Social determinants of health and disease in companion dogs: A cohort study from the Dog Aging Project

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Abstract

Exposure to social environmental adversity is associated with health and survival in many social species, including humans. However, little is known about if and how these health and mortality effects vary across the lifespan, largely due to the difficulty of studying long-lived organisms across much of their lifespan. Here, we leveraged a relatively new and powerful model for human aging, the companion dog, to investigate which components of the social environment are associated with dog health and how these associations vary across the lifespan. We drew on comprehensive survey data collected on 21,410 dogs from the Dog Aging Project and identified five factors that together explained 33.7% of the variation in a dog's social environment. Factors capturing financial and household adversity were associated with poorer health and lower physical mobility in companion dogs, while factors that captured social support, such as living with other dogs, were associated with better health when controlling for dog age and weight. Some of these associations differed across a dog’s lifespan, including a stronger relationship between owner age and health in younger (as compared to older) dogs. Taken together, these findings suggest the importance of income, stability, and owner age on owner-reported health outcomes in companion dogs and point to potential behavioral and/or environmental modifiers that can be used to promote healthy aging across species.

Introduction

The social environment is one of the strongest predictors of health and mortality across mammals, where exposure to less social adversity is associated with lower risk of disease and death [1]. In humans, higher socioeconomic status means access to more resources, including healthcare, and a more predictable, less stressful environment that is associated with lower morbidity and mortality [2]. For example, being socially isolated has a stronger association with mortality than heavy smoking, heavy drinking, and lack of exercise [2,3]. These sociality-health links appear to be rooted deep in evolutionary history: having been identified in species ranging from mice to primates [4–6].

How social adversity impacts older individuals is less clear and may vary based on timing of, severity of, and perceived impact of exposure to adversity [7]. The concept of environmental stability, which is composed of positive socio-economic, built, and natural environmental factors, is another important social environmental factor that plays a role in overall health and disease risk in both early and late life [8]. In humans, urban environments with high residence turnover, high pollution levels, and low economic status are associated with reduced physical mobility, higher risk of disease, and worse health outcomes [9]–all of which can change with age. However, researchers are only recently beginning to explore how the health and mortality associations with environmental factors vary across the lifespan–knowledge that is necessary in order to optimize the distribution of resources and interventions to those who would benefit most.

Even less is known about the health impacts of the social environmental factors for companion animals such as dogs, which are a powerful comparative model for human health and aging due to our shared biology and, importantly, shared environment [10–12]. In large part this is due to a dearth of detailed social environmental data for large samples of dogs of all ages. This has limited our understanding of how our life experiences might affect health and aging, and also limited our ability to help our companion animals live longer, healthier lives.

The use of companion dogs offers a unique opportunity to look across the lifespan at how and when aspects of the social and physical environment may alter aging, health, and survival. For instance, in humans, social adversity such as social isolation early in life can have far-reaching effects on development and, subsequently, on adult health, reproduction, and survival

[13–16]. It is therefore likely that early-life environmental risk factors can impact adult dog health and aging, though we do not understand which environmental exposures are most impactful or if negative effects from early life are reversible. Additionally, older individuals are often more vulnerable to adverse exposures due to a decreased ability to recover from exposures ('resilience'), and a limited capacity for withstanding these exposures ('reserve') [17,18]. For example, older individuals who experience a stressor such as infection or surgery have more risk of adverse outcomes later in life [17]. Thus, the effects of the social environment could differ in strength across the lifespan, and this points to the importance of understanding how these can modify health and survival.

Here, we quantified the environment of companion dogs and examined if variation in the environment is associated with variation in health, disease, and mobility using data from the Dog Aging Project (DAP). We focused on these outcome measures because they all exhibit age-related changes (declines in health and mobility, and increases in disease) in humans and other animals. In particular, mobility is a key phenotypic signature of frailty–the age-related increase of vulnerability to adverse outcomes. Mobility is associated with overall health [19] and declines with age, suggesting that it can be used as a potential biomarker for the susceptibility to chronic disease in older populations [20]. We hypothesized that dogs living in homes with more factors associated with signatures of adverse environments (i.e., low social integration, less stable environments, and lower socioeconomic status) would be less mobile and in poorer health, and have more disease.

Results

Owner survey data from a large cohort of companion dogs

We used a large dataset of companion dogs enrolled in DAP, a community science research project that spans all 50 states in the U.S. [10]. Because our focus is environmental effects on adult health, we restricted our analysis to dogs older than 2 years, which is the age at which most dogs are considered full grown [21]. This restriction resulted in survey data for 21,410 dogs between the ages of 2 and 25.5 years old (Figure 1A), that weighed between 2-210 lbs (Figure 1B), that were roughly balanced between male and female dogs (Fig 1C), and between purebred and mixed-breed dogs (Figure 1D). Additional demographic information on the dogs and their owners can be found in Supplementary Information (Table S1, Figure S1).

We quantified measures of the social environment using data from a large Health and Life Experience Survey (HLES). The HLES is a large questionnaire that covers dog demographic characteristics, physical activity, household and neighborhood environment, dog behavior, diet, medications and preventives, health status, as well as owner demographic characteristics. For this study, we focused on a subset of 43 survey questions that captured components of the social environment (i.e. financial, environmental, social connection components; SI Table 2).

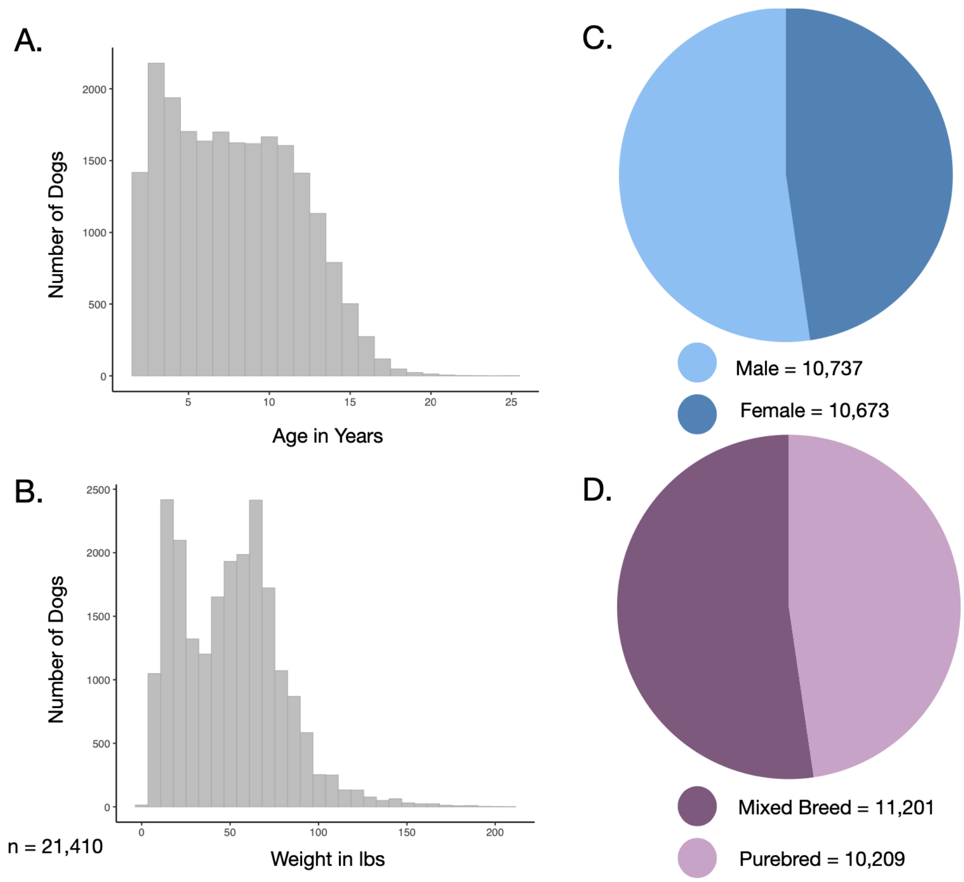

Figure 1. Demographic characteristics of dogs included in this study. Distribution of (a) age and (b) weight of dogs included in this study. The sample was roughly balanced by (c) sex and (d) mixed vs. purebred ancestry. Data are from the Dog Aging Project Health and Life Experience (HLES) Survey, 2019-2020.

