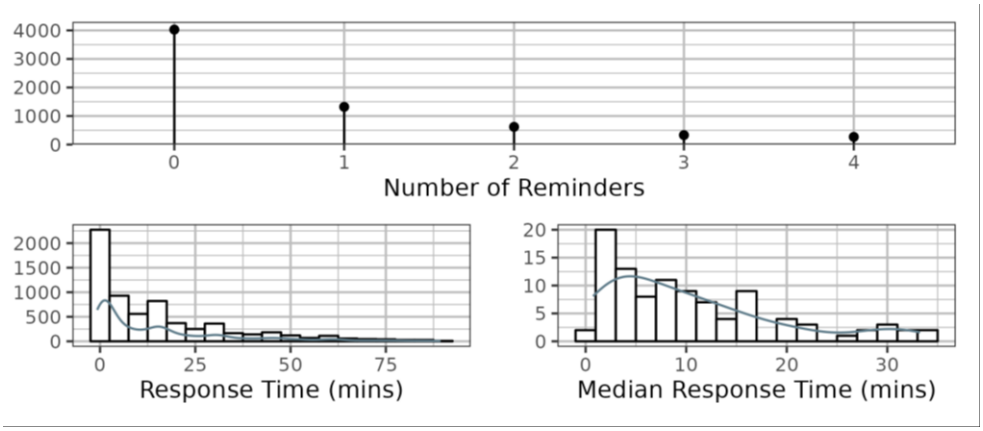


Figure 2

Depressed Mood Across Day and Ping Number and Corresponding Posterior Distributions

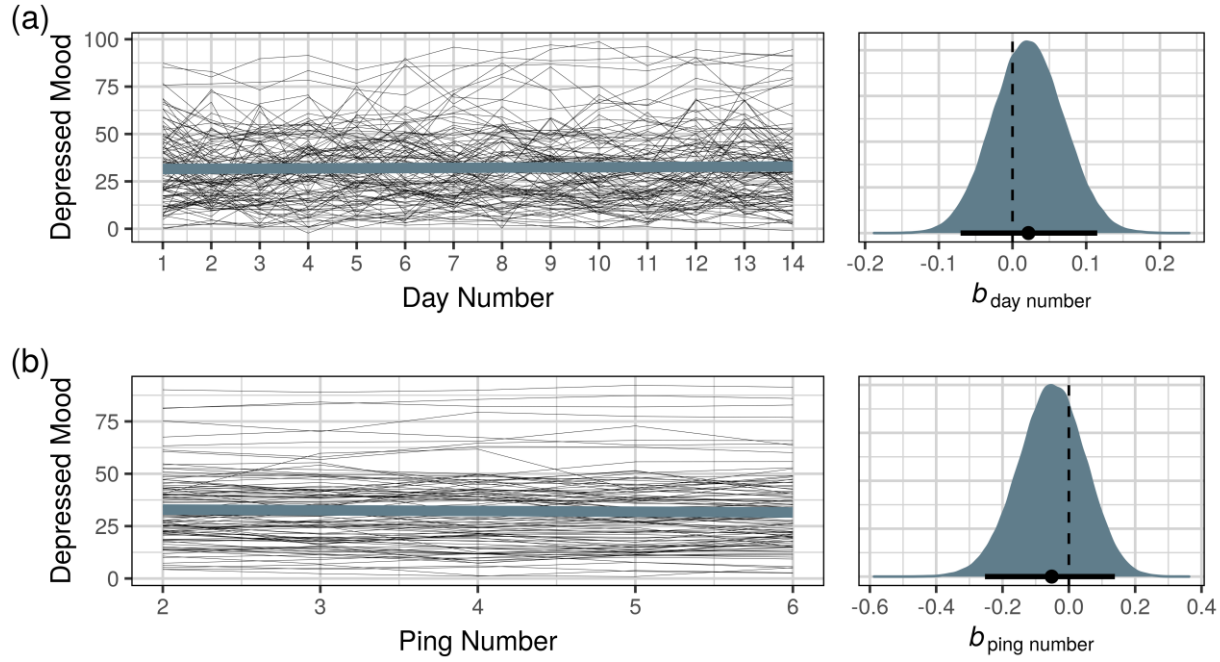


Figure 3

Example Low and High Variation in Depressed Mood Across the Study Period

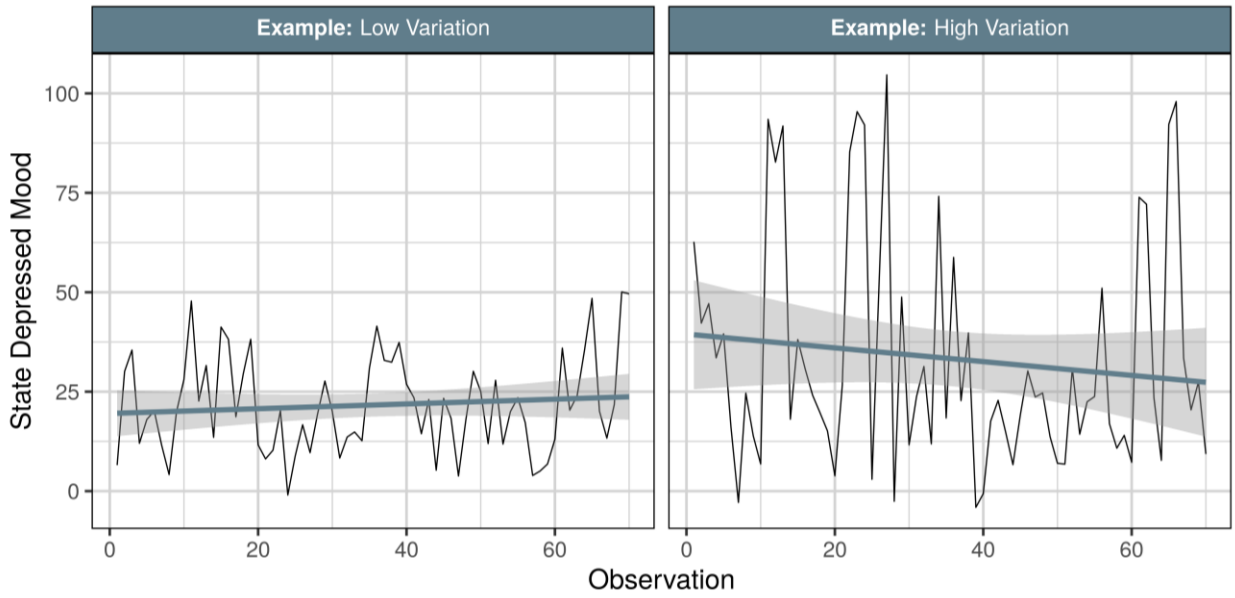
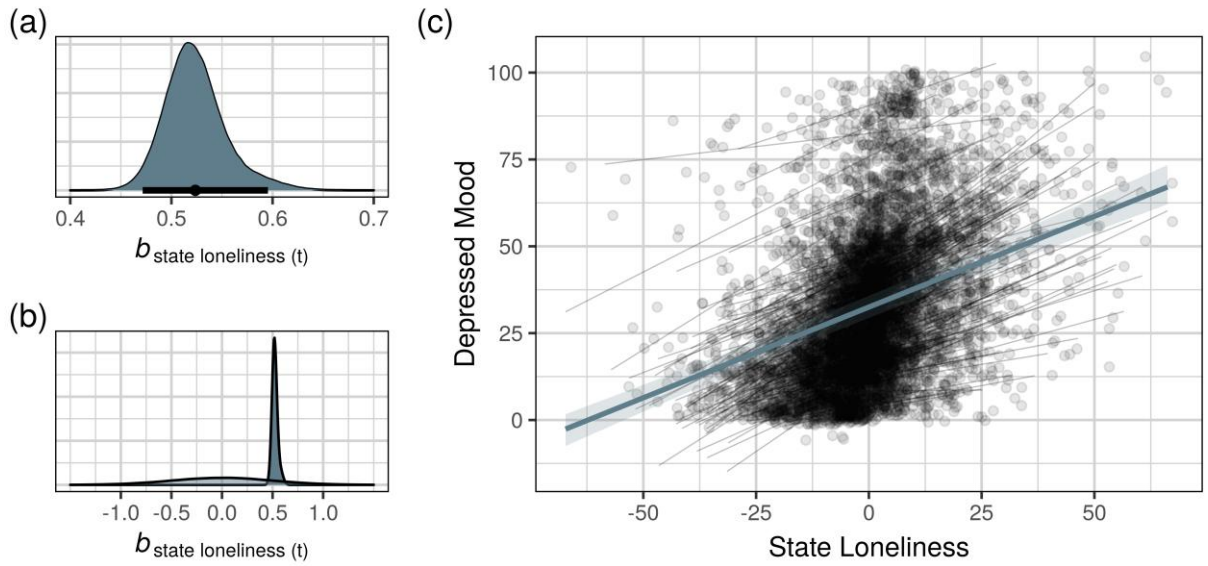


Figure 4
Association Between Loneliness and Depressed Mood



(A) Posterior distribution of the population-level association between state loneliness (*t*) and depressed mood (*t*); **(B)** Posterior distribution superimposed on the prior distribution for the association between state loneliness (*t*) and depressed mood (*t*); **(C)** Average (population-level) association between state loneliness (*t*) and depressed mood (*t*) with participant-level random slopes.

