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Lonely Days: Linking Day-to-Day Loneliness to Biological and Functional Aging

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Objective: Lonelier people age more quickly than their less lonely counterparts. Nevertheless, loneliness has been conceptualized as a stable trait rather than a fluctuating experience. The current study examined whether two markers of loneliness in daily life—average daily loneliness and loneliness susceptibility, that is, day-to-day fluctuations with changing circumstances—were associated with poorer biological, phenotypic, and functional aging outcomes. ***Method:*** Adults who participated in the National Study of Daily Experiences and Biomarker Project of the Midlife in the United States study ($N = 1{,}008$) reported their daily loneliness on eight consecutive evenings, provided blood samples assayed for interleukin (IL)-6 and insulin-like growth factor-1 (IGF-1), and completed assessments of gait speed and grip strength. Self-reports captured difficulties with instrumental activities of daily living, demographics, health conditions, and trait measures of depression and social connection. ***Results:*** Contrary to its traditional treatment as a trait, loneliness varied substantially day to day (intraclass correlation coefficient = .57). Controlling for age, gender, comorbidities, body mass index, education, and time between projects, higher daily loneliness was associated with lower IGF-1, weaker grip, slower gait, and more self-reported functional limitations. Those who were more susceptible to daily loneliness also had higher IL-6 and slower gait. Trait measures of social connection did not predict these outcomes, and daily loneliness measures were largely robust to the effects of depression. ***Conclusions:*** Two signatures of daily loneliness highlight its dynamic nature and show its unique importance for unhealthy aging, underscoring the value of daily approaches for assessing and intervening on loneliness to offset aging-related decline.

Public Significance Statement
Based on decades of research showing the health risks, the Surgeon General has declared loneliness a medical epidemic, but most previous work has treated loneliness as a stable trait that describes individuals. Extending that research by looking at loneliness in daily life, the present study found that feeling lonelier and having greater day-to-day changes in loneliness were linked to altered aging-related biomarkers, slower walking speed, weaker hand grip, and more problems with activities in daily life. These findings demonstrate the importance of daily experiences of loneliness for biological, physical, and functional aging outcomes.

Keywords: loneliness, aging, geroscience, daily diary, ecological momentary assessment

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Loneliness is now considered a public health crisis. Shown in multiple meta-analyses and amplified by the Surgeon General's 2023 report declaring a medical epidemic (Office of the Surgeon General, 2023), loneliness' mortality risks and disease burden are equivalent to known preventable killers such as smoking (Holt-Lunstad et al., 2015). Recent evidence points to accelerated aging as a key pathway linking loneliness to earlier mortality. Based on epigenetic clock data, lonelier people show a faster pace of aging than their less lonely counterparts (Beach et al., 2022). They also have shorter telomeres (Stein et al., 2018; Wilson, Woody, et al., 2019) and higher inflammation (Van Bogart et al., 2021), both key markers of senescence. In tandem, lonelier people display an advanced aging phenotype, with slower gait speed, more functional limitations, and greater frailty compared to the less lonely (Shankar et al., 2017).

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Despite the exciting advancements in this research area, a notable limitation of the literature is the treatment of loneliness as a stable, trait-like risk factor, rather than as an experience that can vary. Indeed, most studies linking loneliness to the physical aging process have only measured loneliness at a single point in time. Yet, a recent study showed that loneliness can fluctuate from day to day (Van Bogart et al., 2021): in data from more than 200 socioeconomically and racially diverse older adults who rated their loneliness five times daily for 2 weeks, 30% of the variance in momentary loneliness corresponded to within-person fluctuations. Average daily loneliness was only moderately correlated with trait loneliness as measured by the three-item University of California Los Angeles (UCLA) scale, underscoring the uniqueness of the momentary measure. Greater average daily loneliness predicted higher C-reactive protein, an acute phase protein and clinically significant inflammatory marker, controlling for depressive symptoms—a known correlate of loneliness and risk factor for elevated inflammation.

Among its advantages, capturing daily loneliness with repeated assessments reduces person-level reporting biases and measurement error in mean levels of loneliness. That is, it may provide a higher-quality metric for differentiating individuals who tend to feel lonelier from those who consistently feel less lonely. In addition, the daily approach can reveal the degree to which loneliness fluctuates. Indeed, some individuals who do not typically feel lonely may be more vulnerable to increased loneliness in reaction to varied daily circumstances—that is, they may have greater social fragility. This daily fluctuation, which we refer to as loneliness susceptibility, may be a separate dimension of loneliness that opens a new window into our understanding of how loneliness affects physical health. Neither average daily loneliness nor loneliness susceptibility have been studied in relation to aging-related outcomes, except for the prior study's correlation between average daily loneliness and inflammatory marker C-reactive protein.

The Current Study: A Hierarchical Approach to Biological and Functional Aging

According to the hierarchical framework of aging metrics (Ferrucci et al., 2018), progression in biological aging over the adult lifespan gives way to declines in the so-called aging phenotype—that is, subtle, perhaps subclinical changes in measures like gait speed and grip strength. In turn, phenotypic declines eventually impact function, that is, the ability to engage in everyday activities independently. Of note, there is remarkable heterogeneity in the timing of aging-related shifts across individuals. For this reason, we cannot make assumptions about a person's biological, phenotypic, and functional aging based on their chronological age. In this way, from the perspective of the metrics of aging model, chronological age does not determine the shape, timing, or one's position on the biology–phenotype–function curve. Loneliness is likely a source of toxic stress that accelerates this aging process (Epel, 2020), evidenced by the plethora of studies linking the risk factor to biological, phenotypic, and functional aging.