Social, financial, and demographic factors

We first set out to reduce the data from the 43 survey questions into a smaller set of factors using exploratory factor analysis. We identified 5 factors that collectively explained 33.7% of the variance in the 43 variables (i.e., survey questions), and labeled the factors based on the survey questions that primarily contributed to each factor (loading >|0.4|): neighborhood stability (factor 1: 10.6% variance explained), income (factor 2: 9.7% variance explained), time with children (factor 3: 5.1% variance explained), time spent with other dogs (factor 4: 4.4% variance explained), and owner age (factor 5: 3.9% variance explained; Figure 2).

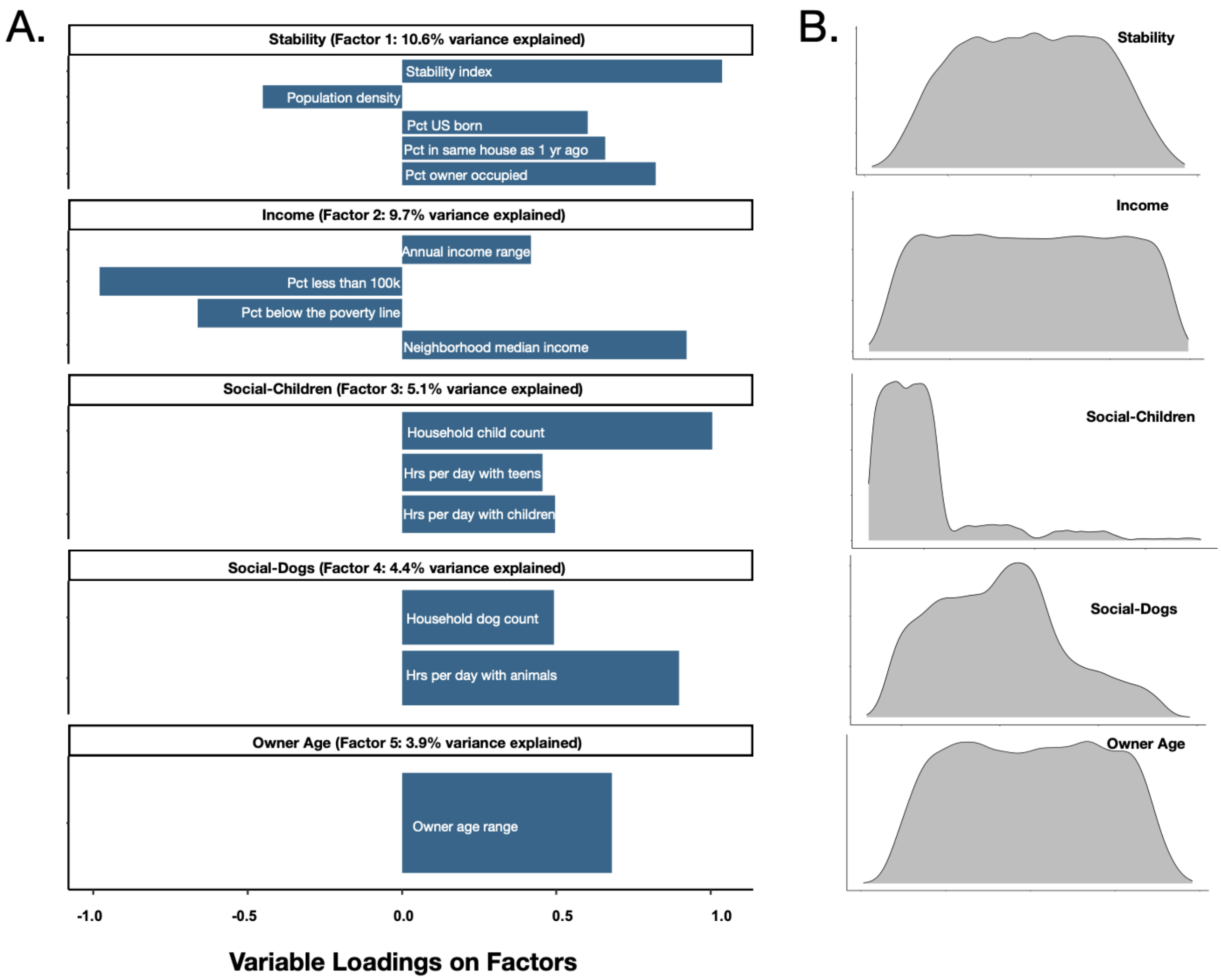

Figure 2. Five factors capture much of the social environmental variation in the Dog Aging Project cohort. (a) Exploratory factor analysis revealed five factors that together explained 33.7% of the variance in survey responses. We named each factor based on the survey questions that loaded the strongest onto each factor (loading > |0.4|). (b) Distribution of factor scores for individual dogs for each of the 5 factors in our sample.

Household environment is associated with dog health, disease, and mobility

Having identified five factors that explain much of the variation in dog social environment, we then investigated possible associations between these factors and three measures of dog health: owner-reported overall health, number of disease diagnoses, and mobility, while controlling for dog age and weight.

Overall Health

Owner-reported dog health was coded as an integer on a scale from 1-6, where 1 is "very poor health" and 6 is "excellent health". Since this is a relatively coarse measure of health, we first wanted to assess its internal validity to capture dog health. As expected, older and heavier dogs were rated as being in the poorest health (β_{age}= -0.421, $p \leq 2 \times 10^{-16}$; β_{weight}= -0.048, $p \leq 2 \times 10^{-16}$; Figure 3).

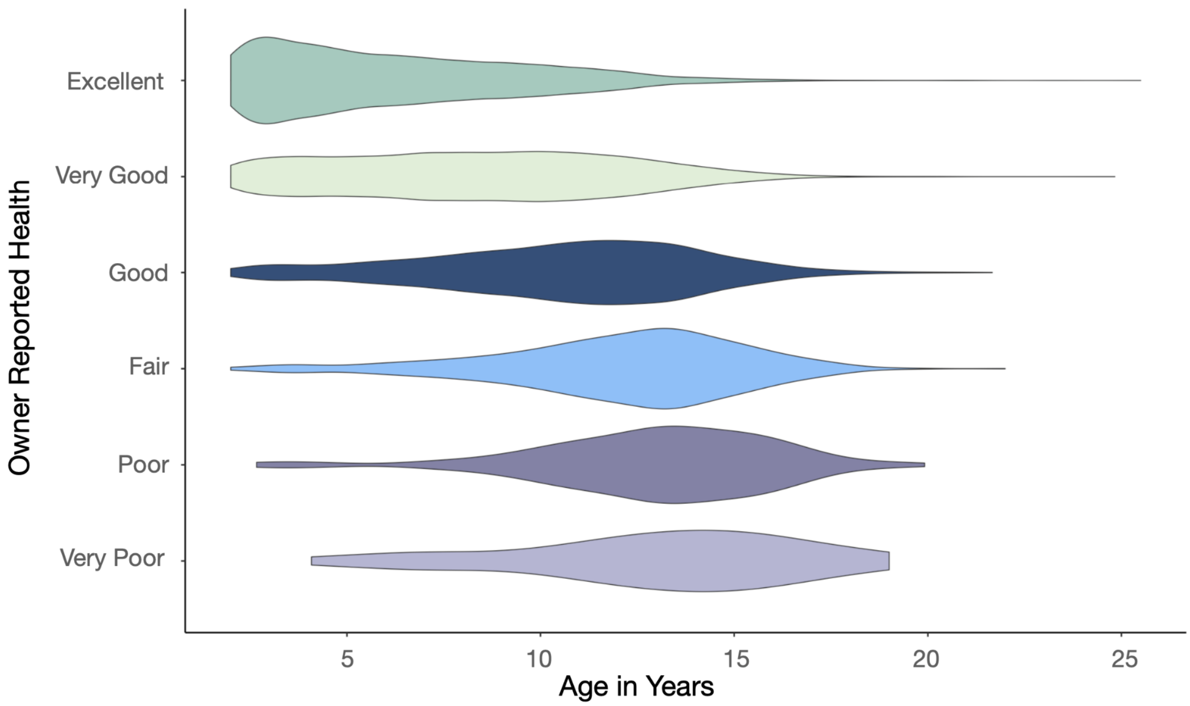

Figure 3. Owners-reported health is worse in older dogs. Dog age was significantly associated with owner-reported health, such that older dogs were reported to be in poorer health compared to younger dogs (β_{age}= -0.421, $p \leq 2 \times 10^{-16}$).