Figure 5

Association Between Loneliness$_{t-1}$ and Depressed Mood

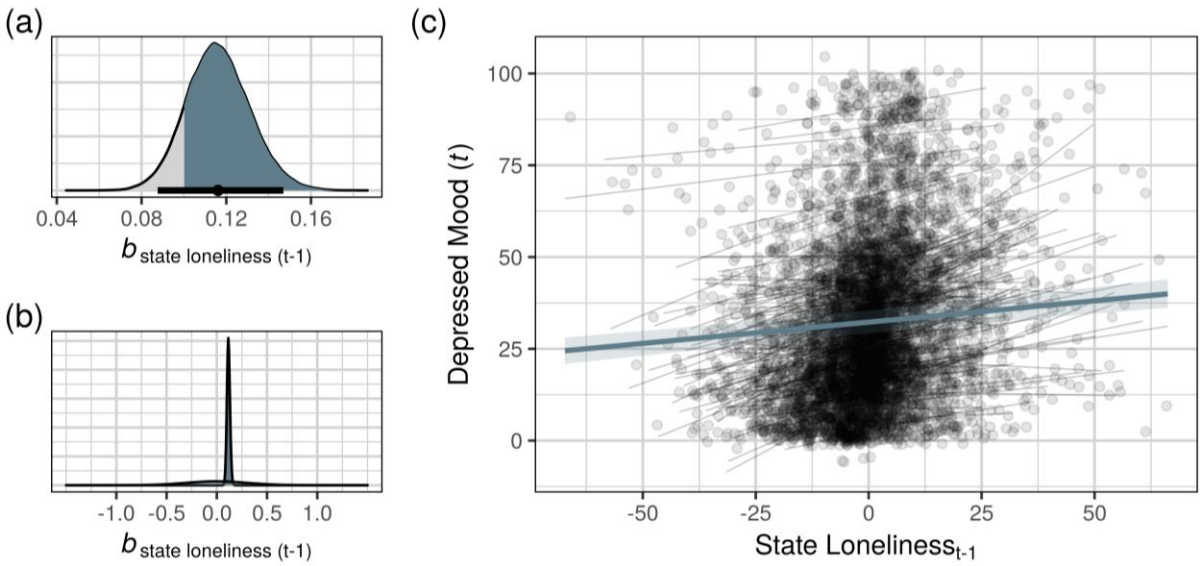


Figure 6

Marginal Effects of the Association Between Depressed Mood and Loneliness

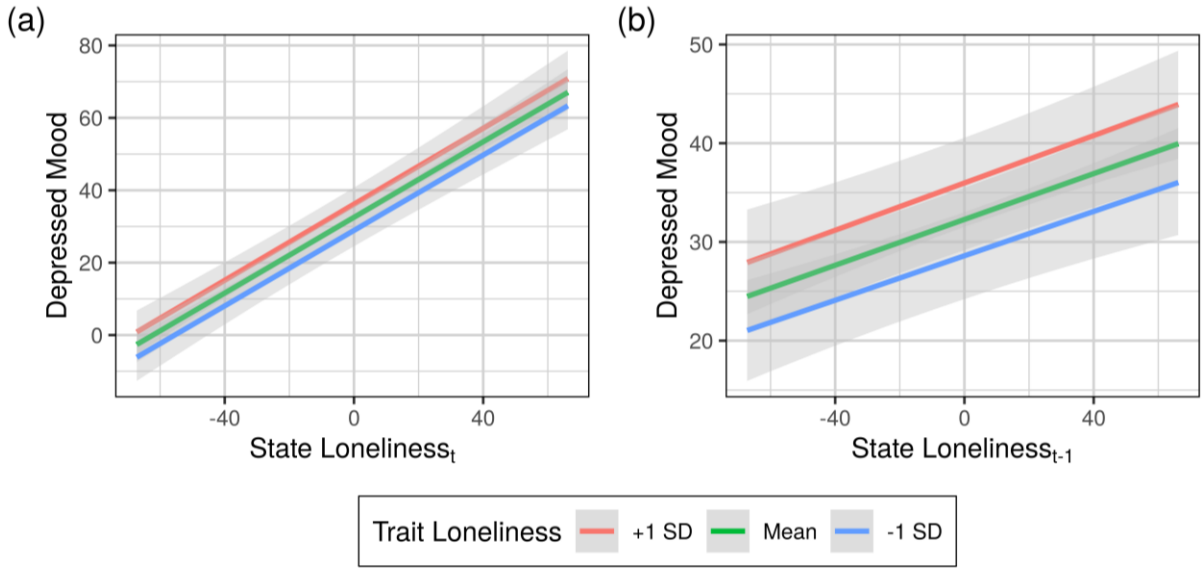


Figure 7

Association Between Depressed Mood and State Loneliness$_{t-1}$ by Social Interaction Satisfaction

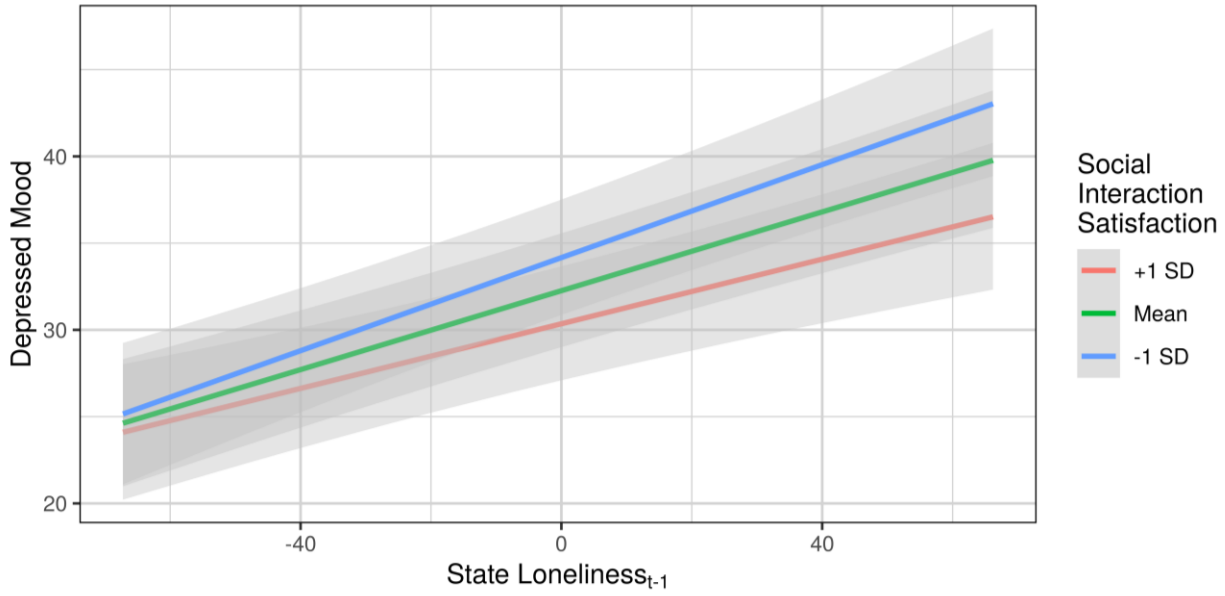


Figure 8

Association Between Depressed Mood and State Loneliness$_{t-1}$ by Perceived Responsiveness

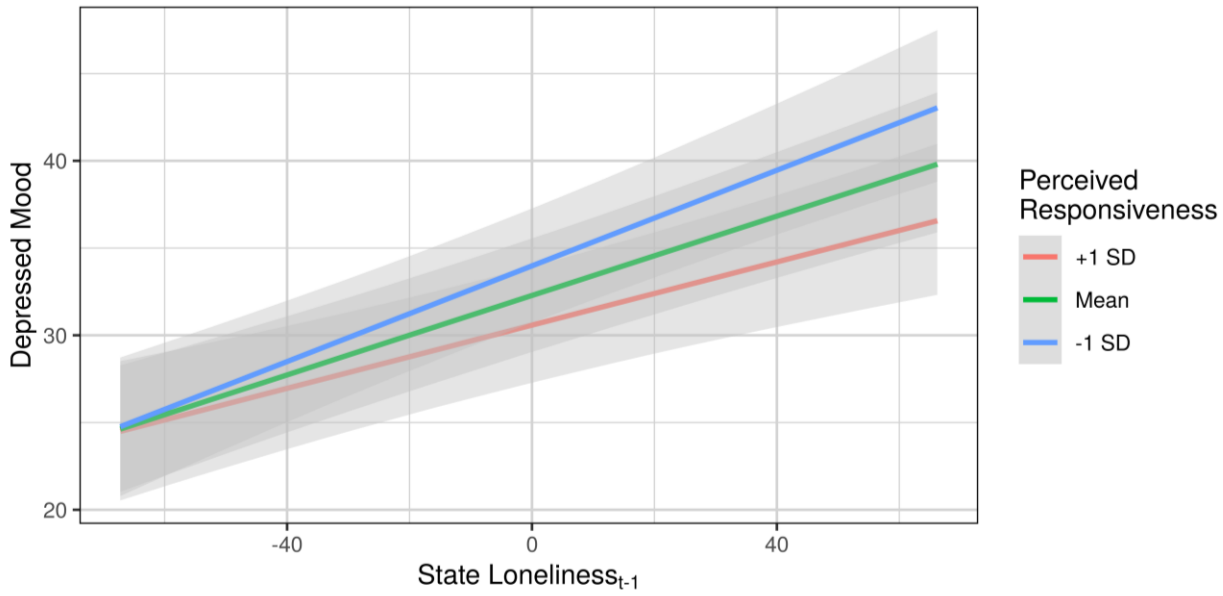


Figure 9

Association Between Depressed Mood and State Loneliness$_{t-1}$ by Self- and Other-disclosure