Building on this rich body of work, the current study aimed to assess whether day-to-day loneliness was associated with aging-related biomarkers as well as phenotypic and functional aging. In this study's large sample of midlife and older adults aged 34–84 years, we expected to see ties to all three levels of aging metrics because the associations between the biological pace of aging and the aging phenotype can emerge early in adulthood. For example, in the Dunedin Study birth cohort, when all participants were 38 years old, they had vastly different biological ages, with some whose biology reflected that they were older than their chronological age and others younger than their chronological age (Belsky et al., 2015). Those who had an accelerated pace of biological aging had weaker grip strength, poorer balance, worse motor ability, and more physical limitations; they also scored lower on cognitive tests and appeared older in photos than their same-aged peers. The fact that these changes happened in adults of younger chronological ages underscores the need to distinguish the aging process from aging people, without attributing stereotyped traits to older adults, for example.

In the current study, proxies for biological aging included proinflammatory cytokine interleukin-6 (IL-6) and insulin-like growth factor-1 (IGF-1). One of the seven pillars of biological aging, inflammation exacerbates other molecular aging processes and plays a mechanistic role in downstream associations with aging-related diseases (Franceschi et al., 2018; Kennedy et al., 2014; López-Otín et al., 2013). IL-6 has an especially prominent role in inflammaging (Franceschi et al., 2018) and robustly predicts aging-related outcomes like frailty and mortality (Adriaensen et al., 2015; Forcina et al., 2022; Michaud et al., 2013). In adults, among its many functions, the hormone IGF-1 promotes bone health and maintains skeletal muscle (Arvat et al., 2000), and thus, lower levels are linked to greater frailty and functional limitations in older adults (Cappola et al., 2003). Low circulating levels of IGF-1 also predict heightened risks for death due to heart disease (Laughlin et al., 2004). Together, high IL-6 and low IGF-1 foreshadow even greater functional limitations and earlier mortality than either one alone (Beberashvili et al., 2013; Cappola et al., 2003). In addition, both IL-6 and IGF-1 respond to psychological stress and resilience factors (Cankaya et al., 2009; Kiecolt-Glaser et al., 2003; Wilson, Bailey, et al., 2019). Phenotypic aging was captured via gait speed and grip strength, gold standard measures, and functional limitations were measured with self-reported instrumental activities of daily living (IADLs). We first hypothesized that higher mean levels of daily loneliness would be associated with higher levels of inflammatory marker IL-6, lower levels of aging biomarker IGF-1, slower gait speed, and greater limitations to IADLs. Beyond typical feelings of daily loneliness, we predicted that greater loneliness susceptibility (i.e., larger fluctuations in daily loneliness) would also be uniquely associated with higher IL-6, lower IGF-1, slower gait speed, weaker grip strength, and more functional limitations.

Method

Participants

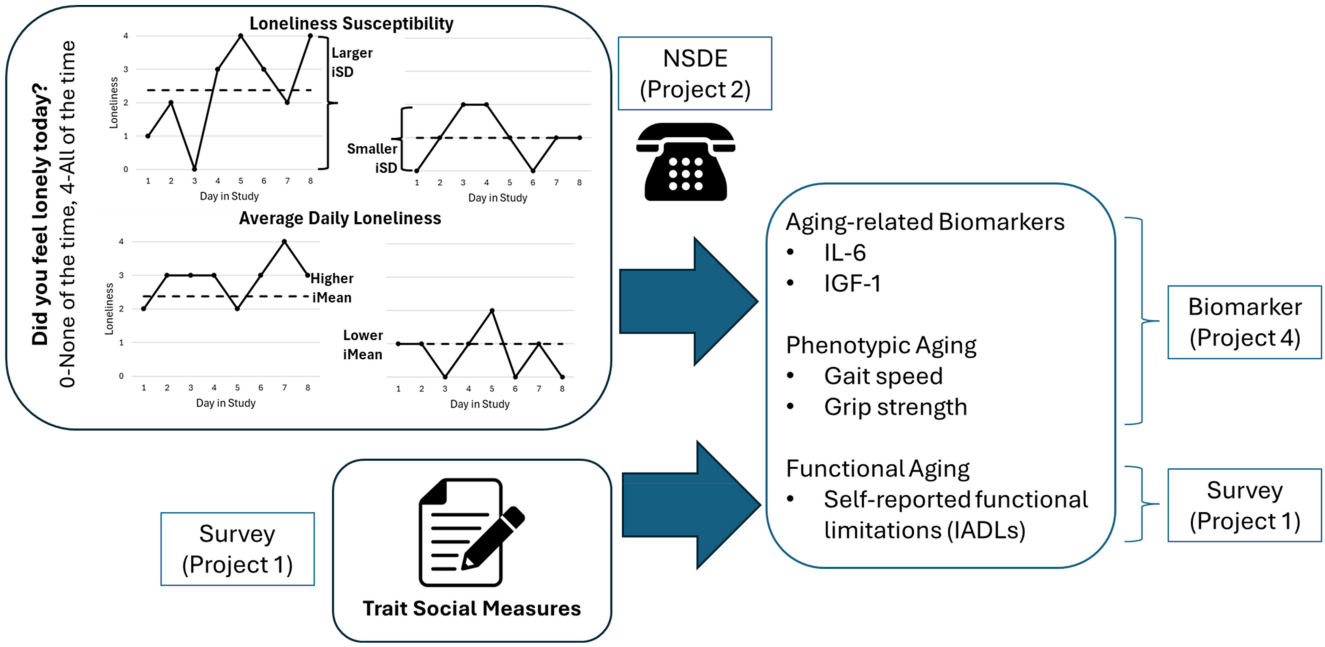
The sample included 1,008 middle-aged and older adults who participated in the National Study of Daily Experiences (NSDE) and the Biomarker Project of the Midlife in the United States (MIDUS) study Wave 2 (2005–2009). Participants in this subsample ranged from 34 to 84 years ($M = 55.34$, $SD = 11.66$) and 54.6% were women. The majority were White (93%), 45.9% had an education level of graduating college or higher, and their self-rated health was "good" on average ($M = 2.29$, $SD = 0.93$).