We then tested if any of the five social environmental factors were associated with health controlling for age and weight. We found that all five factors were significantly associated with health when controlling for age and weight. Higher income was associated with better health (β_{income} = 0.016, $p \leq 2 \times 10^{-16}$), indicating that owners of higher socioeconomic status had reported having healthier dogs, controlling for dog age and weight. Dogs with other and more dogs in their house were also rated as significantly healthier than dogs with fewer companions ($\beta_{social\text{-}dogs}$= 0.019, p = 0.003; Figure 4A). Dogs who lived in more stable households were reported to be healthier than those that did not ($\beta_{stability}$= 0.015, $p \leq 2 \times 10^{-16}$; Figure 4A). Dogs that lived in households with more children were reported to be less healthy than those with fewer children ($\beta_{children}$= -0.017, p = 0.003; Figure 4A). Finally, older owners reported their dogs were in better health compared to younger owners, controlling for dog age and weight (β_{owner_age}= 0.073, $p \leq 2 \times 10^{-16}$; Figure 4A).

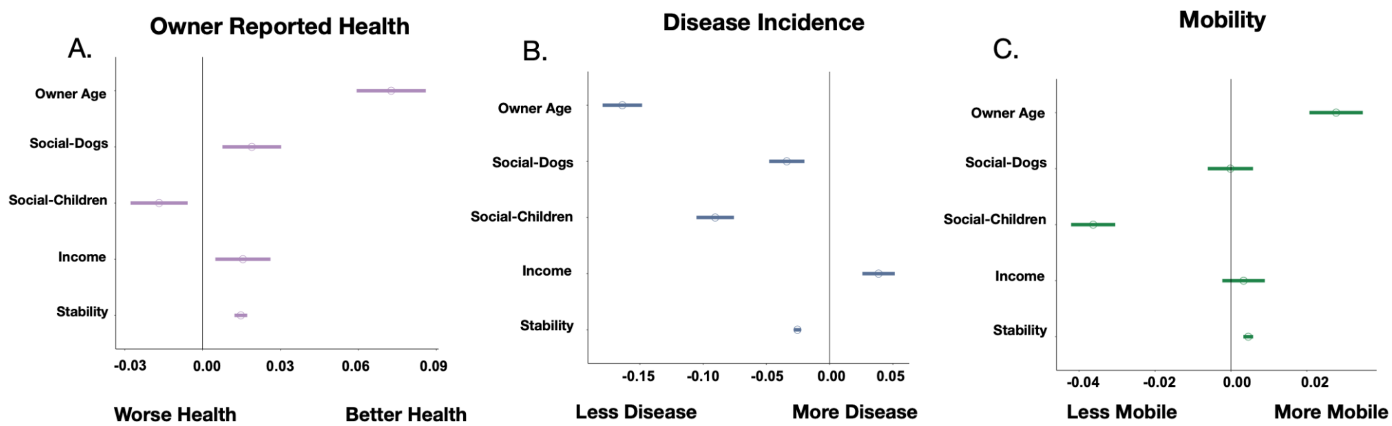

Figure 4. Social environment factors are associated with health, disease, and mobility in companion dogs. Effect sizes of each environmental factor on (a) owner-reported dog health, (b) disease prevalence (cumulative number of diseases reported), and (c) mobility (composite measure of activity level). Points depict the effect sizes (β) of each factor and lines represent the 95% confidence intervals.

Disease Diagnoses

Environmental associations with health were similar when we examined another measure that is associated with health: disease instances (total count of all reported diagnosed diseases; see methods). All five factors were significantly associated with disease instances, controlling for age and weight. Specifically, income was positively associated with the number of reported diseases, while stability, time with other dogs, owner age, and time with people were negatively associated with the number of diseases reported. Dogs in more stable households were reported to have fewer diseases ($\beta_{stability}$= -0.025, $p \leq 2 \times 10^{-16}$) as were dogs with older owners (β_{owner_age} = -0.164, $p \leq 2 \times 10^{-16}$). For the two measures of social integration and connectedness, we found that dogs with more conspecific companions as well as those with more people in the house had significantly lower numbers of reported disease ($\beta_{social\text{-}dogs}$= -0.034, $p = 1.96 \times 10^{-6}$, $\beta_{social\text{-}children}$=

-0.090, $p \leq 2 \times 10^{-16}$) (Figure 4B). Paradoxically, we observed a positive association between income and reported disease instances (β_{income}= 0.039, $p = 3.01 \times 10^{-9}$), which stood in contrast to the negative association between higher income and better owner-reported health.

Mobility

Given that mobility declines with age and can be used as a marker for exposures that might alter the rate of aging, we investigated associations between our environmental factors and composite mobility score that captured measures of physical activity duration, intensity, and frequency where higher mobility score equates to increased mobility (see methods for details on calculation of the composite mobility score). As expected, older dogs were less mobile (β_{age}= -0.12, $p \leq 2 \times 10^{-16}$; SI Table 3), and, when controlling for age, we found that dogs with higher mobility were in better health compared to less mobile dogs of the same age ($\beta = 0.35$, $p \leq 2 \times 10^{-16}$; SI Table 3). This suggests that, similar to humans, we find that in dogs, a more active lifestyle results in better health outcomes [22] (Lee et al.). The dog's social environment was also linked to mobility. Specifically, three of our five factors–stability, time spent with children and owner age–were significantly associated with dog mobility. Mobility was lower in dogs that lived in households with more children and older owners. ($\beta_{children} = -0.04$, $p \leq 2 \times 10^{-16}$, $\beta_{owner\ age} = -0.027$, $p = 1.15 \times 10^{-14}$ respectively). While mobility was higher in households that were more stable ($\beta_{stability} = 4.55 \times 10^{-3}$, $p = 4.52 \times 10^{-12}$: Figure 4B, SI Table 3).

<u>**Effects of environmental determinants of health can vary across the lifespan**</u>

To investigate whether associations between these factors and health, disease, and mobility vary across the lifespan, we extended each regression model to include an interaction term between the environmental factor with age (SI Figure 4). We found five significant interactions between dog age and our environmental factors on owner-reported dog health (SI Table 3). The positive association between household stability and dog health was strongest in the younger dogs, and weakest in older dogs (Figure 5A, $\beta = -0.007$, $p = 4.56 \times 10^{-9}$). Time spent with other dogs was more strongly associated with health when the dog was older rather than younger (Figure 5B, β= 0.022, p= 3.0×10^{-4}). We also found that owner age was more impactful for younger dogs compared to older dogs (Figure 5C, $\beta = -0.058$, $p \leq 2 \times 10^{-16}$). For older dogs, increased time spent with children was more impactful to overall general health than for younger dogs (SI Figure 6, $\beta = -0.02$, $p = 4.0 \times 10^{-3}$). Lastly, income was significantly associated with better owner-reported health and was more strongly associated with health in older dogs compared to younger dogs (Figure 5D, $\beta = 0.011$, $p = 0.04^{2}$).

We then tested for age-by-environment interactions associations on disease and mobility. We saw no significant interactions between environmental factors and age on disease instances. We did find a significant interactive effect between dog age and four environmental factors on mobility. First, a significant interaction between neighborhood stability and dog age on mobility revealed that neighborhood stability is most strongly associated with the mobility of younger dogs compared to older dogs (β= -0.002, p= 6.0×10^{-4}; SI Figure 5A; SI Table 3). Second, the effect of spending time with other dogs on mobility significantly interacted with dog age, where more time was considerably more important for the mobility of older dogs (β= -0.01, p= 8.2×10^{-4}, SI Figure 5B; SI Table 3). Third, the effect of spending time with children on mobility significantly interacted with dog age, where more time with children was more important for the mobility of older dogs (β= -0.007, p= 0.012, SI Figure 5C; SI Table 3). Lastly, having an older owner had a stronger effect on a younger dog's mobility (β= -0.014, p= 7.9×10^{-5}, Figure SI 5D).