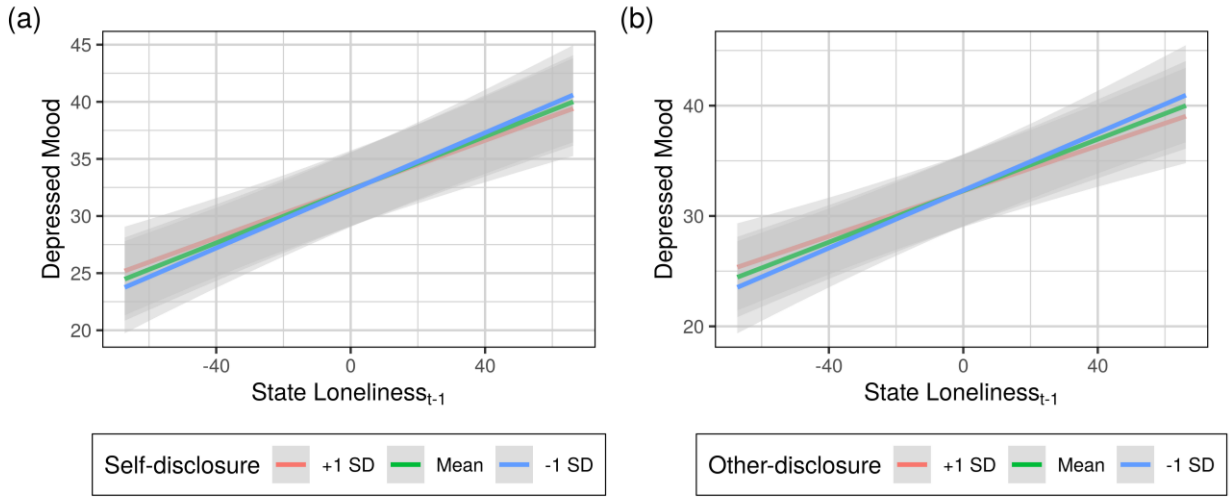


Figure 10

Association Between Depressed Mood and State Loneliness$_{t-1}$ by Social Interaction Quantity

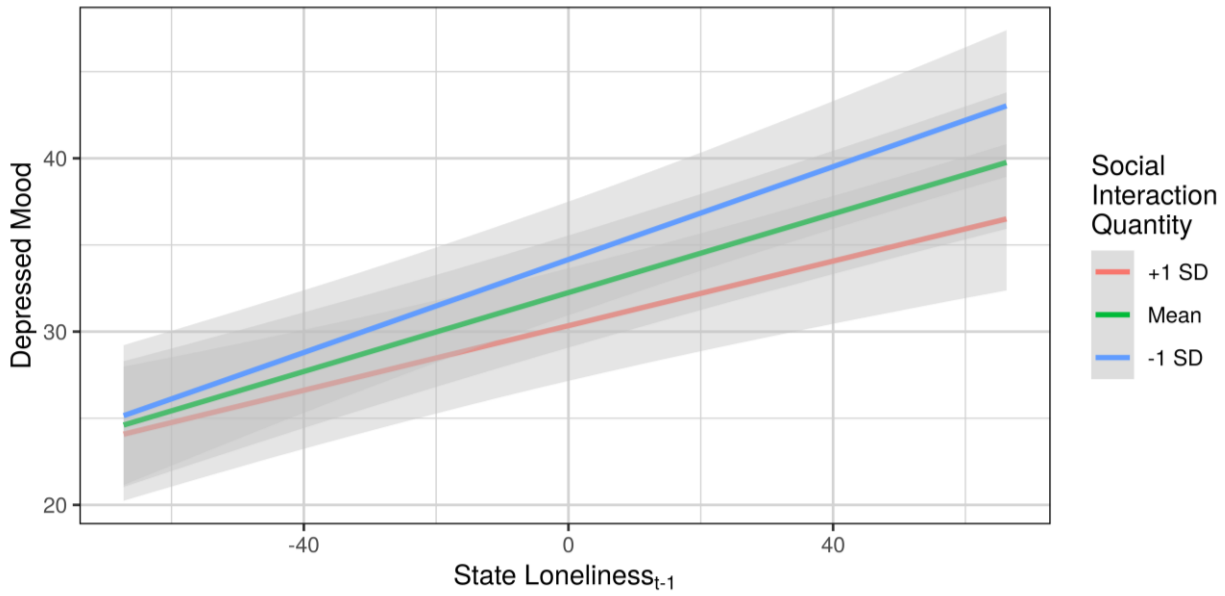


Figure 11

Association Between Depressed Mood and State Loneliness$_{t-1}$ by State Solitude

