Telomeres as integrative markers of exposure to stress and adversity: A systematic review and meta-analysis

Gillian V. Pepper[1]

Melissa Bateson[1]

Daniel Nettle[1]*

1. Centre for Behaviour & Evolution and Institute of Neuroscience, Newcastle University, Henry Wellcome Building, Framlington Place, Newcastle NE2 4HH, UK

* To whom correspondence should be addressed: daniel.nettle@ncl.ac.uk

Version of May 11, 2018

Abstract

Telomeres have been proposed as a biomarker that integrates the impacts of different kinds of stress and adversity into a common currency. There has as yet been no overall comparison of how different classes of exposure associate with telomeres. We present a meta-analysis of the literature relating telomere measures to stresses and adversities in humans. The analysed dataset contained 553 associations from 142 studies involving 407,620 people. Overall, there was a weak association between telomere variables and exposures (greater adversity, shorter telomeres: r = -0.14, 95% CI -0.18 to -0.11). This was not driven by any one type of exposure, since significant associations were found separately for physical diseases, environmental hazards, nutrition, psychiatric illness, smoking, physical activity, psychosocial and socioeconomic exposures. Methodological features of the studies did not explain any substantial proportion of the heterogeneity in association strength. There was, however, evidence consistent with publication bias, with unexpectedly strong negative associations reported by studies with small samples. Correcting for possible publication bias attenuated the overall association substantially (r = -0.08, 95% CI -0.12 to -0.05). Most studies were underpowered to detect the typical association magnitude. The literature is dominated by cross-sectional and correlational studies which makes causal interpretation problematic.

Keywords: Telomeres, stress, adversity, meta-analysis

Introduction

Exposure to stress and adversity across the lifespan is associated with increased morbidity and mortality from many causes. This implies that stress and adversity have a lasting impact on general physiological processes 'under the skin'. However, until recently, there were few candidate markers of this accumulation of physiological damage. In the last 15 years, the idea that telomeres might serve such a role has rapidly gained in scientific popularity. In particular, telomeres offer a potential 'psychobiomarker' that integrates the organism's experience of psychological states, social and environmental contexts, as well as physical damage, into a common currency [1]. Telomeres are DNA-protein complexes that form protective caps on the ends of chromosomes, and are thought to play a key role in preserving chromosomal stability. At the cellular level, critically short telomere length leads to replicative senescence. At the whole organism level, average telomere length reduces with age. Thus, telomere length or attrition is a biomarker of ageing. Since the impact of stress and adversity may be to increase the individual's biological age (as opposed to chronological age), telomere measures offer a metric with which to assess Hans Selye's famous contention that: 'Every stress leaves an indelible scar, and the organism pays for its survival after a stressful situation by becoming a little older' [2].

Interest in using telomeres as a 'psychobiomarker' has grown rapidly, not just in human epidemiology, but also in animal ecology [3], and animal welfare [4]. In the human literature, telomeres have been studied in association with a wide range of exposure variables, including psychological stress [5], psychiatric illness [6], socioeconomic status [7], environmental pollutants [8], nutrition [9], smoking [10] and physical activity [11]. In several of these cases, the number of studies is sufficient that meta-analyses have appeared [12–20], often finding that telomere length is associated with the exposure, though weakly and variably. Reviewing the associations between telomeres and different exposures separately is appropriate to answer questions about that particular exposure. However, it loses sight of the most exciting promise of telomeres as a 'psychobiomarker': namely their potential to integrate the consequences of quite different kinds of stress and adversity into a common currency. Here, we set out to simultaneously review relationships of telomere length and attrition with all the *different* kinds of stress and adversity that are being studied.

Having a single integrated dataset allows several possibilities not available in separate, specialist meta-analyses. First, it offers a synoptic survey of the whole burgeoning field of telomere epidemiology. Second, it allows explicit comparison of different association strengths on the same scale (is the association of telomeres with psychological stress generally weaker or stronger than the association with physical disease, or exposure to pollution?). Third, it offers potential to address unanswered questions about telomere dynamics, such as whether, overall, early-life stressors are more strongly associated with telomere shortening than stressors experienced in adult life, as has been suggested [21]. Fourth, it leads to a large dataset within which some methodological issues of broad relevance can be examined. These include whether different tissue types produce different patterns, and whether the popular telomere-length measurement method, quantitative polymerase chain reaction (qPCR) [22] leads to generally weaker associations than other methods. This should be expected, since measurement error is generally found to be higher in qPCR than more intensive methods [23], and measurement error attenuates observed correlations.