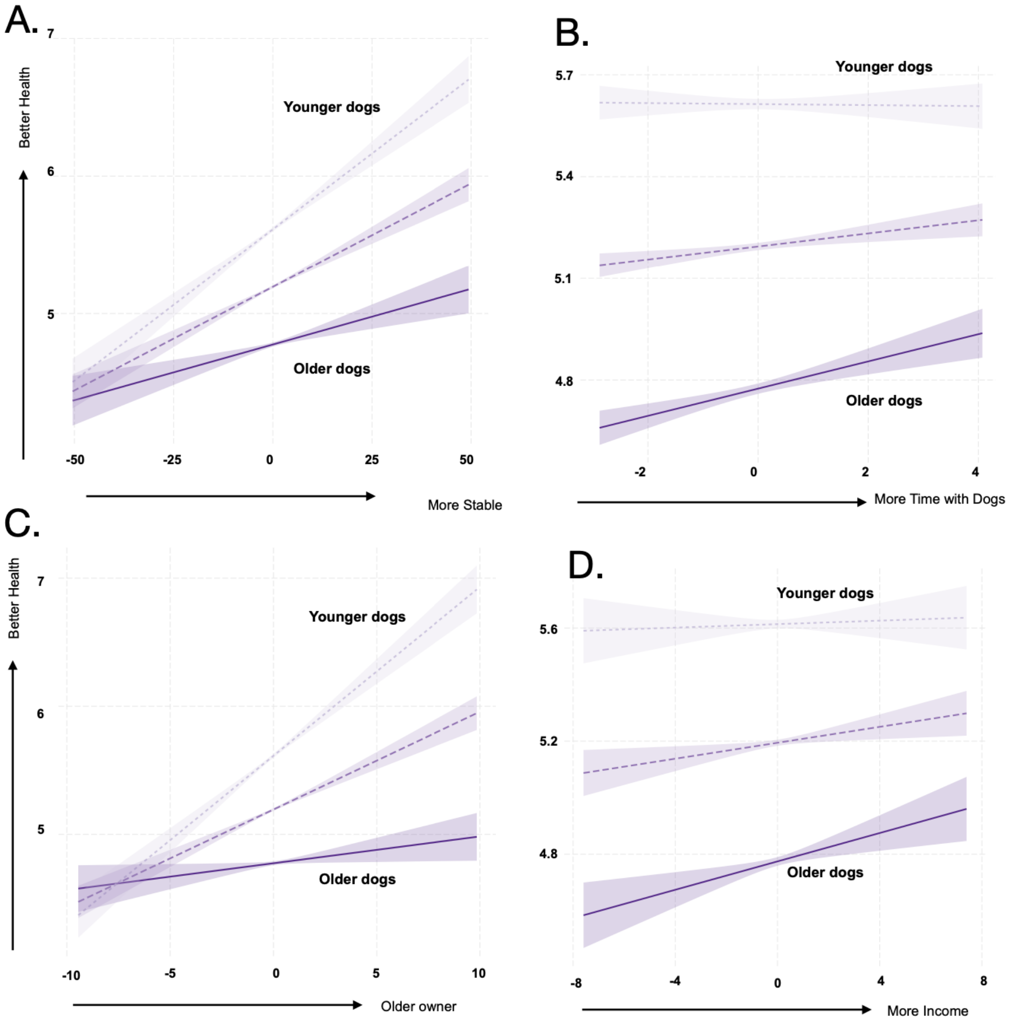

Figure 5. Age-dependent associations between health and environmental factors. (a) Household stability was more strongly associated with health for younger dogs compared to older dogs. (b) Dog sociability was more strongly associated with health for older dogs compared to younger dogs. (c) The factor of owner age was more strongly associated with health for younger dogs compared to older dogs. (d) Owner income was more strongly associated with health for older dogs compared to younger dogs. All graphs show predicted trends and 95% confidence intervals for a hypothetical population of dogs aged 4 (lightest purple), 7.9 (intermediate purple), and 11.8 (darkest purple) years old.

Complex pathways connecting social-environmental variables and health owner-reported canine health.

Environmental factors could have both direct and indirect effects on health. To examine these putative paths, we took an orthogonal modeling approach, structural equation modeling (SEM), which can capture more complex relationships among the environmental variables and health. We chose SEM because it has more flexibility, the capacity to represent complex relationships, and supports integration of results into broader theory [23]. To do so, we first organized our variables into latent factors that represent concepts known to fundamentally influence mammalian health and that were chosen to maximize the interpretability of the latent factors [24,25]. These variables were the output variables from the factor analysis on the social environmental dataset. The latent factor of health was informed by the same variables that we used as outcome variables in our linear models: health, disease instances, and physical activity (mobility). Our latent factor of finance was informed using measures from the census median income, percent living below the poverty line, and percent of households making less than $100,000 US per year as well as owner-reported annual income range. The latent factor of the local environment was informed by census-tract population density, neighborhood walk score, percent of individuals in the same household one year ago, and percent of the population that was born in the US. These variables were selected as measures that capture unique information about the dog's neighborhood environment. Lastly, our social latent variable was informed by the measurable variables of routine hours per day with dogs, children, and adults.

We generated two models to run; the first model (M1) describes direct paths from the latent factor of finance, environment, and social interactions to our outcome of health (SI Figure 2). The second model (M2) describes all direct paths indicated in M1 but with the added indirect path between finance and environment (SI Figure 3). These two models were both hypothesized to reliably describe the system and were tested for model fit before proceeding to the structural equation modeling analysis. Both showed good model fit according to established parameters [26] (M1: CFI = 0.838, RMSEA = 0.061, SRMR = 0.051, TLI = 0.797 ; M2: CFI = 0.835, RMSEA= 0.061, SRMR = 0.052, TLI = 0.796). Here we will present results for M2, which includes a pathway from the financial factor to the environmental factor, which is a better representation of the system given the established literature [27,28]. In humans we know that the quality of the environment is influenced by the finances of the household thus providing support for evaluating M2 as the generalizable model [29].

As with our linear models, we found evidence for all three latent variables associated with the latent factor capturing health. However, the relative importance of the latent factors varied: the effect of the social factor was ~5x larger than the effect of finance and the local environment on our health outcome ($\beta_{Social} = 0.107$, $\beta_{Finance} = 0.015$, $\beta_{Environment} = -0.023$). In line with our linear models, we found that increased income and more social interaction with humans and other dogs both predicted better health. In contrast, a more urban environment with less stability was associated with worse health, pointing to the complex relationship between overall health and the environment. These data capture a previously hypothesized indirect pathway from finance through the local environment that our linear models failed to identify, suggesting that the local environment might be an important mediator between finance and health.