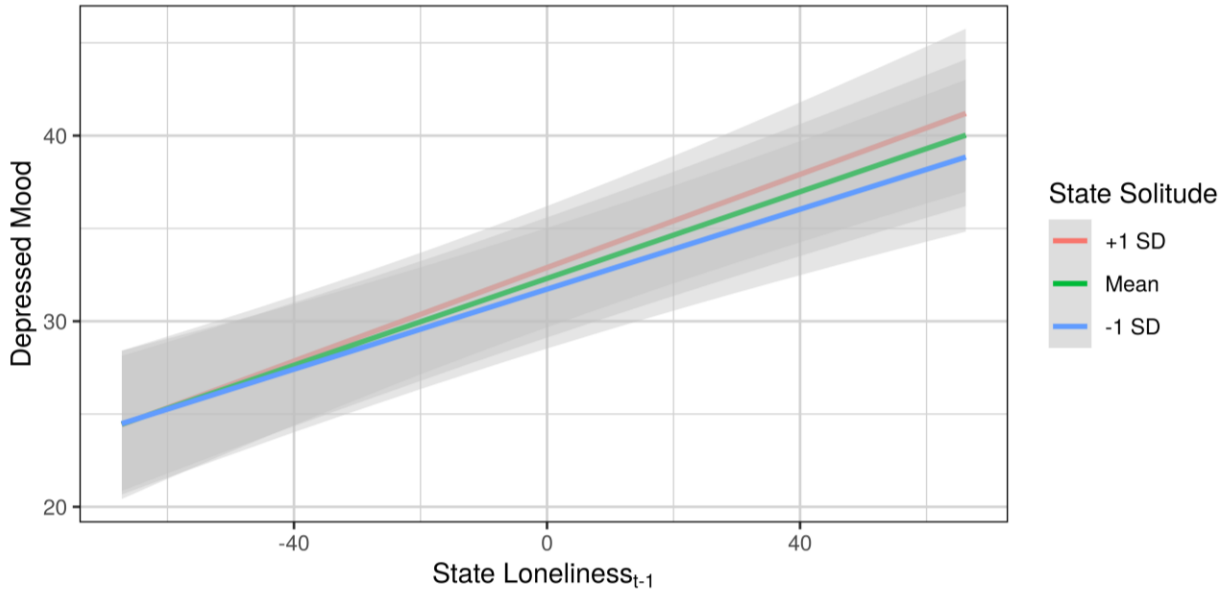


Figure 12

Association Between Depressed Mood and State Loneliness by Gender

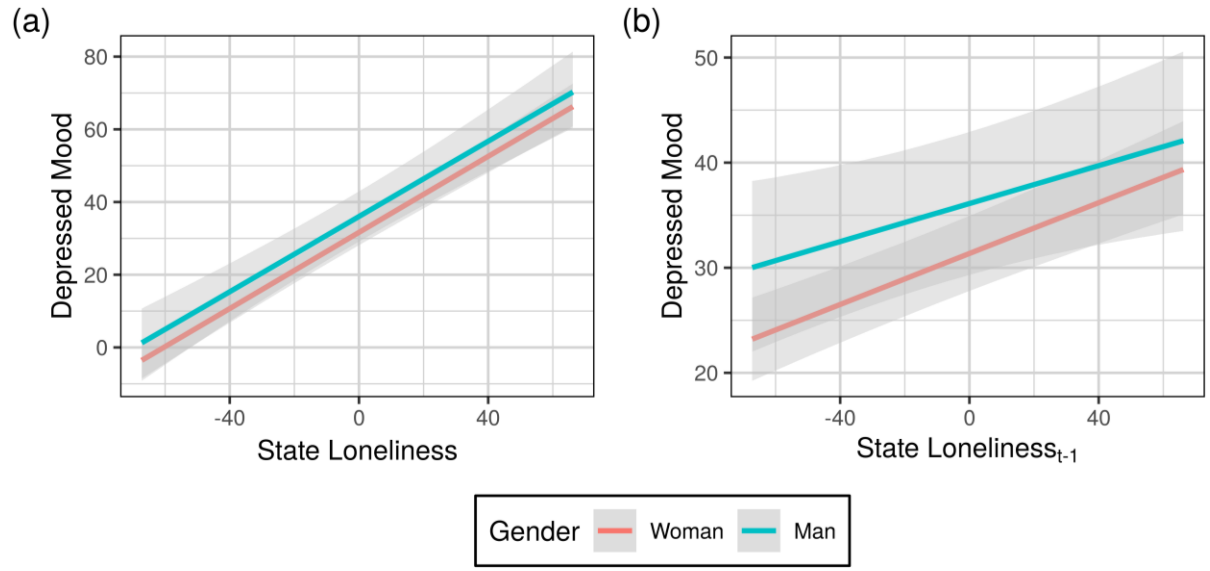


Figure 13

Association Between Depressed Mood and State Loneliness and Different Lags

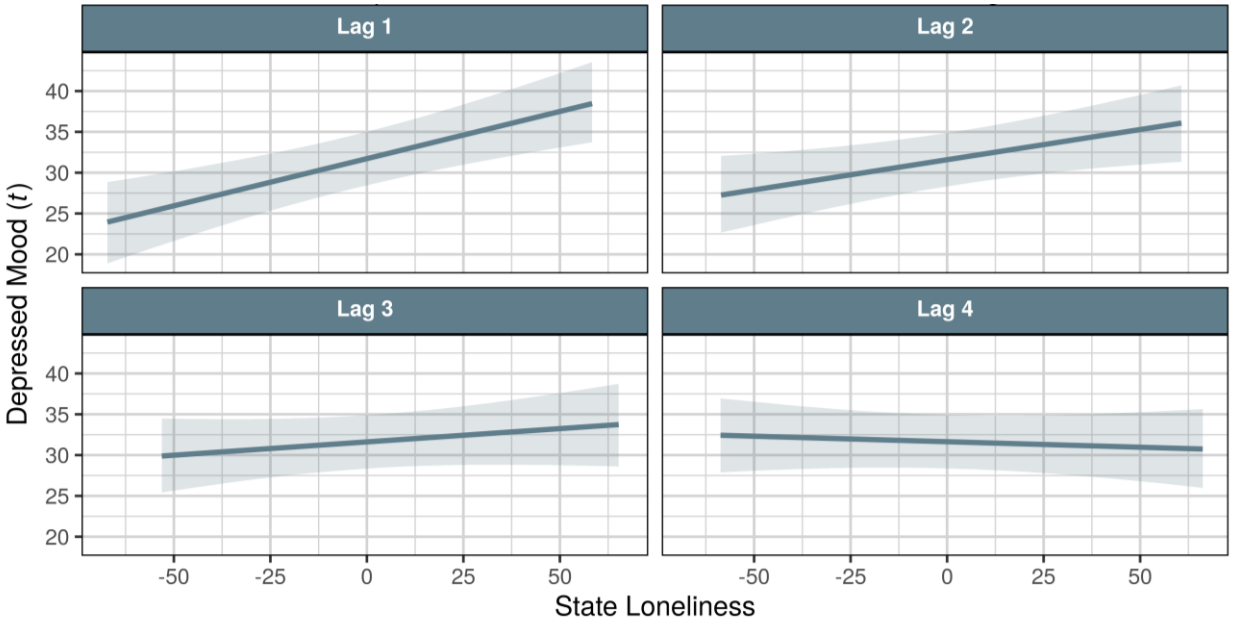


Figure 14

Posterior Distribution of the Association Between Depressed Mood and State Loneliness Autocorrelation

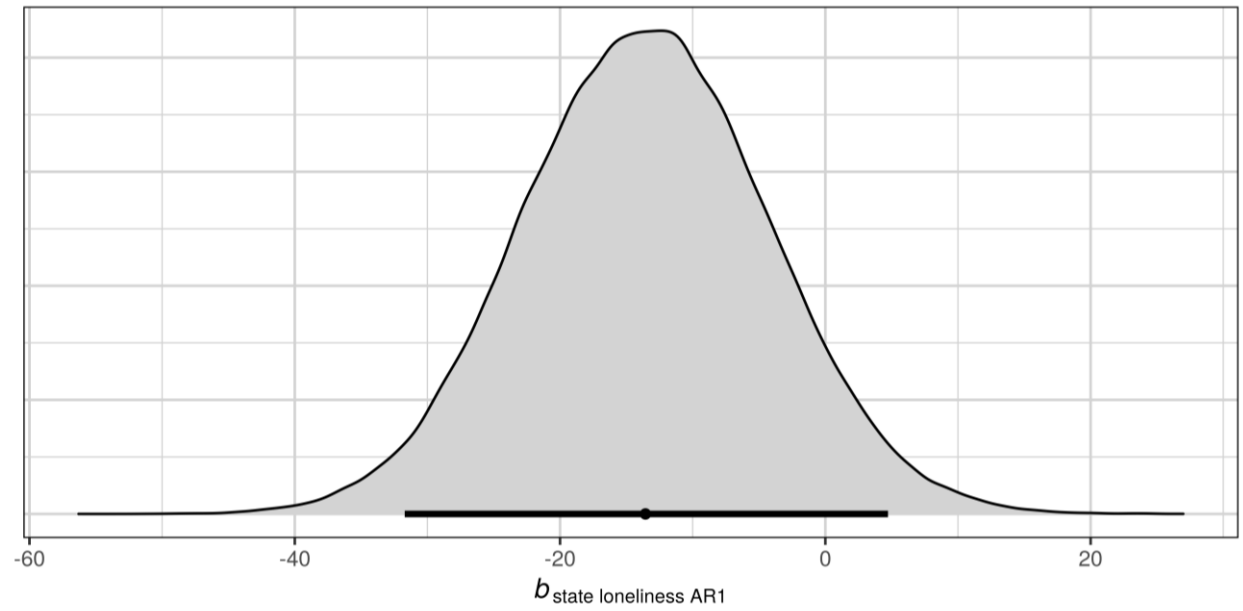
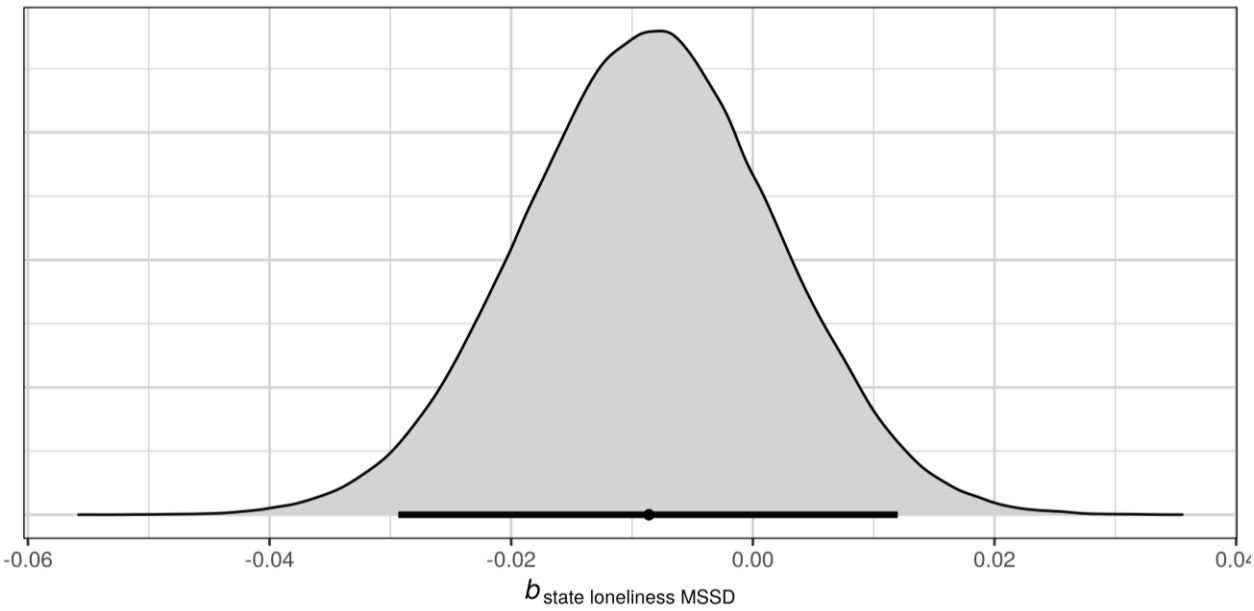