With these objectives in mind, we carried out a systematic review and meta-analysis of the published literature on telomeres in relation to stress and adversity *in vivo*, to May 2016. Our searches involved the terms 'stress' and 'adversity' in combination with 'telomere'. We extracted all associations with telomeres reported in the papers, not just the associations of primary interest to the original authors. Our search strategy was not guaranteed to find the whole of the literature on telomeres and any

particular exposure variable, as authors may not always have used the descriptors we searched. However, our searches did produce the largest telomere literature dataset assembled to date, and we believe that though not exhaustive, it constitutes a good transect through the field of telomere epidemiology. We converted all associations to the common format of correlation coefficients, and aligned their direction, so that a negative correlation always indicates that greater stress or adversity is associated with shorter, or more rapidly shortening, telomeres.

Methods

Our methods are described in detail in our protocol, which was registered via the Open Science Framework prior to data extraction [24]. Raw data files and data analysis scripts are freely available in an online archive on the Zenodo repository [25].

Search strategy and inclusion criteria

We searched the Scopus and PubMed databases for papers including the words "stress" or "adversity", and "telomere". All records up to the date of the search (11th May 2016) were screened (n = 2404). We removed duplicates and then screened the remaining papers based on their titles and abstracts. In summary, this involved removing any papers that: 1) were not complete original research papers available electronically and in the English language; 2) used study organisms from outside the animal kingdom; 3) did not study whole organisms; 4) used genetically modified organisms; 5) experimentally applied non-naturalistic exposures in captive animals; 6) examined telomere length in transplanted tissues or organs; 7) were presented as concerning the physiological consequences of telomere length, rather than the correlates of exposures; 8) examined intergenerational questions (e.g. the effects of paternal infection status on offspring telomere length); or 9) used the same data set, or participants reported in a previously recorded paper, to address a exposure-telomere relationship we had already recorded (where this occurred, the first-recorded association was the one used). This led to a candidate set of 283 papers.

Although our searches were based on the terms "stress" and "adversity", we extracted all reported associations with potential exposure variables found in the papers returned by our search, whether or not they were the focus of the study's stated objectives. This included control variables and covariates as long as sufficient detail was provided of them. Thus, our search strategy consisted of finding papers on the subjects of stress/adversity and telomeres, and sampling the full variety of exposures that fell out of the papers captured by the search.

Association format

Associations could only be used if convertible into a correlation coefficient, the common association metric that we chose based on initial scoping and piloting. Standard conversion formulae were used [26–29], and the conversion algorithms are provided in the data repository (https://doi.org/10.5281/zenodo.1189538). Usable statistics comprised: correlation coefficients, standardised βs from regression models; unstandardized βs where standard deviations for the independent and dependent variables were provided; unstandardized betas from regressions with dichotomous independent variables where the standard deviation of the dependent variable was provided; F-ratios from ANOVAs comparing two groups; t-statistics; Cohen's *d* or standardised mean difference statistics; group means with standard errors; and group means with standard deviations. Where several alternative analyses were presented, we chose the one closest to the raw data, to maximise comparability between studies that included different control variables in multivariate models. For 122 papers (43% of candidates), the reported information was not sufficient to create a usable correlation coefficient.

Data extraction

Data from 218 associations (30%) were extracted independently by both GP and DN. Any differences were identified and resolved as part of the process of refining our data extraction methods. The remaining associations were extracted by either GP or DN, with GP checking and correcting the whole dataset after extraction. As well as the statistics necessary for association conversion, we extracted bibliographic information, sample size, and a series of classificatory variables as described in table 1. The life stage prior to birth was classed as embryonic, and the life stage prior to sexual maturity (4745 days for human females / 5,110 days for males [30]) was defined as childhood. We also identified any associations that could be considered sub-parts of others, for example, separate-by-sex associations where the combined association was also reported, or associations between telomeres and sub-scales where the association with the main scale was also reported. We did not include these sub-scale and sub-group associations in our final analyses, though they are included in the data set, in case they are of interest to others.

Final dataset

The extracted data are the 'unprocessed data' file in the data archive. We categorized exposure variables *a posteriori*. We created both broad categories (11 categories plus 'Other', as specified in table 1), and fine ones, for example using specific diseases rather than 'physical disease', and specific types of psychosocial or socioeconomic measures (35 fine categories, plus 'Other'). No categories (broad or fine) were created if the number of independent associations (i.e. from different papers) was less than 3 prior to the exclusions described below.