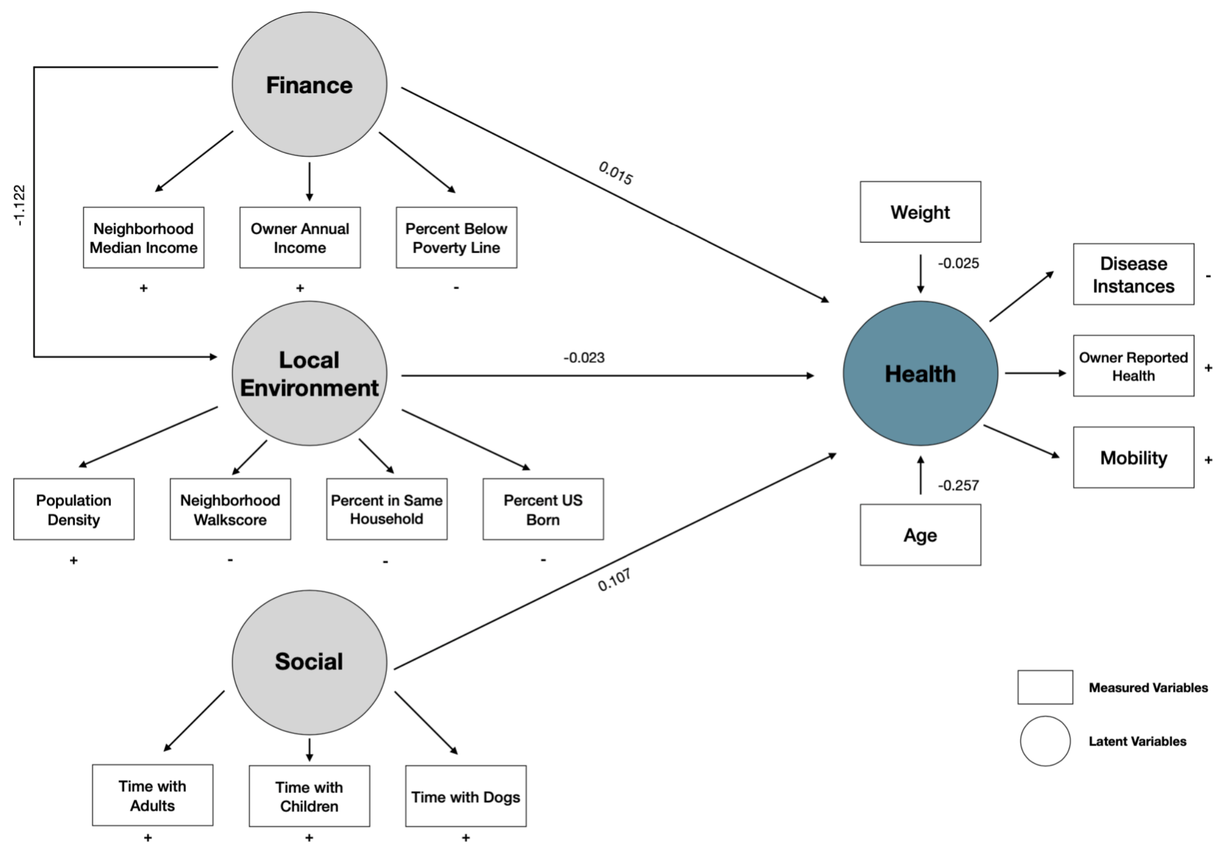

Figure 6. Structural equation modeling captures a complex network of environmental effects on health. A structural equation metamodel of how the social environment and its manifest variables can influence general health. Path coefficients explain effect sizes and directionality of each major path. Latent factors (circles) are informed by measured variables (squares) that were chosen via factor analysis, and the direction of the effect of each measured variable on the latent variables is indicated next to or below the variable (+: positive association; -: negative association).

Discussion

Using the largest observational dataset of companion dog environment and health, we identified measures of the social and physical environment that were associated with age-associated changes in health, mobility, and disease. Owner age was significantly positively associated with dog age, such that older owners were more likely to have older dogs. No factors were significantly correlated with dog weight, which we used as a coarse proxy for breed ancestry due to the large inter-breed differences in dog size [30,31]. Health, mobility, and disease measures were observed to change with age and, when controlling for age, these health metrics were also associated with environmental determinants. We also identified key changes in the environment that were associated with the health and mobility of dogs in an age-dependent manner. Unsurprisingly, age was the strongest predictor of health deficits. However, not all dogs exhibited the same age-related changes in health, disease, and mobility, and some of this inter-individual variation was linked to the environment.

Similar to humans, we found that measures of income and social connectedness (or companionship) predicted better health in dogs, although dogs from wealthier owners had more diagnosed diseases [32–34]. This counterintuitive association does not necessarily mean that dogs from wealthier owners had more diseases, especially given the fact that dogs from higher SES households were reported as healthier by their owners. Rather, this finding points to the role that money plays in how often dogs are diagnosed with illness across households while also generating new questions on the directionality of the relationship between income and health [24,35]. Dogs who live in households with wealthier owners might seek veterinary care more frequently, thus resulting in more disease diagnoses, even if the diseases are not more prevalent in higher SES households. Mobility was also associated with environmental factors and showed unique age-dependencies. This recapitulates what we see in humans, where individuals who live in lower income neighborhoods and experience adverse community-level factors, such as decreased access to green space, unequal resource distribution and access (e.g. healthcare or food), have poorer health outcomes [36,37].

We also found that younger dogs with older owners experienced better health outcomes compared to older dogs who had older owners. These data suggest the importance of understanding different lifestyle factors between owners of various age groups that could include career choice and living situation among other things. We also acknowledge that the distribution of dog age is highly non-random with respect to owner age which could also explain these results. We found that younger dogs who lived in less stable households were in worse health than older dogs who lived in stable homes, suggesting that, similar to humans, environmental adversity could play a particularly important role in early life [38–40]. Older dogs who lived in higher-income households were found to be in better health compared to older dogs in lower-income households, while the health of younger dogs was less impacted by income variation, suggesting that dogs may be less sensitive to economic adversity in early life [41,42]. Younger dogs' mobility experienced a large age-associated change when living in more stable neighborhoods compared to older dogs, suggesting that the benefits of living in a SES household while important across the lifespan is more helpful in earlier life. Older dogs who lived in less stable neighborhoods were much less mobile than older dogs in more stable neighborhoods, showing far worse mobility scores, suggesting that, similar to older people in lower socioeconomic neighborhoods, dogs experience a reduction in activity that could ultimately result in accelerated negative health outcomes [43,44].

All of our measures are not fully independent, suggesting a more complex network of paths among variables and thus how they impact health outcomes; and it is already known that health is influenced by a variety of predictors both directly and indirectly. Our SEM approach captured this complex network in one system. While the results of our SEM largely recapitulated our linear models, the SEM allowed us to propose a generalizable model for the environmental impacts on companion dog health and aging. In this particular model given the variables included, finance has a direct influence on health, environment has a direct influence on health, and there is an indirect path from finance through environment that influences health. This path is supported in the human literature, where we see that socioeconomic status dictates where a person will live and thus their environment as well as access to healthcare and both of these contribute to both positive and negative health outcomes [45,46].

While the strengths of this dataset include the large sample size (n= 21,410) of the study cohort and the depth of the HLES survey data, there are some limitations. Given the limitations of our observational study, the results of our analysis should not be used to influence medical decisions, behavioral, or policy changes related to the care of companion dogs. First, our dataset comprises both mixed-breed and purebred dogs, and genetic background and dog breed are both known to be associated with dog health and disease [30,47]. However, our results remained largely consistent when we examined pure and mixed breed dogs independently, as well as when we controlled for individual breeds based on owner-reported breed (SI Table 4, SI Table 5). The Dog Aging Project is currently sequencing the genomes of 10,000 dogs in the project [12], which will allow us to more accurately control for genetic background as well as identify putative gene-by-environment interactions that impact health, disease, or mobility. Second, all data in the HLES are owner-reported and can thus be affected by subjective error, bias, and/or interpretation of survey questions. The strong dog age association with all three of our outcome measures–health, disease incidence, and mobility–suggests that the survey is an instrument that, on average, accurately captures the variables we cannot objectively measure. The mobility metric is limited to only evaluating the dog's ability to perform activities rather than capturing frailty or age-related decline. Due to the limited nature of survey questions, we attempted to generate a composite metric that could roughly capture age-related decline without someone carrying out a defined physical examination of the dog. Our independently generated metric also had a strong association with health, suggesting that our composite measure was capable of capturing age-related decline appropriately within the context of the survey. This measure would be improved by an owner-independent measure or collaborative measure of frailty or musculoskeletal decline, with the goal of connecting activity level to general health outcomes and aging. In future research, we will draw on electronic veterinary medical records, molecular and immunological measures, and at-home physical tests to generate a more accurate measure of frailty in the companion dog. We found that owner age was significantly associated with our health-related outcomes, but why this pattern occurs is unknown. One possible mechanism is the link between owner age and dog activity levels, where a recent analysis in the Dog Aging Project found that older owners had more active dogs (Lee, Collins, et al), which is linked to better health. Further answers to this question could elucidate the complex relationships between owner age and our other factors and their associations with health. This suggests that as the Dog Aging Project continues, investigators will need to pay particular attention to owner age in our dataset, as it has a potential association with physical activity, cognitive function, and now perceived health. Lastly, we did not consider education level along with income in our SEM and we recognize the limitation placed on our analysis due to the average household income being well above the U.S average (US average: $67,521 in 2020, DAP average: $110,000-$119,999, [48]). This underscores the need to recruit a diverse set of participants to account for the variation of environmental exposures a dog is subject to [12].

Overall, our study provides further evidence for the strong link between the social environment and health outcomes, in a novel model for human aging – the companion dog. This highlights the need for more attention to the role of the social environment on health and disease and continued investigation of how each environmental factor can contribute to increased healthspan in both companion dogs and humans. As we move from cross-sectional to longitudinal data, we will gain much stronger inferential capacity to identify putative causal factors that affect trajectories of health and aging. These data provide us with an exciting opportunity to learn more about how our environment shapes our overall health and will drive new insights into what promotes overall longevity.

Methods

Study population

The Dog Aging Project (DAP) is a community science project that aims to understand how genes, lifestyle, and the environment influence aging and disease outcomes (Promislow et al. 2021, [49]. For this study we drew on the first phase of survey data released on May 10, 2021 from 27,541 dogs completed by owners on or before December 31, 2020. Study data were collected and managed using REDCap (Research Electronic Data Capture) electronic data capture tools hosted through the DAP [50,51].