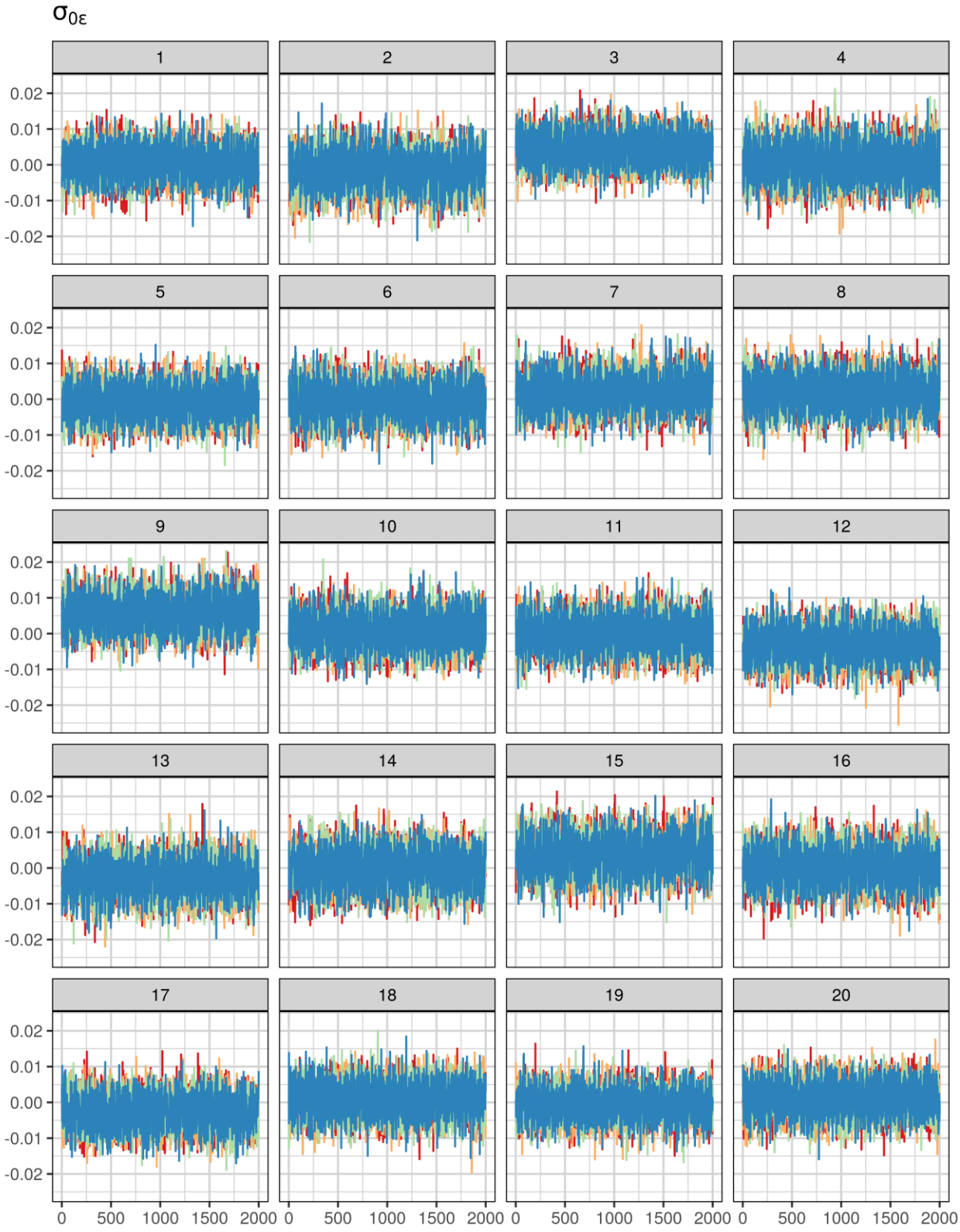
Figure 15

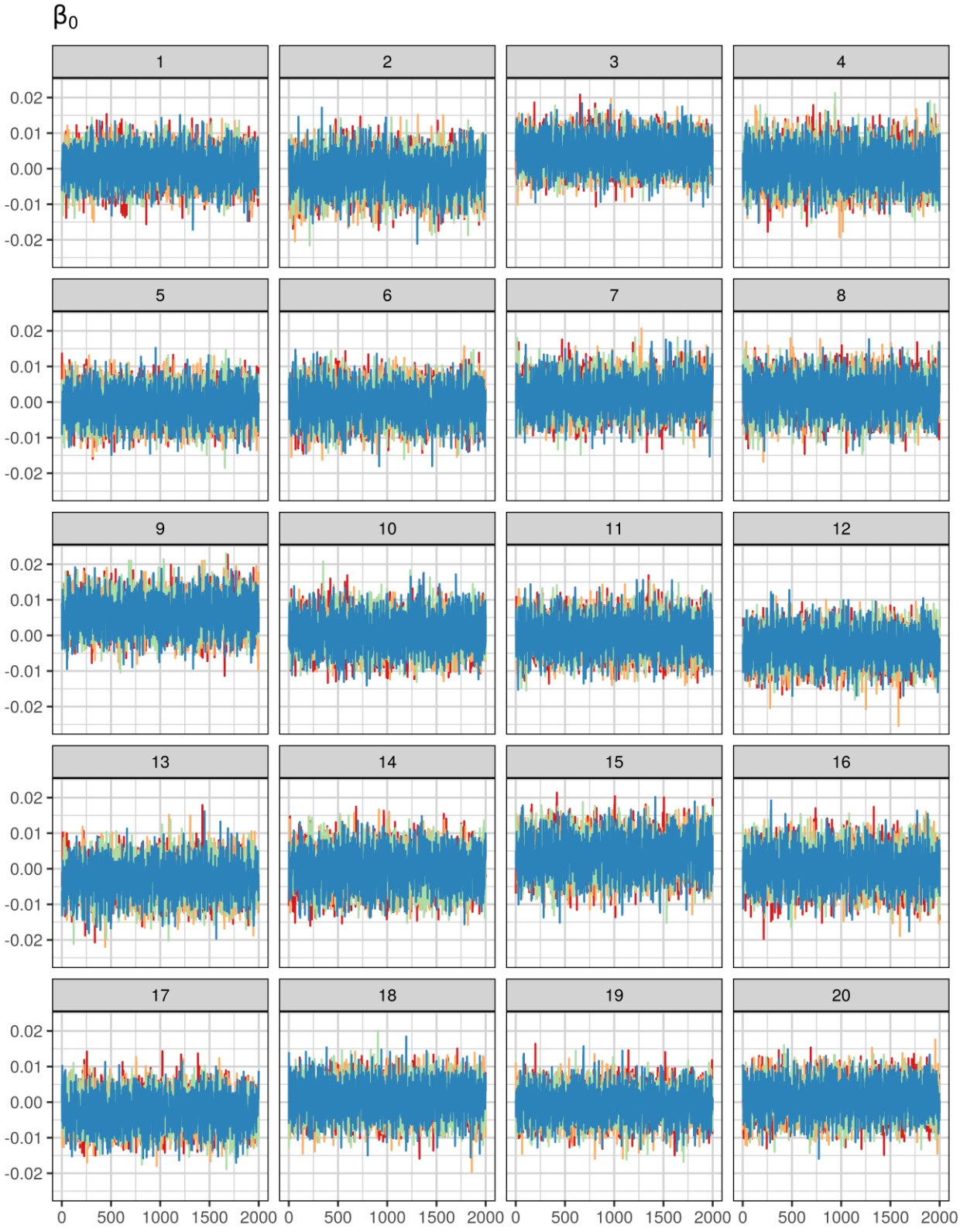
Posterior Distribution of the Association Between Depressed Mood and State Loneliness MSSD