Procedure

An overview of the study design and measures is depicted in Figure 1. As part of the NSDE daily diary substudy, participants provided self-reports via semistructured telephone interviews on eight

Figure 1

Overview of Study Design and Measures



Note. All data used in this study come from Wave 2 of the MIDUS study. The primary predictors are average daily loneliness (the iMeans) and loneliness susceptibility (the iSDs) derived from the MIDUS daily diary project, the NSDE. Among the outcomes, the aging-related biomarkers and phenotypic measures come from the Biomarker project; the measure of functional aging derives from the survey, Project 1. Trait social measures, which were collected in the primary survey (Project 1), serve as exploratory covariates. Telephone icons created by Freepik—Flaticon. iSD = person-level standard deviations of loneliness; NSDE = National Study of Daily Experiences; iMeans = person-level means of loneliness; IL-6 = interleukin-6; IGF-1 = insulin-like growth factor-1; IADL = instrumental activities of daily living; MIDUS = Midlife in the United States study. See the online article for the color version of this figure.

consecutive evenings. Participants rated how lonely they felt that day, from which person-level means (iMeans) and standard deviations (iSDs) were calculated to capture average daily loneliness and loneliness susceptibility. In a separate lab visit (range: 4.67 months before to 3.89 months after NSDE), participants completed two timed 50-ft walks to index gait speed (minimum of two trials, measured in seconds), squeezed a dynamometer three times with each hand to measure their maximum grip strength in kg/force, self-reported functional limitations, and provided fasting blood samples (drawn between 6 and 8:30 a.m.) from which biomarkers of interest were assayed. Sociodemographic and self-reported health characteristics were assessed in a survey.

Self-Report Measures

Daily Loneliness

During each end of day interview, participants answered "How much of the time today did you feel lonely?" with possible frequencies: 0 = *none of the time*, 1 = *a little of the time*, 2 = *some of the time*, 3 = *most of the time*, and 4 = *all of the time*. These numeric values were then used to calculate a iMean to assess each person's average daily loneliness and iSD to assess fluctuation in daily loneliness or loneliness susceptibility.

Self-Reported Functional Limitations

IADLs, a measure of self-reported functional limitations, was captured by asking participants to rate their difficulty, from 0 = *not at all* to 4 = *a lot*, with the following seven activities: lifting or carrying groceries; climbing several flights of stairs; bending, kneeling, or stooping; walking more than a mile; walking several blocks; vigorous activities (e.g., running and lifting heavy objects); and moderate activities (e.g., bowling and vacuuming). Scores were averaged with higher values indicating greater limitations.

Trait Positive Social Relations

A sum composite score ($\alpha = .77$) was calculated from seven items assessed in the preliminary survey, rated on a scale of 1 = *strongly agree* to 7 = *strongly disagree*. Items included "Maintaining close relationships has been difficult and frustrating for me"; "I often feel lonely because I have few close friends with whom to share my concerns"; and "I have not experienced many warm and trusting relationships with others." They also included four reverse-coded items: "Most people see me as loving and affectionate"; "I enjoy personal and mutual conversations with family members and friends"; "People would describe me as a giving person, willing to share my time with others"; and "I know that I can trust my friends, and they know they can trust me." Higher scores represent more positive social relations.

Community Belonging

A sum composite score ($\alpha = .79$) was calculated from three items assessed in the preliminary survey, rated on a scale of 1 = *strongly*

agree to 7 = *strongly disagree*: "I don't feel I belong to anything I'd call a community" and two reverse-coded items "I feel close to other people in my community" and "My community is a source of comfort." Higher scores represent greater community belonging.

Depression

Depression was measured using the World Health Organization Composite International Diagnostic Interview Short Form, a validated scale assessing clinical depressive episodes over the previous 12 months (Kessler et al., 1998). This scale was chosen because it provided a measure of syndromal depression and did not overlap with loneliness, a limitation of the Center for Epidemiological Studies-Depression survey (Radloff, 1977).

Assays

Fasting blood serum samples were assayed for IL-6 and IGF-1. Specifically, IL-6 was assessed via immunoelectrochemiluminescence, measured using a V-plex Custom Human Cytokine Kit (Meso Scale Diagnostics [MSD], Rockville, Maryland, United States), MSD Sulfotag, and MSD Sector Imager, where a voltage applied to the plate electrodes causes the captured Sulfo-tag to emit light. The instrument measures the intensity of the emitted light to provide a quantitative measure of analytes in each sample. The interassay coefficient of variation ranged between 5% and 15%, while the intraassay coefficient of variation was 4.73%. IGF-1 was measured using a two-site sandwich immunoassay on a Siemens Immulite 2000 analyzer. Assays were performed at the ARUP Laboratories in Salt Lake City, Utah and at the MIDUS biomarker core laboratory in Madison, Wisconsin, United States.