The final dataset analysed here ('processed data' file) differs from the unprocessed data in a number of regards. We excluded 19 associations from non-human animals, since we deemed these too few (typically one study per species) for further analysis. We excluded the 132 associations based on subscales and sub-groups of other associations present in the dataset. Finally, we excluded 14 associations where the exposure variable was a medical treatment—the designs of these studies generally confounded effects of the treatment on telomeres with effects of the disease the treatment was for.

For analysis, we reversed 152 correlations in sign to align all correlations into the same direction; that is, so that a negative correlation indicates that greater stress and adversity is associated with short (or shortening), rather than long (or lengthening), telomeres. For example, we reversed correlations where the exposure variable represented higher socioeconomic status, better sleep, or more parental care, to align them with the more common case where a higher value of the exposure indicates more adversity (e.g. disease, psychosocial stress, pollution exposure). The case of nutritional variables was challenging, since it was often unclear if higher consumption was predicted to be positive or negative in effect. We therefore reversed the direction of all nutritional variables, so that a negative correlation means a deficit in consumption is associated with short telomeres. This had little impact on the results, since the overall associations for many nutritional categories were null. The categories with the strongest associations—fruit, legumes and vegetables, and vitamins—are cases that clearly conform to our assumed 'more is better' principle.

Data analysis

Data were meta-analysed in R [31] using the 'metafor' package [32]. Since the dataset includes multiple associations from the same studies, we used multilevel meta-analytic models containing nested random effects of association and study. The full analysis script is included in the data archive.

Results

Description of dataset

The final data set consisted of 553 associations from 142 unique studies of human participants (associations per study 1-43, mean 3.89). One hundred and seventy-three associations were reported by the study authors as being statistically significant, 354 as null, and 26 were not reported as either null or significant. **Error! Reference source not found.**Table 1 describes the studies and associations included. Typically, they used qPCR to measure telomeres; did so in leucocytes or whole blood; and were correlational and cross-sectional rather than longitudinal in design. This meant that the telomere variable was overwhelmingly a single measure of average length, rather than the rate of attrition. Associations with both length and attrition are included in our main analyses, though we test whether study design moderates observed correlations. The studies were mostly of adults, and mostly related to sources of stress and adversity that were experienced in adulthood.

Overall association and publication bias

The distribution of correlations between exposure measures and telomeres is shown in figure 1a. Though the modal correlation was close to zero, the distribution was asymmetric, with 405 correlations less than zero (indicating that greater adversity is associated with shorter telomeres), and only 147 greater than zero (indicating that greater adversity is associated with longer telomeres). The majority of correlations fell into what is conventionally defined as a 'small' effect size ($-0.2 < r < 0.2$), with 298 small negative correlations and 134 small positive ones. There were 108 instances of a moderate or large negative association, against just 13 of a moderate or large positive association. In a simple meta-analytic model with no moderators, the overall estimate of association was conventionally small and significantly negative ($r = -0.14$, 95% CI -0.18 to -0.11, $p<0.001$). Thus, greater adversity was correlated with shorter telomeres. There was a large degree of heterogeneity between associations ($Q_{552} = 12870.18$, $p<0.001$), and most of the variability (87%) resided at the between-study level rather than between associations from the same study.

The estimated association may have been affected by publication bias. The funnel plot of correlation coefficient against sample size showed the inevitably broader range of observed correlations at smaller sample size. However, the funnel was asymmetric, with strongly negative correlations appearing at small sample sizes, but rather few of the strongly positive correlations that ought also to be expected in these small studies (figure 1b). This pattern is consistent with differential non-publication of small studies that have null results or results against expectation. To test this formally, we divided sample sizes into four bins (fewer than 100, 101-250, 251-1000, more than 1000; these bins represent approximate quartiles of sample size). We then added sample size bin to the meta-analytic model as a moderator (this is the conceptual equivalent of the Egger test for the multilevel model situation). Sample size bin explained a significant portion of the variability ($Q_3 = 31.644$, $p<0.001$). In particular, associations with sample sizes of 'fewer than 100' were significantly more negative than the reference category of more than 1000 ($B = -0.18$, 96% CI -0.25 to -0.10, $p < 0.001$; figure 1c). The other sample size bins did not differ significantly from the reference category of 'more than 1000'. Because the trim and fill methodology for imputing the associations assumed to be missing is not defined for the multilevel situation, we performed all subsequent analyses both on the whole dataset and, in parallel, on only the 376 correlations from 79 studies where the sample size was greater than 100 (henceforth the 'reduced dataset'). The central estimate from the reduced dataset was considerably weaker than the full dataset ($r = -0.08$ compared to $r = -0.14$, 95% CI -0.12 to -0.05, $p<0.001$), with substantial heterogeneity ($Q_{375} = 4550.48$, $p < 0.001$), and again, most of the variation (88%) residing between studies, rather than between associations within studies.