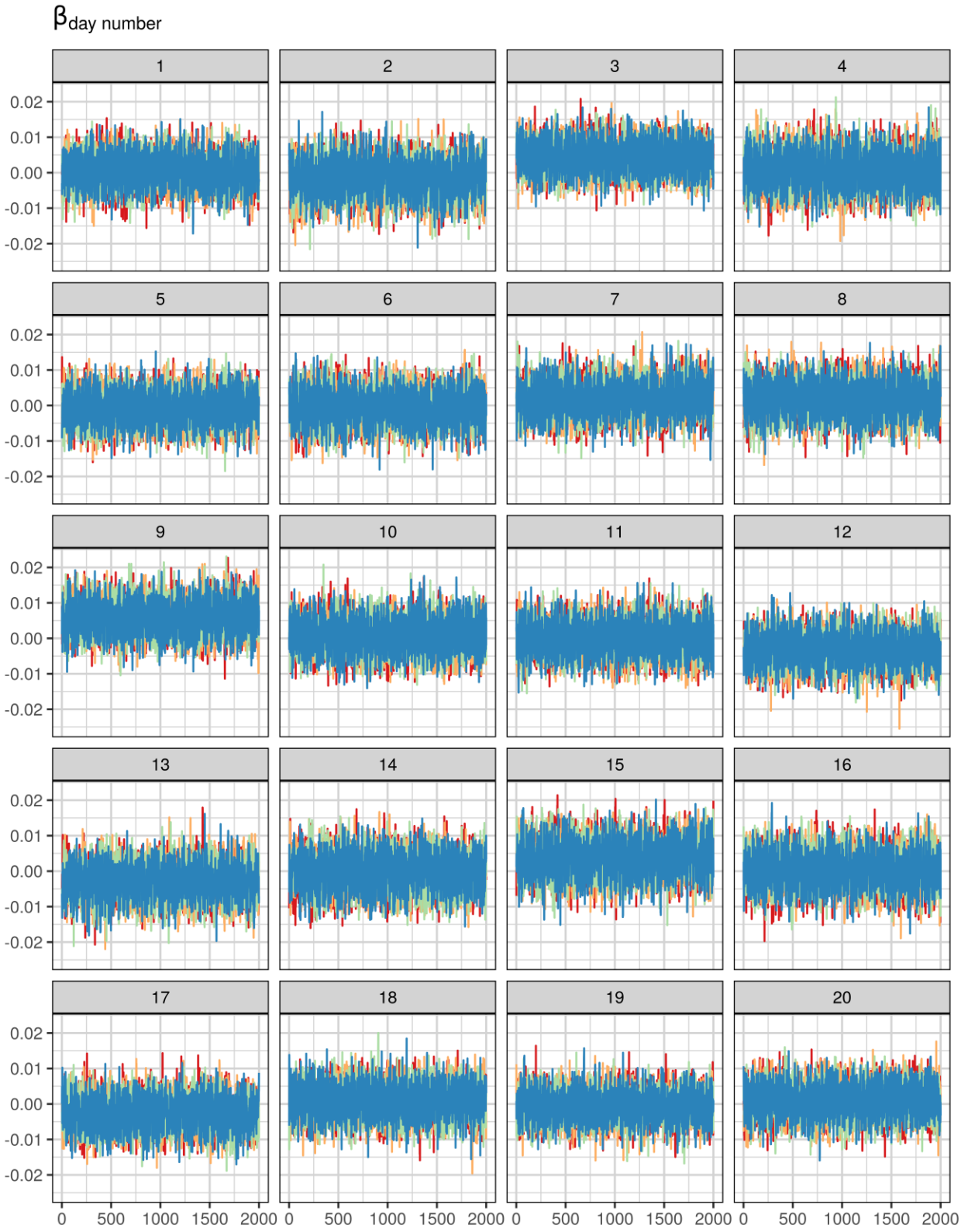


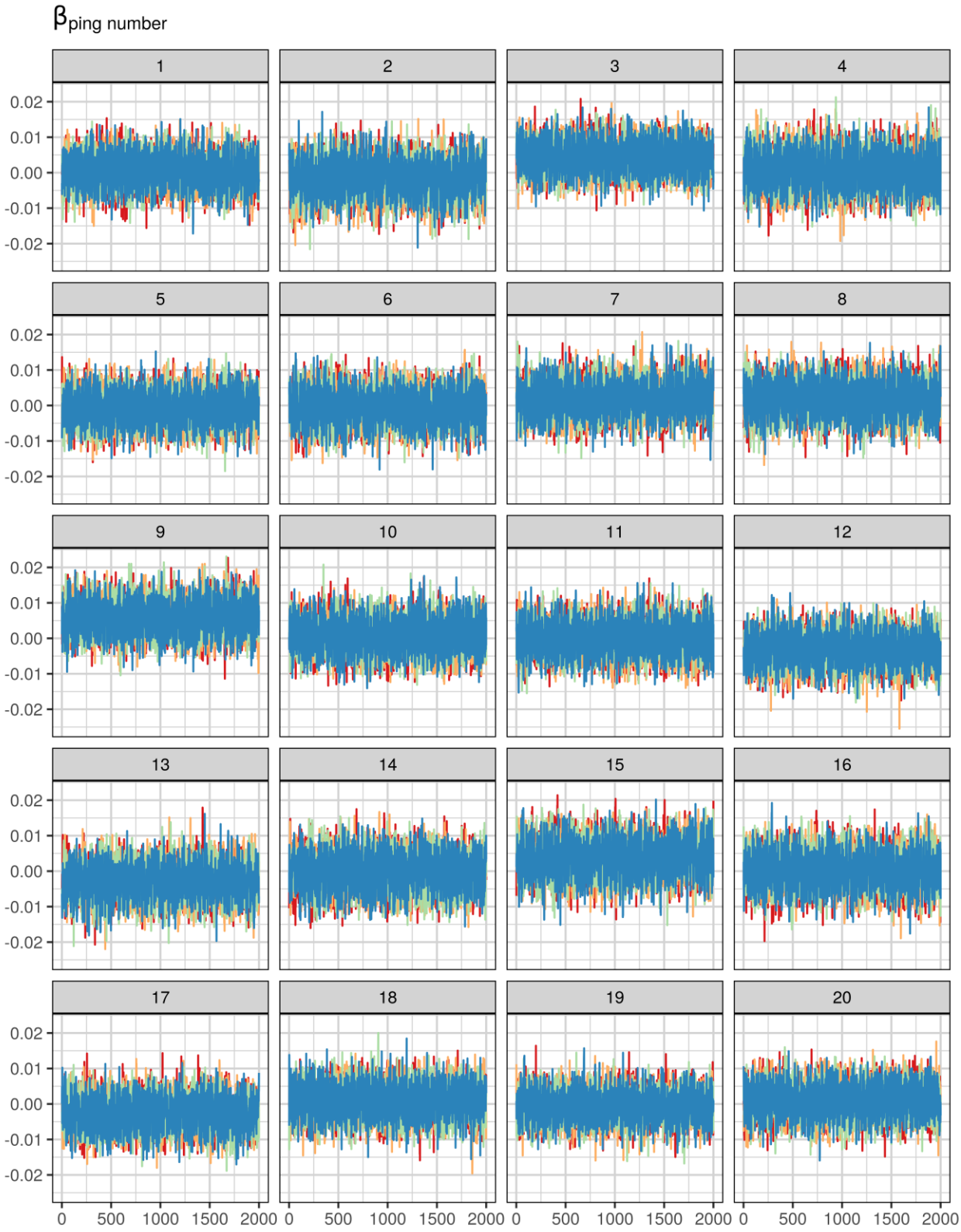
Appendix A

MCMC Convergence and Model Diagnostics




β0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
500
1000
1500
2000


β day number
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
500
1000
1500
2000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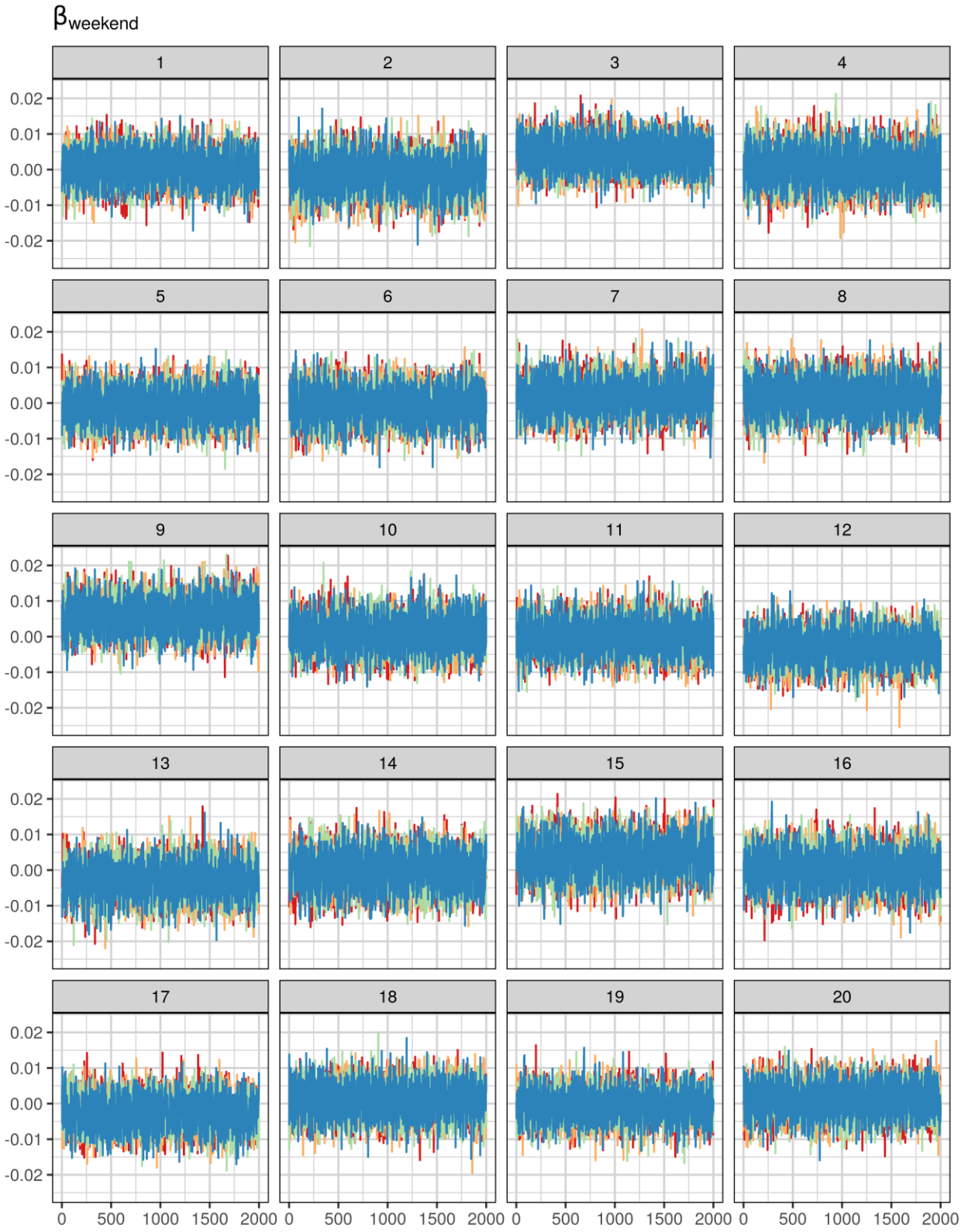