Analytic Plan

To assess hypotheses, multiple regression models were fit in sequence. To explain, we used a two-step approach, wherein person-specific means and standard deviations were calculated first, and then used as between-person predictors in a multiple regression model. This is the most prominent and widely accepted method for examining person means and standard deviations of daily phenomena as predictors of between-person outcomes (Koffer et al., 2017; Ram & Gerstorf, 2009). An alternative approach would be to estimate the person means and standard deviations simultaneously in a heterogeneous variance multilevel model alongside a joint multiple regression model that contains the between-person outcomes. This alternative method can be especially valuable when the multilevel portion of the model is being used to estimate more complex terms like regression slopes that require daily confounds to be covaried out for the slope to be meaningful (e.g., Wilson et al., 2017). However, this more complex method is not widely used (Ram, 2022) and was not needed to examine person means and standard deviations as predictors in the current study. Thus, we chose the two-step regression method for the sake of simplicity and ease of replicability.

In the model sequence, average daily loneliness was first tested as a predictor of aging-related outcomes, controlling for age, gender, body mass index (BMI), comorbidities, education, and the time lag between the daily diary period and the biomarker assessment. It was important to first examine average daily loneliness apart from loneliness susceptibility because the two were strongly correlated, with stronger fluctuations also raising mean levels. Second, loneliness susceptibility was added to the model, as this predictor cannot be properly interpreted without controlling for average daily loneliness. Finally, supplemental exploratory analyses considered the effects of trait-level measures of social connection (i.e., positive social relations and community belonging) and depression. They were first added to the previous models to examine robustness and to determine whether these trait measures predicted outcomes independently of daily loneliness. However, given that the addition of trait measures resulted in significant loss of sample size, we also probed the robustness of daily loneliness with nonsignificant trait effects trimmed. Finally, gender differences in the links between daily loneliness and outcomes were explored. Multicollinearity indices were examined in all models.

Results

Contrary to its traditional treatment as a trait, loneliness varied substantially day to day (43% within-person variance, intraclass correlation coefficient [ICC] = .57). Those who had high levels of loneliness susceptibility (iSD) also had high average daily loneliness, reflected in a strong correlation of .73. Both measures of daily loneliness were weakly correlated with trait social measures and depression in the expected directions (Table 1). Zero-order correlations also show weak associations between average daily loneliness and gait speed ($r = .13$) and IADLs ($r = .13$), as well as between loneliness susceptibility and IL-6 ($r = .08$), gait speed ($r = .15$), and self-reported functional limitations ($r = .10$).

Consistent with prediction and shown in Figure 2, those who were lonelier in daily life (i.e., had higher average daily loneliness) had lower IGF-1 (estimate = −7.51, $SE = 3.48$, $p = .031$), slower gait (estimate = 1.07, $SE = 0.31$, $p = .0006$), weaker grip (estimate = −1.32, $SE = 0.57$, $p = .021$), and more self-reported functional limitations (estimate = 0.23, $SE = 0.06$, $p = .0003$) than people who were less lonely on average in daily life, above and beyond age, gender, comorbidities, BMI, education, and the time between projects (see Model 1 of Tables 2–4). To aid in the interpretation of effect magnitudes, we compare significant associations of daily loneliness to the benchmark effect of comorbidities on the outcomes, except for IGF-1, which comorbidities did not significantly predict. For IGF-1, we instead compare to the effects of age and BMI. For each 1 *SD* increase in average daily loneliness, IGF-1 was 3.31 ng/ml lower, which is smaller than the effect of a 1 *SD* (6.47-point) increase in BMI (5.69 ng/ml lower) and the effect of a 1 *SD* (∼one decade) increase in age (12.59 ng/ml lower). With each 1 *SD* increase in average daily loneliness, there was a corresponding 0.47-s slowing in gait speed, whereas a 0.59-s decrease in gait speed accompanied a 1 *SD* increase in comorbidities (i.e., three additional chronic conditions). With each 1 *SD* increase in average daily loneliness, there was a corresponding 0.58 kg decrease in grip strength compared to the 0.77 kg decrease that coincided with a 1 *SD* increase in comorbidities (∼three chronic conditions). With each 1 *SD* increase in average daily loneliness, there was a corresponding 0.10-point increase in self-reported functional limitations, smaller than the 0.27-point increase that accompanied a 1 *SD* increase in comorbidities. Average daily loneliness was not related to IL-6 (estimate = 0.06, $SE = 0.04$, $p = .176$).

In addition, depicted in Figure 3, those who were more susceptible to feeling lonely (i.e., whose loneliness fluctuated more from day to

Table 1
Descriptive Statistics and Zero-Order Correlations of Continuous Study Variables

Variable	*M* (*SD*)	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Average daily loneliness	0.15 (0.44)	—												
2. Loneliness susceptibility	0.16 (0.35)	.73*	—											
3. Age	55.34 (11.66)	−.09*	−.10	—										
4. Log IL-6	−0.15 (0.64)	.05	.08*	.25*	—									
5. IGF-1	127.79 (50.42)	−.06	−.04	−.25*	−.21*	—								
6. Gait speed	15.10 (4.54)	.13*	.15*	.20*	.27*	−.15*	—							
7. Grip strength	37.60 (12.45)	−.06	−.03	−.26*	−.12*	.27*	−.22*	—						
8. Self-reported functional limitations	1.70 (0.83)	.13*	.10*	.25*	.27*	−.17*	.39*	−.23*	—					
9. Education	14.64 (2.60)	−.03	−.07*	−.06*	−.16*	.14*	−.16*	.06*	−.18*	—				
10. Comorbidities	4.13 (2.96)	.14*	.10*	.36*	.23*	−.17*	.29*	−.24*	.42*	−.05*	—			
11. BMI	29.69 (6.47)	.02	.05	−.03	.35*	−.12*	.28*	.08*	.27*	−.14*	.16*	—		
12. Trait positive social interactions	40.90 (7.05)	−.26*	−.26*	.18*	.00	−.04	−.07*	−.13*	−.08*	.10*	−.05	−.04	—	
13. Trait community belonging	15.23 (4.11)	−.18*	−.20*	.15*	.03	.02	−.02	−.06	−.12*	.14*	−.05	−.03	.57*	—
14. Depression	0.05 (1.80)	.27*	.21*	−.13*	.08*	−.03	.09*	−.08*	.22*	−.08*	.20*	.06	−.24*	−.24*