Dog Aging Project survey data

The Health and Life Experiences Survey (HLES) includes a number of small surveys that cover dog demographic characteristics, physical activity, environment, dog behavior, diet, medications and preventatives, health status, and owner demographic characteristics. The DAP Environment Dataset contains geographically defined data from secondary sources pertaining to the dog's external environment. Environmental data are based on respondents' primary and (where applicable) secondary address information, provided in the HLES owner contact form. Environmental metadata was generated from the U.S. Census Bureau (2019) and the 2015-2019 American Community Survey 5-year Public Use Microdata Samples. Respondent addresses are geocoded and linked to existing data that characterize various aspects of the dog's external environment. 56,285 Environment data records (two per dog) are included in the 2020 Curated Data Release, reflecting all study participants who became DAP pack members on or before December 31, 2020, and released on May 10, 2021 (n=27,541). We selected only the data corresponding to the primary residence information for the year 2020. We removed participants under 2 years of age in order to only include dogs that are fully grown (American Animal Hospital Association life stages guidelines). After applying all these criteria, 21,410 dogs remained in the final dataset used for downstream analysis.

Mobility metric

We generated a mobility metric to capture the overall activity level of a dog. This metric was calculated by taking the z-score for each activity related variable in the HLES (pa_activity_level, pa_avg_activity_intensity, pa_on_leash_walk_frequency, pa_other_aerobic_activity_frequency, pa_physical_games_frequency, pa_avg_daily_active_total, and pa_on_leash_walk_avg_total) then assigning each dog a score which corresponded to the average of their z-score on the activity related variables.

Disease instances metric

The disease instance outcome metric was generated by summing the number of owner-reported diseases for each dog. We excluded diseases that did not have a severe effect on overall dog health as described in (Bray et al) and detailed in SI Table 6).

Stability metric

The stability metric is a combined variable that encompasses the percentage of the population that was in the same home 1 year ago, the percent of homes that are owned by the occupant, and the percentage of the population born in the United States. Each dog received a stability score calculated from taking the z-score of the variables and averaging them. These data were collected from the U.S. Census Bureau (2019).

Manual curation of variables

We excluded variables that were less than 98% complete and redundant variables that captured similar metrics (e.g., swimming/aerobic activity which can be captured by overall activity level).

Factor analysis

Exploratory factor analysis was performed on a set of social environmental variables selected based on previous literature and what we hypothesized described the social environment of a dog (n=43; SI Table 2). We performed the factor analysis using the Psych package (version 2.0.8) in R [52]. We used all default settings for fa() except nfactors = 5.

Linear modeling

We modeled our outcome variables as a function of all five factors, age, and weight, as well as the interaction between age and each factor (SI Figure 4). Because disease instances were based on count data, we modeled this outcome using a generalized linear model with a Poisson link function. Both health and mobility were run using a linear modeling approach. We subset our data to re-run these models for both pure and mixed-breed dogs as well as a model that included breed as a random effect (SI Table 4, SI Table 5, SI Figure 4).

SEM Confirmatory Factor analysis

Confirmatory factor analysis was performed on a manually curated set of variables for use in the structural equation modeling analysis. This analysis was used to verify the structure of our observed set of variables. This was performed using the cfa() function under the Lavaan package (version 0.6-9) in R [53].

Model Specification

The latent factor structure was defined based on known relationships in the literature studied primarily in humans ([54–57], SI Table 7). To specify the model for this study, we chose measured (manifest) variables based on the following criteria, they: 1) had clear individual interpretability, 2) were likely to capture different aspects of the latent factor, 3) were continuously distributed, 4) did not have missing data, and 5) together maximized sample variance as recorded in factor analysis. We defined the structural equation model (SEM) using the Lavaan (version 0.6-9) package in R[53]; structural equation meta-models and model syntax were adapted from guidelines for a graph-theoretic implementation of structural equation modeling [23]. Prior to implementation of the SEM, 13 variables were standardized to a mean of zero and standard deviation of 1 to account for scale differences among variables, and models were run using unweighted least squares. Two models were tested, with the difference being the addition of a pathway in model two from finance to environment. Fit for each of the two models was assessed through several metrics and associated cutoffs for "good" agreement between data and model: Root Mean Squared Error of Approximation (RMSEA, <0.08), Comparative Fit Index (CFI, >0.9), Standardized Root-Mean Squared Residual (SRMR, <0.08) and the Tucker-Lewis Index (TLI, >0.9) [26]. Comparative model fit was assessed using the corrected Akaike Information Criterion (AICc). Confirmatory factor analysis on both latent and indicator variables was conducted using the cfa function in R. All structural models were generated using the TidySEM and SEMplot packages in R [58][59].

Author Contributions

All authors contributed to writing – review & editing. B.M.M: conceptualization, methodology, data curation, writing – original draft, formal analysis, visualization, and project administration. L.B: conceptualization, methodology, data curation, formal analysis, writing – original draft and visualization. K.J: data curation, formal analysis, and visualization. G.A.D.: data curation, formal analysis, methodology and visualization. S.S: conceptualization. D.C.: data curation. M.D.: data curation. DAP consortium: resources and manuscript editing. N.S.M.: conceptualization, methodology, writing – original draft, funding acquisition, and project administration.

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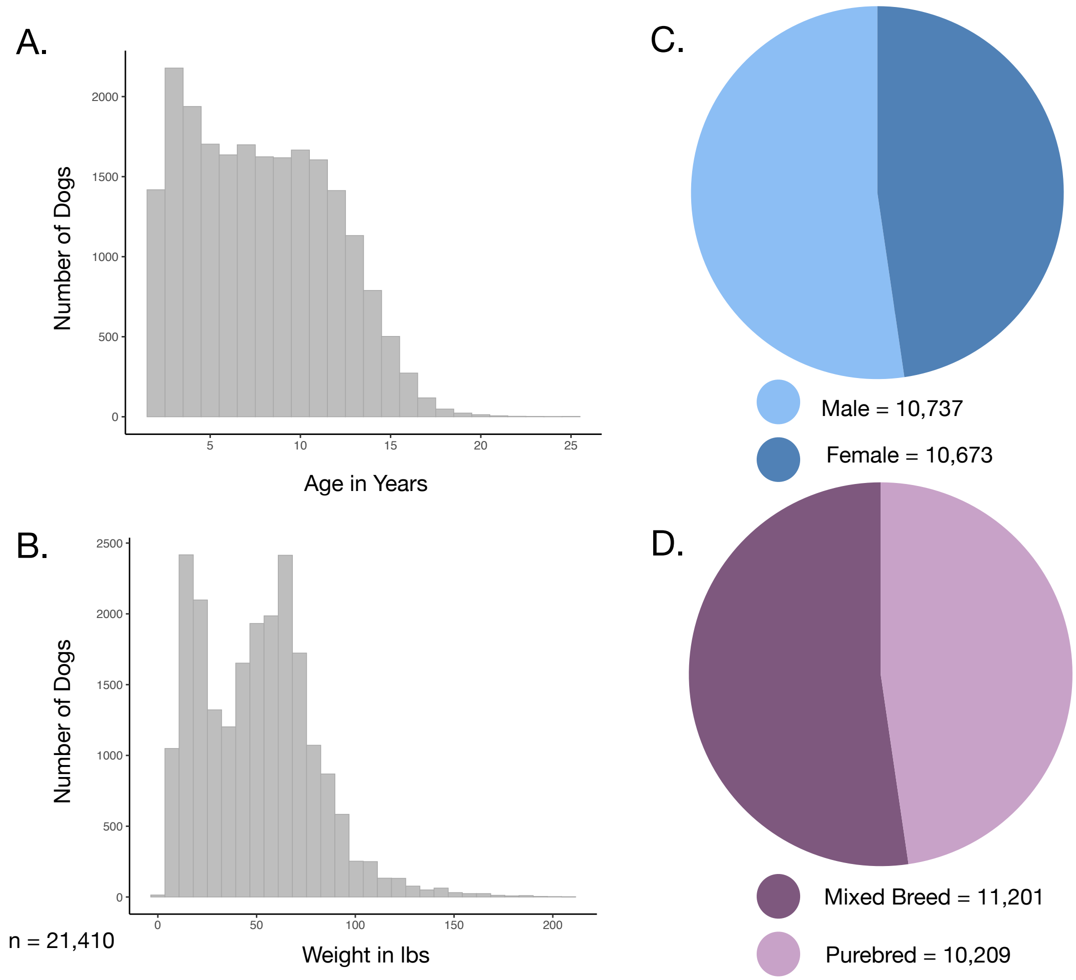

Figure 1. Demographic characteristics of dogs included in this study. Distribution of (a) age and (b) weight of dogs included in this study. The sample was roughly balanced by (c) sex and (d) mixed vs. purebred ancestry. Data are from the Dog Aging Project Health and Life Experience (HLES) Survey, 2019-2020.