Table 1. A summary of the characteristics of the studies and associations included in the analysis.

	Unique studies	Associations	Percent of associations
Adversity type			
Physical disease	55	98	17.72
Environmental hazard exposure	8	11	1.99
Nutrition	10	87	15.73
Psychiatric illness	35	82	14.83
Smoking	35	44	7.96
Alcohol consumption	11	15	2.71
Sleep quality	6	24	4.34
Physical activity	11	16	2.89
Psychosocial adversity	42	99	17.90
Parental care	4	8	1.45
Socioeconomic status	22	46	8.32
Other	12	23	4.16
Techniques			
qPCR	113	474	85.71
Southern blot	24	55	9.95
Flow-FISH or Q-FISH	6	21	3.80
TelSeq	1	3	0.54
Tissues			
Buccal cells	7	11	1.99
Blood / White blood cells	130	533	96.38
Other tissues	6	9	1.63
Life stage at exposure			
Embryonic exposure	8	12	2.17
Childhood exposure	23	77	13.92
Adulthood exposure	123	460	83.18
Not reported	3	4	0.72
Life stage at telomere measurement			
Embryonic	3	5	0.90
Childhood	10	53	9.58
Adult	127	489	88.43
Not reported	3	6	1.08
Sex of sample			
Male	18	71	12.84
Female	29	93	16.82
Both	100	389	70.34
Study design			
Cross-sectional	136	515	93.13
Longitudinal	7	38	6.87
Correlational	139	542	98.01
Experimental	6	11	1.99
Total	**142**	**553**	