Note. IL-6 = interleukin-6; IGF-1 = insulin-like growth factor-1; BMI = body mass index.
* $p < .05$.

day) also had higher IL-6 (estimate = 0.15, *SE* = 0.08, $p = .015$) and slower gait speed (estimate = 1.78, *SE* = 0.56, $p = .002$; see Model 2 of Tables 2–4). That is, with each 1 *SD* increase in loneliness susceptibility, there was a corresponding 5.39% increase in log-transformed IL-6 compared to the 6.10% increase in IL-6 with each 1 *SD* increase in comorbidities (~three chronic conditions). A 1 *SD* increase in loneliness susceptibility was linked to a 0.55-s slower gait speed, quite similar to a 0.59-s decrease in gait speed with a 1 *SD* increase in comorbidities. Tolerance values for average and fluctuations in loneliness ranged from 0.46 to 0.51 and variance inflation factors ranged from 1.96 to 2.18 across models, well within acceptable standard cutoffs for multicollinearity.

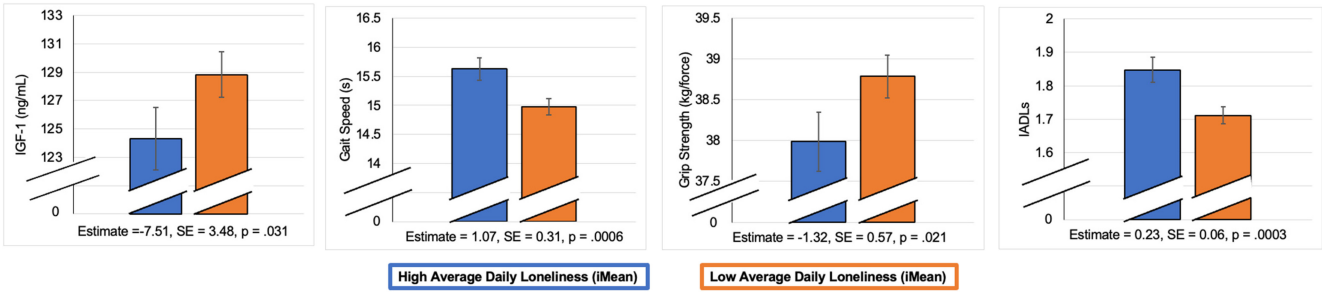
Depicted in Table 1, trait measures of positive social relations and community belonging were moderately correlated with one another ($r = .57$), and both shared weak, negative correlations with depression ($r = -.25$, $r = -.24$). In supplemental analyses, trait measures of positive social relations and community belonging did not independently predict any of the aging-related outcomes (see Model 1 of Supplemental Tables 1–3 in the online supplemental materials). Depression was significantly associated with greater self-reported functional limitations (estimate = 0.05, *SE* = 0.01, $p = .0005$) and higher IL-6 (estimate = 0.02, *SE* = 0.01, $p = .0483$), consistent with prior work.

When including both trait measures of social connection and depression in the models (see Supplemental Tables 1–3 in the online supplemental materials), average daily loneliness remained significantly associated with self-reported functional limitations and gait speed, and loneliness susceptibility remained significantly associated with IL-6. However, average daily loneliness was attenuated in its association with grip strength (estimate = −1.07, *SE* = 0.69, $p = .122$) and IGF-1 (estimate = −7.40, *SE* = 4.36, $p = .090$); likewise, the relation between loneliness fluctuation and gait speed was attenuated (estimate = 0.83, *SE* = 0.53, $p = .117$). Notably, including these trait measures decreased the sample size for some of the models by over 10%, decreasing power to detect effects. None of the significant associations differed by gender according to ancillary analyses (*p*s = .11–.96).

Discussion

In a large national sample of midlife and older adults, daily loneliness shared clear associations with a profile of advanced biological, phenotypic, and functional aging. As expected, those who were lonelier on a daily basis also had lower IGF-1, weaker grip, slower gait, and more self-reported functional limitations. In addition, adults who were more susceptible to loneliness—that is, whose

Figure 2
Associations Between Average Daily Loneliness and Biological, Phenotypic, and Functional Aging-Related Outcomes



Note. Error bars indicate *SEs* of the mean. IGF-1 = insulin-like growth factor-1; IADL = instrumental activities of daily living; iMeans = person-level means of loneliness. See the online article for the color version of this figure.

Table 2
Multiple Regression Models With Aging-Related Biomarkers IL-6 and IGF-1 as Outcomes

	IGF-1						IL-6					
	Model 1			Model 2			Model 1			Model 2		
Predictor	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
Intercept	117.80	2.01	<.0001	117.87	2.02	<.0001	−0.13	0.02	<.0001	−0.12	0.02	<.0001
Average loneliness	**−7.51**	**3.48**	**.031**	−8.96	5.17	.0836	0.06	0.04	.176	−0.04	0.06	.5651
Loneliness susceptibility				1.30	6.39	.8385				**0.15**	**0.08**	**.047**
Female	19.76	3.06	<.0001	19.99	3.08	<.0001	−0.02	0.04	.6006	−0.02	0.04	.5352
Age	−1.08	0.14	<.0001	−1.10	0.14	<.0001	0.01	0.00	<.0001	0.01	0.00	<.0001
Education	1.69	0.58	.0038	1.70	0.59	.004	−0.02	0.01	.0015	−0.02	0.01	.0028
Comorbidities	−0.50	0.57	.3779	−0.52	0.57	.3678	0.02	0.01	.0133	0.02	0.01	.0106
BMI	−0.88	0.24	.0002	−0.87	0.24	.0003	0.03	0.00	<.0001	0.03	0.00	<.0001
Time between P4 and P2	1.39	1.03	.1785	1.43	1.04	.1698	−0.02	0.01	.1577	−0.02	0.01	.1446