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
500
1000
1500
2000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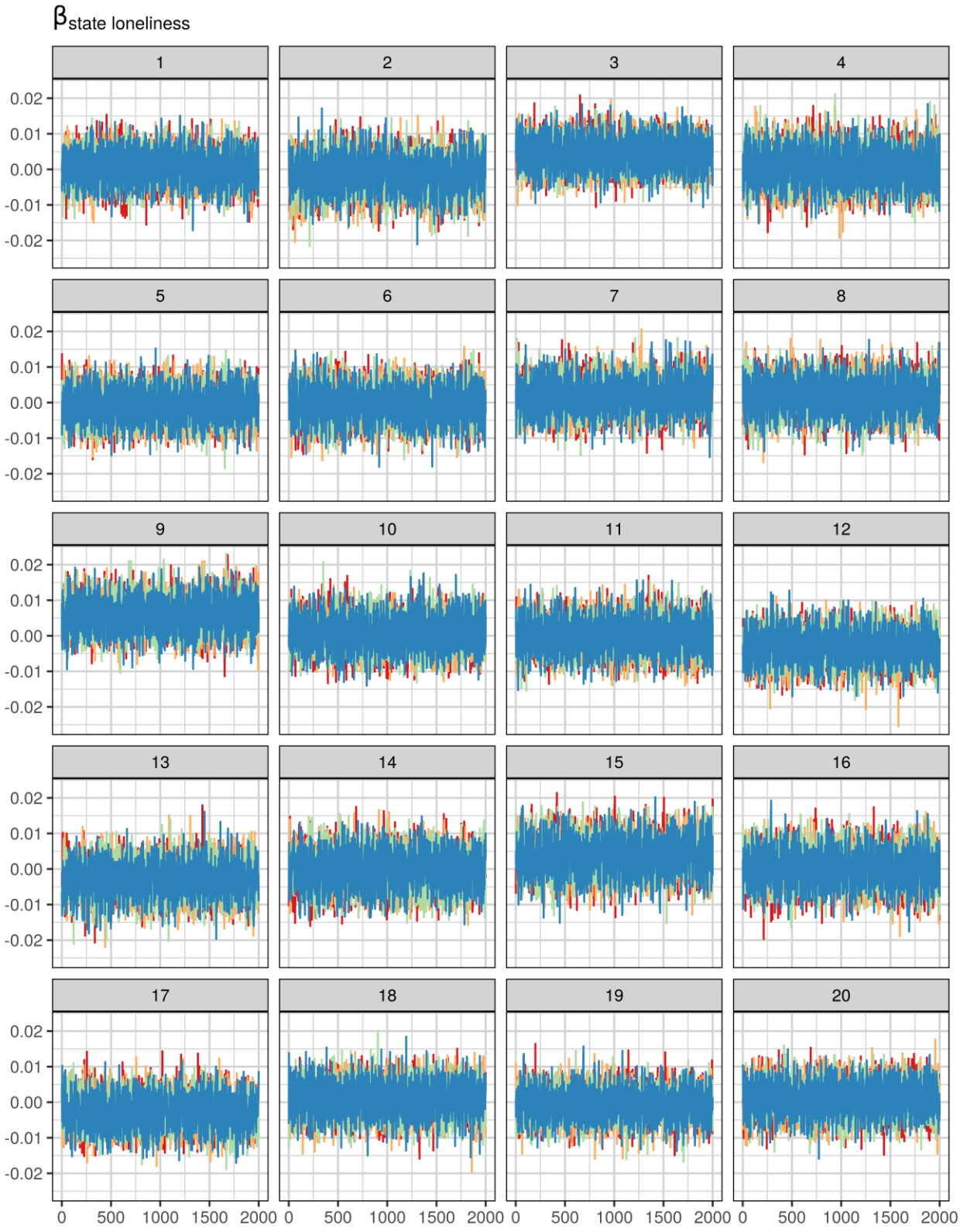
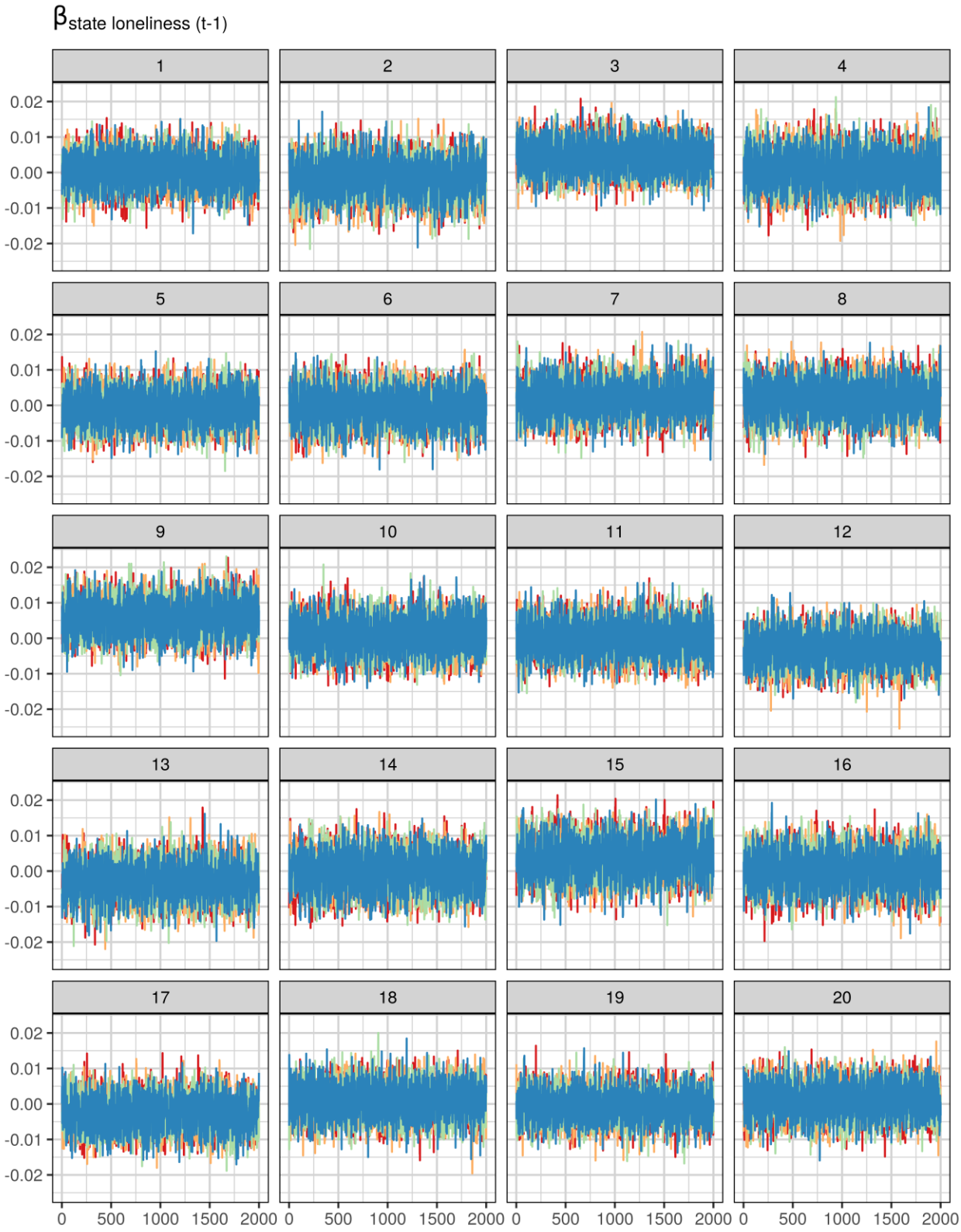
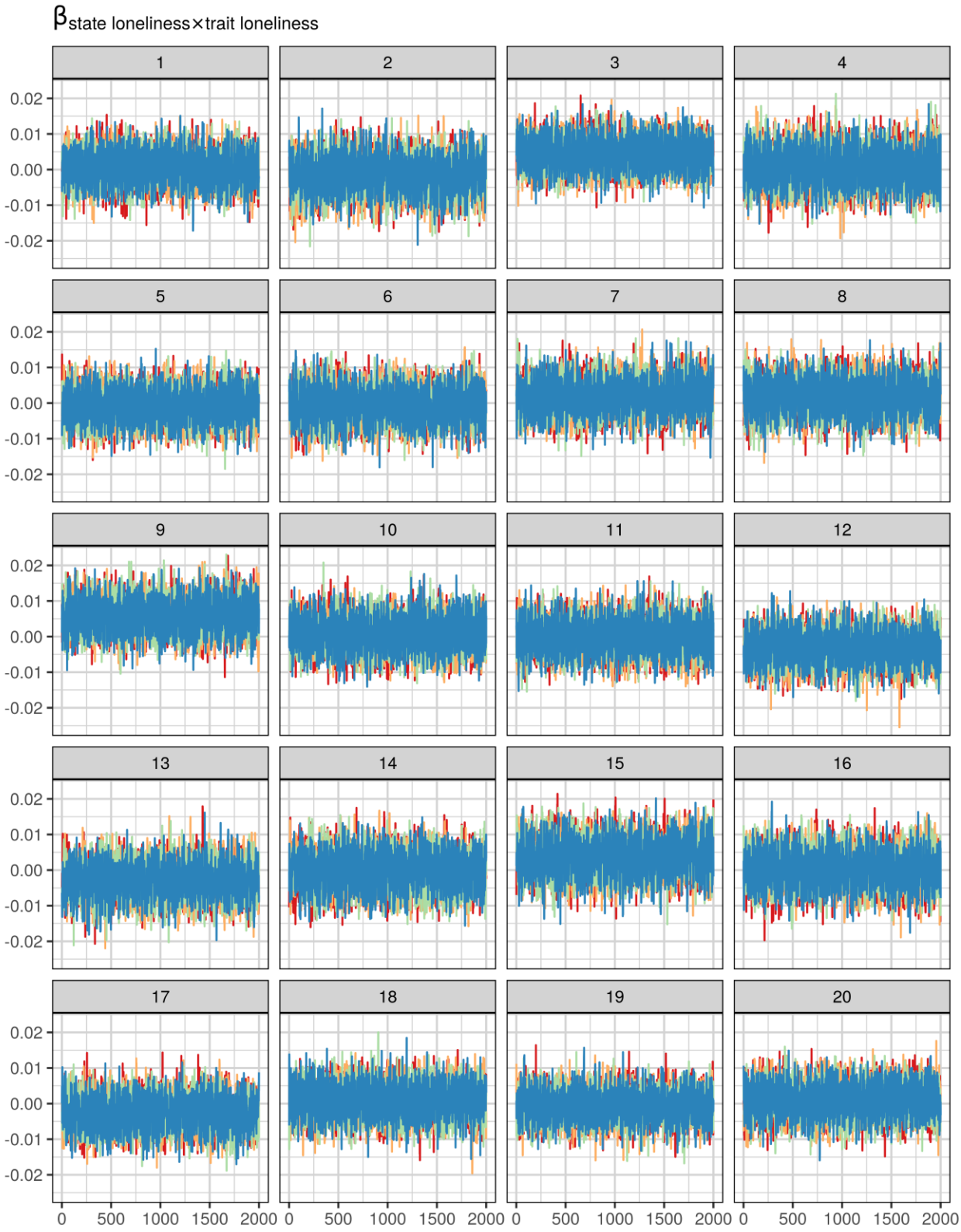
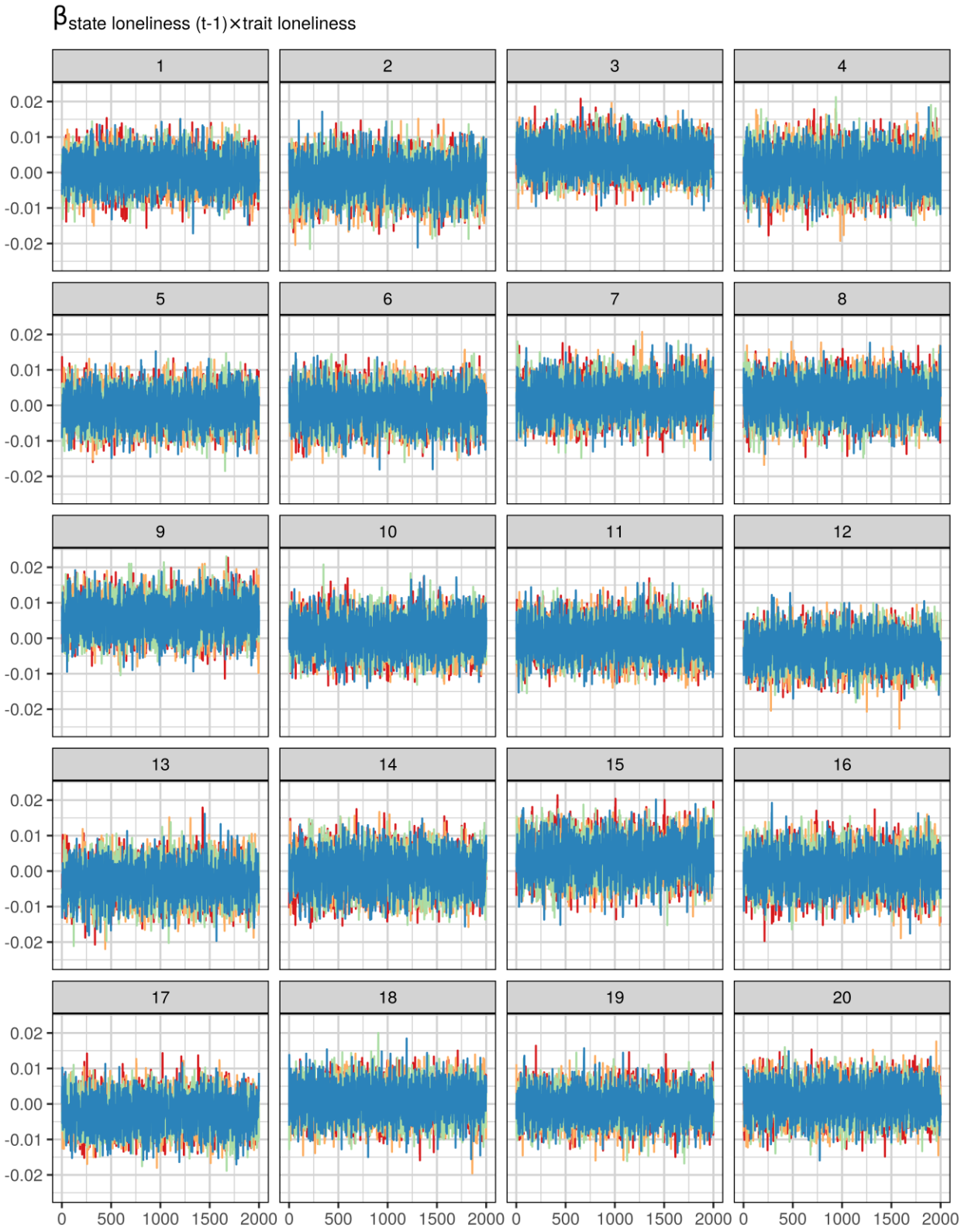
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
500
1000
1500
2000