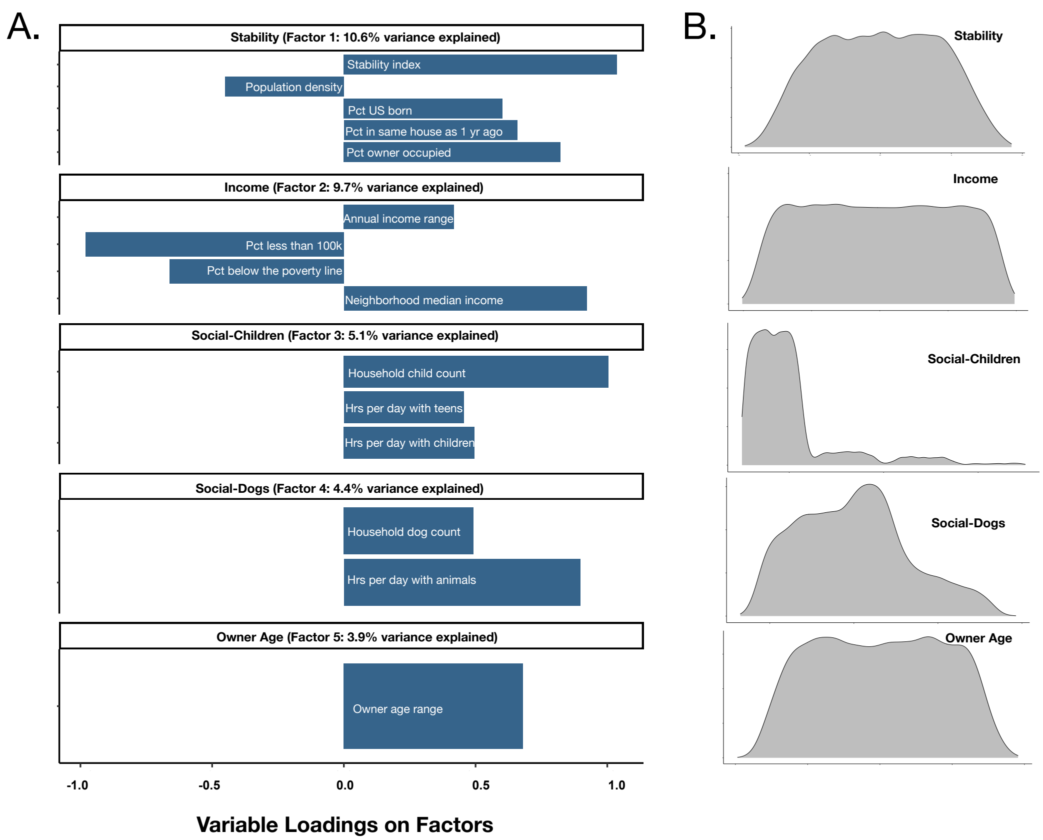

Figure 2. Five factors capture much of the social environmental variation in the Dog Aging Project cohort. (a) Exploratory factor analysis revealed five factors that together explained 33.7% of the variance in survey responses. We named each factor based on the survey questions that loaded the strongest onto each factor (loading > |0.4|). (b) Distribution of factor scores for individual dogs for each of the 5 factors in our sample.

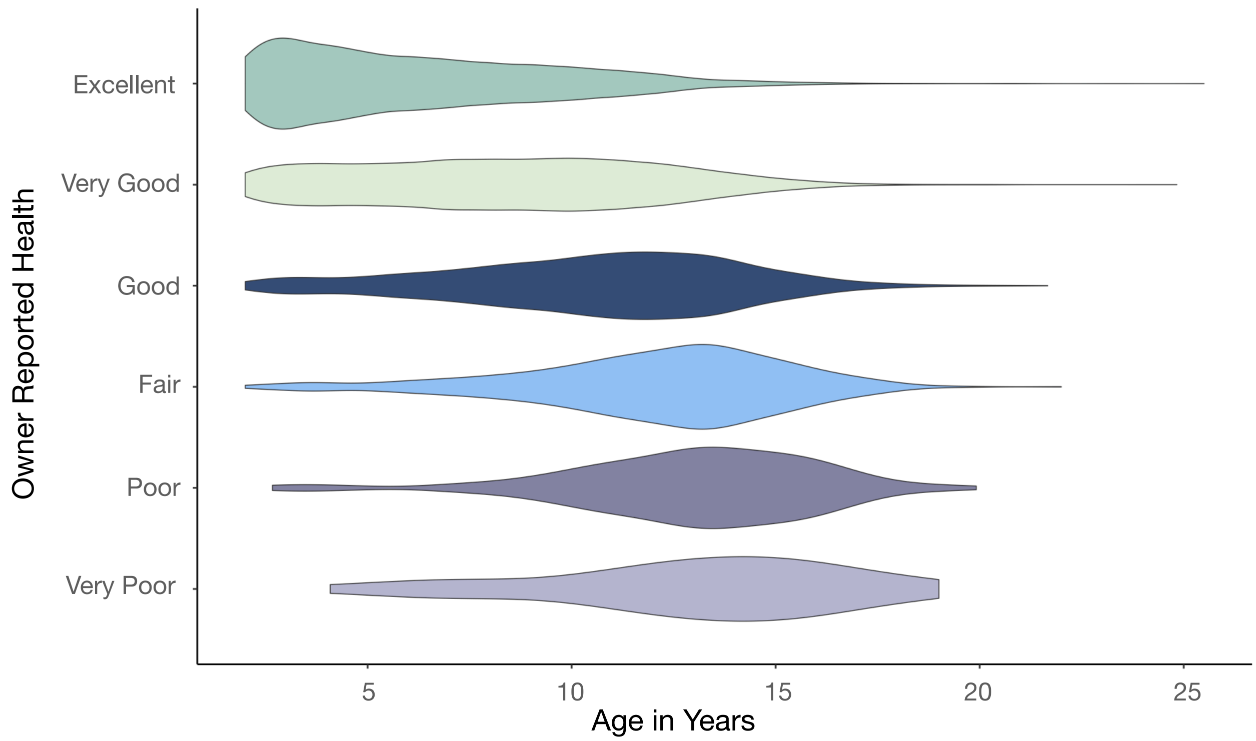

Figure 3. Owners-reported health is worse in older dogs. Dog age was significantly associated with owner-reported health, such that older dogs were reported to be in poorer health compared to younger dogs (β_{age}= -0.421, $p \leq 2 \times 10^{-16}$).

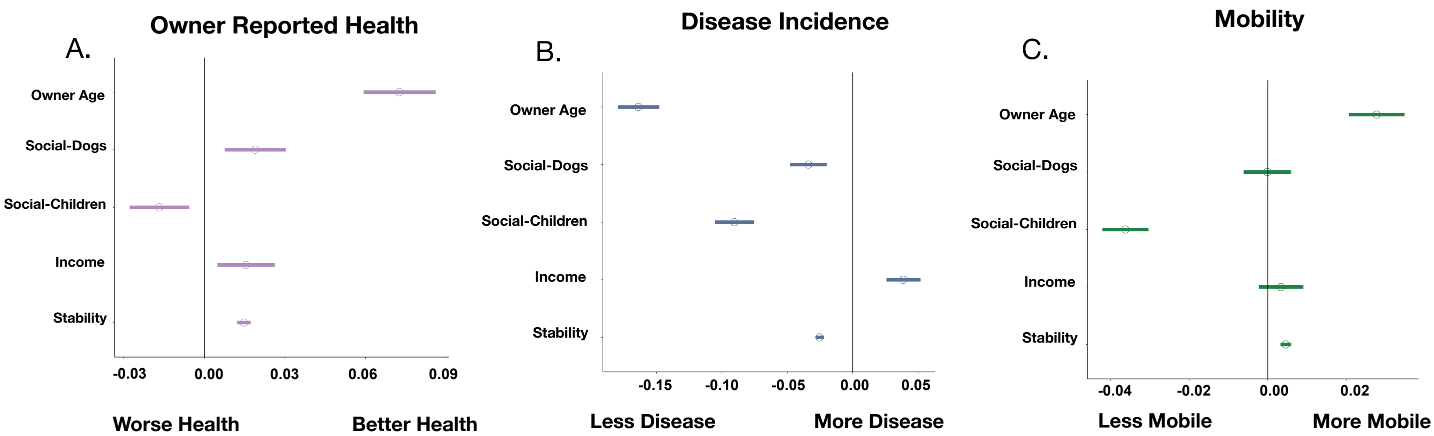

Figure 4. Social environment factors are associated with health, disease, and mobility in companion dogs. Effect sizes of each environmental factor on (a) owner-reported dog health, (b) disease prevalence (cumulative number of diseases reported), and (c) mobility (composite measure of activity level). Points depict the effect sizes (β) of each factor and lines represent the 95% confidence intervals.