Note. $N_{IGF-1} = 982$; $N_{IL-6} = 982$. IL-6 = interleukin-6; IGF-1 = insulin-like growth factor-1; *B* = beta; BMI = body mass index; P4 = Project 4 (biomarker project); P2 = Project 2 (daily diary). Significant estimates of daily loneliness ($p < .05$) are bolded.

loneliness fluctuated more from day to day—had higher IL-6 and slower gait. Trait measures of social connection and depression were weakly related to daily measures of loneliness and did not explain their associations with the outcomes. The current findings uncover two distinct daily-life signatures of loneliness that highlight its dynamic nature and suggest the potential value of just-in-time interventions to prevent accelerated aging associated with this well-known risk factor.

Given that little is known about the everyday experience of loneliness, it was important to begin by characterizing the extent to which loneliness varied from day to day. Indeed, if loneliness is highly stable across days, with an intraclass correlation coefficient close to 1, then it would be better conceptualized as a between-person phenomenon, a stable trait. In this case, the primary advantage of capturing daily loneliness is to increase measurement precision through repeated samples that reduce recall bias. Conversely, an ICC close to 0 would indicate that loneliness fluctuates a great deal, so much that between-person differences are indistinguishable in comparison. In that scenario, the average level of loneliness is much less important than the overall degree of variation; more moments and days of loneliness may confer greater risk. In the current study's large, primarily White, educated sample of adults aged 34–84 years, the ICC was .57, pointing to both meaningful between-person differences in daily loneliness and notable fluctuations from day to day. In other words, the daily experience of loneliness could not be fully understood without capturing both mean levels of daily loneliness and the deviations around those means. In Van Bogart et al.'s study (2021), the ICC was higher (.70), suggesting greater stability across measurement occasions. This contrast was surprising because their study sampled loneliness more frequently—five times daily for 2 weeks. The stability may have been because of a floor effect, as loneliness levels were very low. In both our study and the previous one, correlations between daily and trait measures were modest, suggesting that the measures captured distinct phenomena. Notably, neither study used a full, gold-standard measure of trait loneliness: Van Bogart et al. relied on the brief three-item UCLA scale, and although the UCLA measure was not administered in MIDUS, the included measures of social relations and community belonging provided a conceptual parallel, reverse scored.

Not only did the current study capture meaningful between- and within-person variance in daily loneliness, but it also linked average daily loneliness to the aging process. Namely, adults who experienced more loneliness in daily life also showed lower levels of

Table 3
Multiple Regression Models With Aging-Related Phenotypic Markers Gait Speed and Grip Strength as Outcomes

	Grip strength						Gait speed					
	Model 1			Model 2			Model 1			Model 2		
Predictor	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*	*B*	*SE*	*p*
Intercept	29.51	0.33	<.0001	29.50	0.33	<.0001	15.61	0.17	<.0001	15.61	0.18	<.0001
Average loneliness	**−1.32**	**0.57**	**.0214**	−0.74	0.85	.3886	**1.07**	**0.31**	**.0006**	0.09	0.45	.8498
Loneliness susceptibility				−0.83	1.05	.4318				**1.58**	**0.56**	**.0048**
Female	18.13	0.50	<.0001	18.18	0.51	<.0001	−0.93	0.27	.0005	−0.95	0.27	.0004
Age	−0.30	0.02	<.0001	−0.30	0.02	<.0001	0.06	0.01	<.0001	0.06	0.01	<.0001
Education	−0.05	0.10	.568	−0.07	0.10	.4421	−0.17	0.05	.0011	−0.16	0.05	.0024
Comorbidities	−0.26	0.09	.0058	−0.25	0.09	.0069	0.25	0.05	<.0001	0.25	0.05	<.0001
BMI	0.15	0.04	<.0001	0.15	0.04	.0001	0.17	0.02	<.0001	0.17	0.02	<.0001
Time between P4 and P2	0.01	0.17	.94	0.00	0.17	.9908	0.09	0.09	.3299	0.08	0.09	.3756

Note. $N_{GripStrength} = 991$; $N_{Gait\ Speed} = 985$. *B* = beta; BMI = body mass index; P4 = Project 4 (biomarker project); P2 = Project 2 (daily diary). Significant estimates of daily loneliness ($p < .05$) are bolded.