βstate loneliness
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
500
1000
1500
2000


βstate loneliness (t-1)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
500
1000
1500
2000


βstate loneliness×trait loneliness
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
500
1000
1500
2000


βstate loneliness (t-1)×trait loneliness
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.02
0.01
0.00
-0.01
-0.02
0
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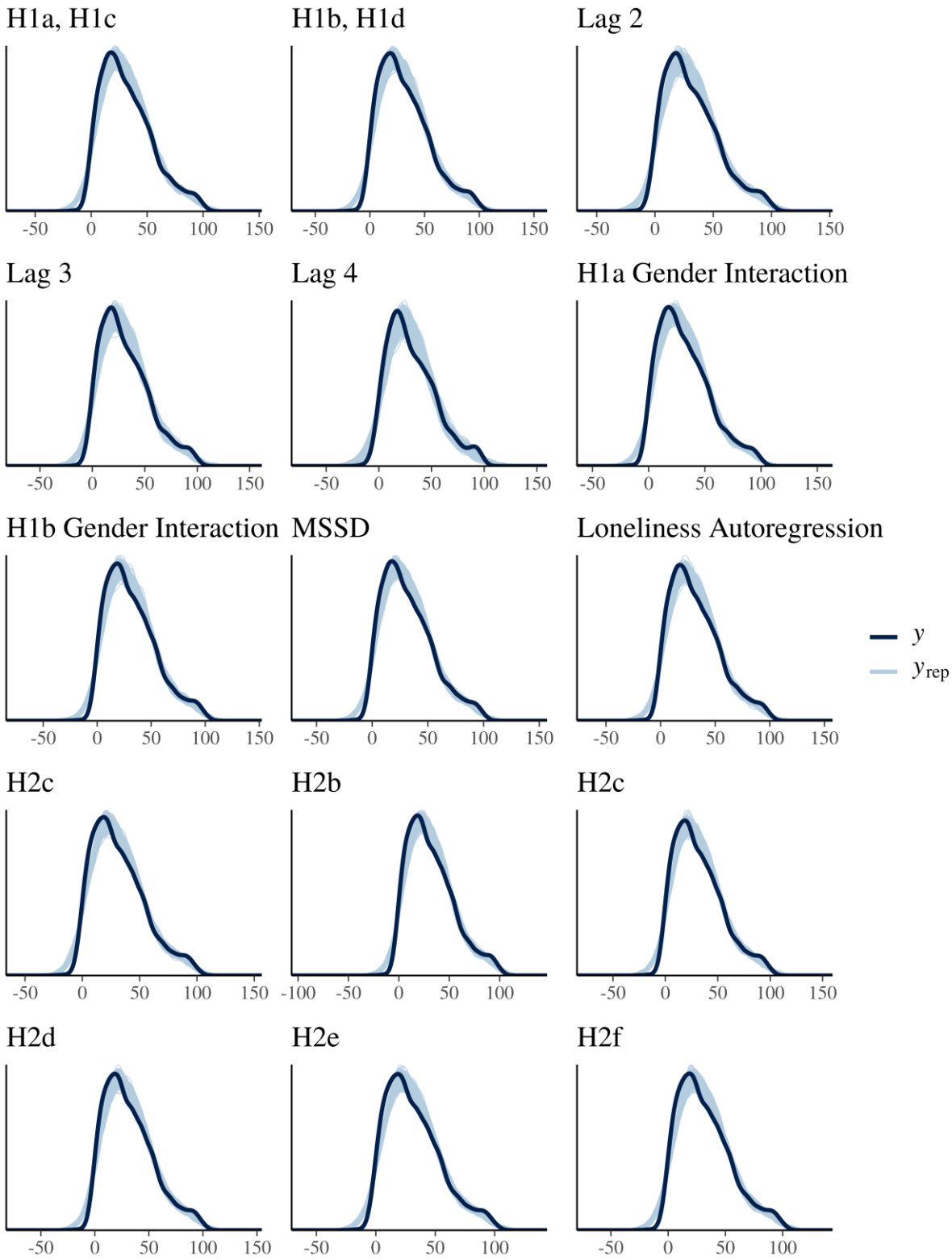
1000
1500
2000


H1a, H1c
H1b, H1d
Lag 2
Lag 3
Lag 4
H1a Gender Interaction
H1b Gender Interaction
MSSD
Loneliness Autoregression
H2c
H2b
H2c
H2d
H2e
H2f
y
y_rep