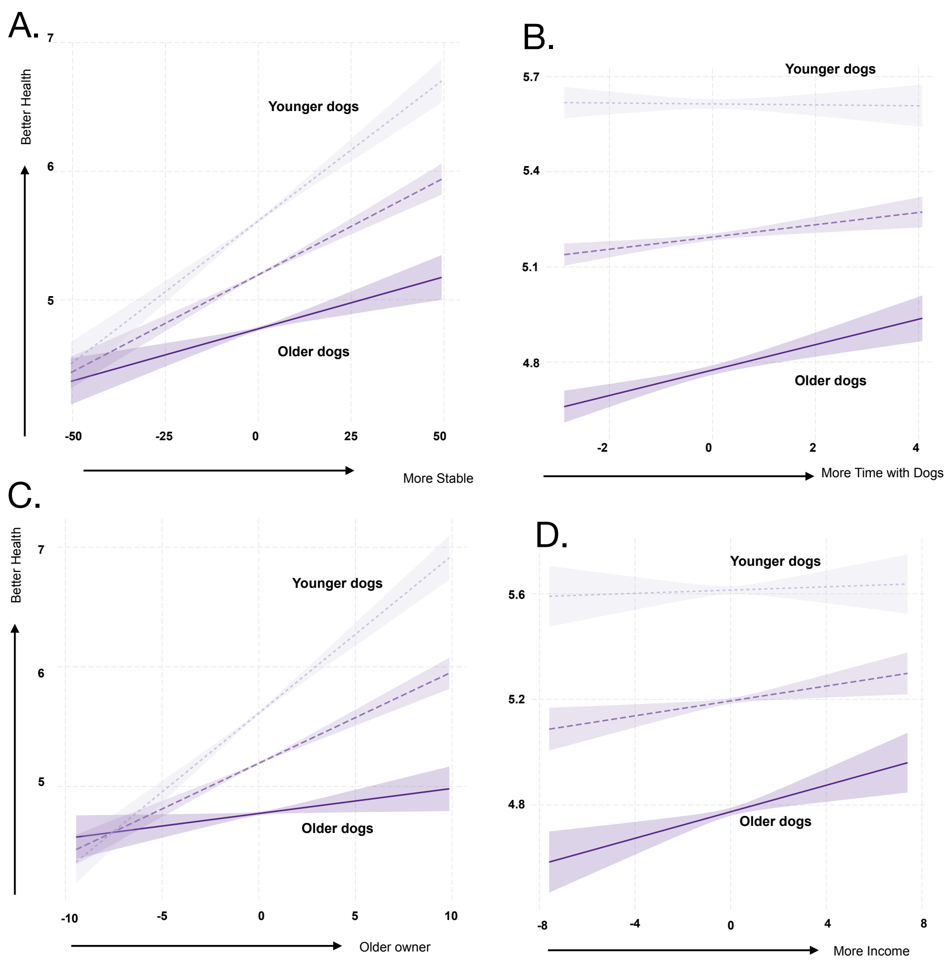

Figure 5. Age-dependent associations between health and environmental factors. (a) Household stability was more strongly associated with health for younger dogs compared to older dogs. (b) Dog sociability was more strongly associated with health for older dogs compared to younger dogs. (c) The factor of owner age was more strongly associated with health for younger dogs compared to older dogs. (d) Owner income was more strongly associated with health for older dogs compared to younger dogs. All graphs show predicted trends and 95% confidence intervals for a hypothetical population of dogs aged 4 (lightest purple), 7.9 (intermediate purple), and 11.8 (darkest purple) years old.

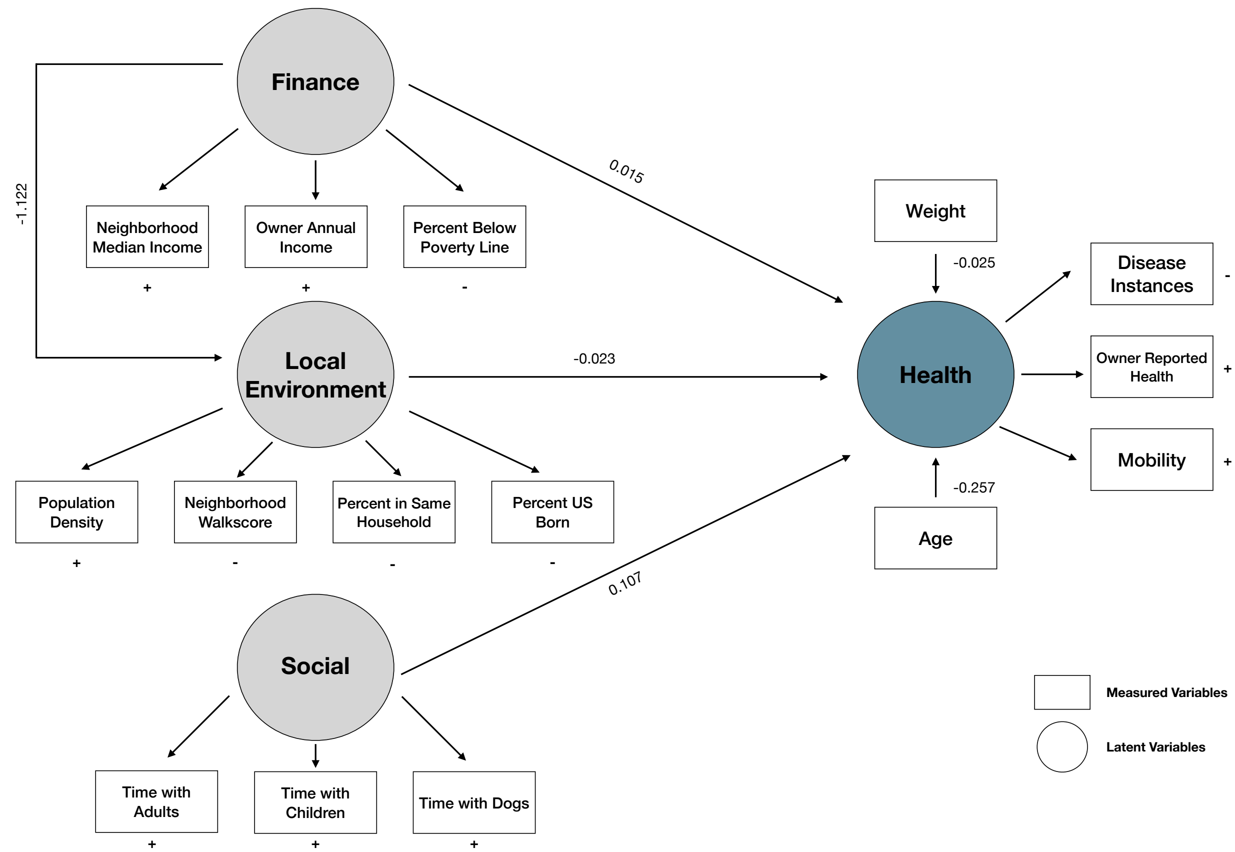

Figure 6. Structural equation modeling captures a complex network of environmental effects on health. A structural equation metamodel of how the social environment and its manifest variables can influence general health. Path coefficients explain effect sizes and directionality of each major path. Latent factors (circles) are informed by measured variables (squares) that were chosen via factor analysis, and the direction of the effect of each measured variable on the latent variables is indicated next to or below the variable (+ : positive association; - : negative association).