Table 4
Multiple Regression Model With Self-Reported Functional Limitations

	IADL					
	Model 1			Model 2		
Predictor	*B*	*SE*	*p*	*B*	*SE*	*p*
Intercept	1.87	0.03	<.0001	1.87	0.03	<.0001
Average loneliness	**0.23**	**0.06**	**.0003**	**0.22**	**0.09**	**.0117**
Loneliness susceptibility				0.02	0.11	.8766
Female	−0.25	0.05	<.0001	−0.25	0.05	<.0001
Age	0.01	0.00	<.0001	0.01	0.00	<.0001
Education	−0.04	0.01	.0001	−0.04	0.01	.0001
Comorbidities	0.09	0.01	<.0001	0.09	0.01	<.0001
BMI	0.03	0.00	<.0001	0.03	0.00	<.0001
Time between P4 and P2	0.00	0.02	.8603	0.00	0.02	.781

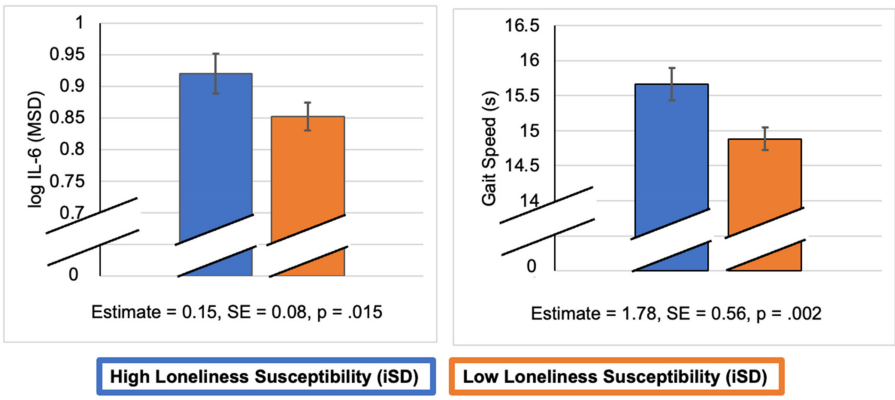
Note. $N_{IADL} = 865$. IADL = Instrumental Activities of Daily Living; B = beta; BMI = body mass index; P4 = Project 4 (Biomarker project); P2 = Project 2 (daily diary). Significant estimates of daily loneliness ($p < .05$) are bolded.

aging-related biomarker IGF-1, poorer objective measures of physical function, and more self-reported functional difficulties. Extending prior research that has linked trait loneliness to these outcomes, this work underscores the value of capturing the dynamic experience of loneliness in daily life in efforts to understand unhealthy aging. Associations with average daily loneliness could not be attributed to depression, comorbidities, or sociodemographics—all known correlates of loneliness. Including trait measures of social connection and depression attenuated a few of the associations, but this was likely because of the reduced sample size, given that the trait measures themselves did not predict these outcomes. The results highlight the importance of daily loneliness and may point to proximal mechanisms of perceived social connection and belonging as a fundamental need. Indeed, individuals who tend to feel lonelier day-to-day may also interpret ambiguous or neutral cues as threatening (Cacioppo et al., 2014; Lam et al., 2021), triggering longer and more frequent sympathetic adrenomedullary and hypothalamic–pituitary–adrenal axes responses, in turn raising inflammation (Jaremka et al., 2013). This study also adds to the evidence that psychosocial risks are associated with lower circulating levels of IGF-1 (Laughlin et al., 2004; Wilson, Bailey, et al., 2019), which itself can be disrupted and downregulated by chronic inflammation (Witkowska-Sędek & Pyrżak, 2020).

Apart from experiencing loneliness consistently on a daily basis, people who were more susceptible to loneliness and thus showed greater day-to-day variability also had higher IL-6 and slower gait speed. Accordingly, even a person who is not always lonely may be at risk for poorer biological and functional outcomes if they tend to feel lonely in response to changing circumstances. There are myriad potential triggers of transitory loneliness, both internal and external: having less social contact than usual on a given day, feeling left out of a group, discussing a conflictual topic with a loved one, receiving unsatisfactory social support in the midst of a stressor, or even withdrawing from others because of sickness or depressed mood. The goal of this study was to examine the resulting changes in loneliness and their role in aging-related outcomes rather than trace the empirical roots of loneliness; indeed, potential triggers were not exhaustively captured in the parent study. Notably, loneliness susceptibility and average daily loneliness were strongly correlated, suggesting a lawful relationship wherein greater fluctuations resulted in higher means. Despite this, with a correlation of $r = .73$, half of the variance in loneliness susceptibility was unique from average daily loneliness, making it possible to capture independent associations with aging-related outcomes. Even so, when loneliness susceptibility was included, many associations with average daily loneliness were attenuated, owing to the strong correlation and the muddied interpretation of average daily loneliness with susceptibility in the model. Samples with higher average daily loneliness would likely show even greater separation of loneliness susceptibility from mean levels; measuring daily (or momentary) loneliness for a longer period would also create more opportunities to capture variation. Beyond mean levels, populations may vary in their susceptibility to loneliness, with those in stressful times (e.g., navigating health problems and financial strain) and periods of transition (e.g., bereavement, retirement, and relocation) likely at greater risk.

Taken together, these findings provide empirical support for loneliness as a dynamic phenomenon and show that two unique signatures

Figure 3
Associations Between Loneliness Susceptibility and Biological and Phenotypic Aging-Related Outcomes



Note. Error bars indicate *SEs* of the mean. IL-6 = interleukin-6; MSD = Meso Scale Diagnostics; iSD = person-level standard deviations of loneliness. See the online article for the color version of this figure.

of daily loneliness track with key outcomes related to the aging process. In this way, the data highlight the importance of capturing loneliness with daily diary or ecological momentary assessment and intervening where it unfolds. Indeed, just-in-time interventions may be an especially impactful way to target daily experiences of loneliness. Likewise, for existing intervention programs, intensive longitudinal assessments can provide a more sensitive, dynamic measure of efficacy compared to trait measures, which are more heavily laden with response style biases that may obscure subtle change processes. For instance, loneliness may fluctuate more in the initial phases of an intervention, when individuals begin to try new skills with varying degrees of success, and then may stabilize at lower levels by the end of the intervention (Bamberger, 2016; Ram & Diehl, 2014). In this way, intensive repeated measurement of loneliness could provide a new window into change processes that may unfold over the course of an intervention.

Investigating the relations between daily loneliness and markers of the aging process risk inadvertently reinforcing implicit associations that connect older adults to loneliness and frailty, unless explicitly addressed. Here, it is critical to distinguish the aging process—a within-person cascade of biological, phenotypic, and functional changes that unfolds over time and with widely varying timescales across people—from the assumed attributes of aging individuals. According to stereotype embodiment theory and convincing empirical evidence, negative aging stereotypes—internalized over the lifespan and activated, even unconsciously, by identifying (or being identified) as old—can themselves damage physical health, function, cognition, and emotional well-being (Levy, 2009; Levy et al., 2014; Pietrzak et al., 2016). Importantly, the current study's results themselves link daily loneliness to markers of the aging process controlling for chronological age, which underscores that the associations emerge across adulthood and occur regardless of chronological age. In this way, both daily loneliness and negative aging stereotypes may fuel toxic stress that accelerates the biological aging process for adults of all ages.

Taken together, for many of the outcomes, the effects of daily loneliness were only slightly smaller than the effects of comorbidities, which are assumed to contribute an important degree of variance to aging-related outcomes. With inflammation elevated by 5%, gait slowed by half of a second, grip weakened by half of a kilogram, many of the magnitudes are small. Even so, the consequences of daily loneliness for the aging process may amount to meaningful changes if exerted consistently over long periods of time. This work adds mechanistic insight to a robust literature that has demonstrated the definitive links between trait loneliness and heightened mortality risks (Holt-Lunstad et al., 2015). As Holt-Lunstad et al. noted, the hazards of social disconnection (and poor-quality relationships) are as great or greater than known health risk factors such as smoking and obesity, and thus should be prioritized as a public health intervention target (Holt-Lunstad et al., 2010, 2015, 2017).

This work represents an early effort to link daily loneliness to the aging process, and thus, there are many important next steps for future research. For example, loneliness susceptibility should be assessed in other samples, as the degree of fluctuation may vary across populations. This sample is primarily White and educated, and thus, the findings may not generalize to more vulnerable, underrepresented populations. Other work should seek to replicate this design using a full, gold-standard measure of trait loneliness such as the 20-item UCLA scale. Although the content of the social measures paralleled many of the UCLA survey items, they did not predict outcomes as expected and thus may offer a weak test of the direct comparison between daily and trait measures. In addition, psychometric work is needed to determine the best approach to measuring daily and momentary loneliness. The current study used a single item, and although ecological momentary assessment measures must be very brief, it remains unclear whether a few item scale would have been superior in both precision and ability to reliably capture fluctuation. In the models, we controlled for the time interval between the diary study and the outcomes, most of which were measured as part of the Biomarker Project. These components belonged to the same wave of the MIDUS study and, therefore, were treated as conceptually concurrent. Indeed, the outcomes are expected to be reasonably stable, and daily processes are assumed to represent larger patterns that are typical of that general time period (Surachman et al., 2021; Wilson & Marini, 2023). Finally, future research should examine the degree to which daily signatures of loneliness remain stable over time and whether they predict longer-term prospective changes in unhealthy aging. The timescale over which these associations manifest and over which daily loneliness patterns change are both unknown.

In conclusion, these findings reveal the unique importance of daily loneliness for objective measures of aging, extending beyond the widely studied effects of trait loneliness. Both higher daily loneliness and greater susceptibility to loneliness—a novel signature that can only be captured using an intensive longitudinal approach—may share key roles in paths to unhealthy aging. In turn, these associations foreshadow the potential promise of intervening on loneliness in daily life, where health risks unfold.

Resumen

Objetivo: Las personas más solitarias envejecen más rápidamente que las menos solitarias. Sin embargo, la soledad se ha conceptualizada más como un rasgo estable que como una experiencia variable. El estudio actual examinó si dos marcadores de soledad en la vida diaria-la soledad diaria promedio y la susceptibilidad a la soledad, es decir, las fluctuaciones diarias con las circunstancias diarias cambiantes- se asociaban con peores resultados de envejecimiento biológico, fenotípico y funcional. ***Método:*** Los adultos que participaron en el Estudio Nacional de Experiencias Diarias y el Proyecto de Biomarcadores de la Edad Media en los Estados Unidos ($N =$ 1,008) informaron su soledad diaria durante ocho noches consecutivas, proporcionaron muestras de sangre analizadas para detectar interleucina (IL)-6 y el factor de crecimiento insulínico-1 (IGF-1), y completaron evaluaciones de la velocidad de la marcha y la fuerza de agarre. Los autoinformes capturaron dificultades con las actividades instrumentales de la vida diaria (IADL, por sus siglas en inglés), datos demográficos, condiciones de salud, y medidas de rasgos de depresión y conexión social. ***Resultados:*** Contrario a su tratamiento tradicional como rasgo, la soledad varió sustancialmente día a día (ICC = .57). Al controlar por edad, género, comorbilidades, índice de masa corporal, educación, y tiempo entre proyectos, una mayor soledad diaria se asoció con un IGF-1 más bajo, un agarre más débil, una marcha más lenta, y más limitaciones funcionales autoinformadas. Aquellos que eran más susceptibles a la soledad diaria también tenían niveles más altos de IL-6 y una marcha más lenta. Las medidas de rasgos de conexión social no predijeron estos

resultados, y las medidas de soledad diaria fueron robustas ante los efectos de la depresión. ***Conclusiones:*** Dos signos de soledad diaria presentados aquí resaltan su naturaleza dinámica y muestran su importancia única para el envejecimiento no saludable, subrayando el valor de los enfoques diarios para evaluar e intervenir en la soledad para compensar el deterioro relacionado con el envejecimiento.

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