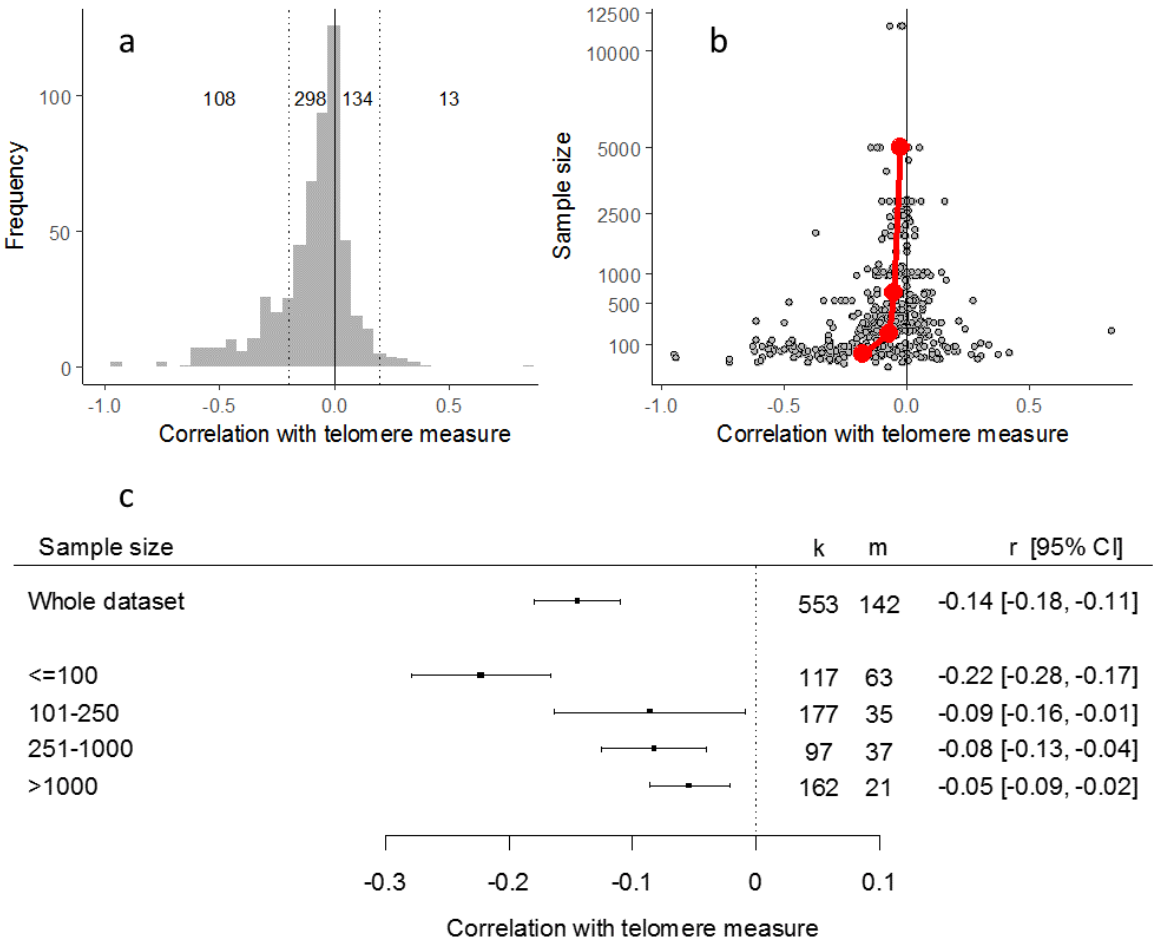

Figure 1. Features of the meta-analysed data. a. The distribution of correlations between exposures and telomere length or telomere attrition in the 553 associations of the whole dataset. The numbers give the number of correlations in the moderate or strong negative (r <= -0.2), small negative (-0.2 < r < 0), small positive (0 < r < 0.2), and moderate or strong positive (r >= 0.2), effect size bins respectively. b. Funnel plot of sample size against observed correlation between telomere measure and exposure variable. Red points represent the mean correlation observed for sample sizes in bins fewer than 100; 101-250; 251-1000; and more than 1000. c. Forest plot of central correlation estimate and 95% confidence interval for the whole dataset, and separately for the four bins of sample size. The *k* column represents the numbers of correlations and the *m* column the number of unique studies.

Categories of exposure

We divided our exposure variables into 11 broad categories plus 'other' and added category of exposure to the meta-analytic model. Exposure category did not explain a significant amount of the heterogeneity (whole dataset: $Q_{11} = 17.92$, $p = 0.08$; reduced dataset: $Q_{11} = 15.00$, $p = 0.18$), suggesting that type of exposure, at this coarse level, does not explain a substantial amount of the variation in association between telomeres and exposure variables. We also fitted separate meta-analytic models to the correlations in each of the 12 broad exposure categories (figure 2). In the whole dataset, the central estimate of association was numerically negative for all categories, and significantly so for all except alcohol, sleep, parental care and 'other'. In the reduced dataset, environmental hazard additionally became non-significant, though there were few remaining studies. In some categories, excluding small studies markedly reduced the central correlation estimate, for example: psychosocial (from $r = -0.16$ to $r = -0.06$); psychiatric illness (from $r = -0.12$ to $r = -0.07$); and physical disease (from $r = -0.16$ to $r = -0.11$). In other categories, such as smoking, socioeconomic status, and physical activity, excluding the smaller studies had minimal effect on the (already weaker) central correlation estimates.

We also created a finer 36-category classification of exposures. For example, we considered each disease, condition or psychosocial construct for which multiple independent data points were available separately. The fine categories explained a significant amount of heterogeneity in both the full ($Q_{35} = 59.43$, $p < 0.01$) and reduced datasets ($Q_{32} = 57.54$, $p < 0.01$; note only 33 of the 36 fine categories were represented in the reduced dataset). We took smoking as the reference category as this association is estimated with good precision due to a large number of studies. Compared to smoking, in the full dataset, we found significantly stronger negative correlations for environmental hazards (B = -0.16, 95% CI -0.26 to -0.05, p = 0.005) and lower vitamin consumption (B = -0.22, 95% CI -0.397 to -0.07, p = 0.003). Parkinson's disease gave a significantly weaker negative correlation than smoking (B = 0.25, 95% CI 0.06 to 0.45, p = 0.01). In the reduced dataset, HIV & AIDS and poor parental care gave significantly stronger negative correlations than smoking (B = -0.14, 95% CI -0.25 to -0.03, p = 0.02 and B = -0.14, 95% CI -0.27 to -0.01, p = 0.04 respectively). Parkinson's disease and low carbohydrate consumption gave significantly weaker ones (B = 0.40, 95% CI 0.20 to 0.60, p < 0.001 and B = 0.09, 95% CI 0.00 to 0.19, p = 0.04 respectively). We also considered whether the associations in the 36 fine categories differed significantly from zero when considered separately (figure 3). In the full dataset, smoking, anxiety, cardiovascular disease, depression, diabetes, lower education, environmental hazards, lower fruit, legume and vegetable consumption, lower income, lower meat, fish and egg consumption, lower physical activity, PTSD, schizophrenia, stress, traumatic experience, and lower vitamin consumption were all significantly correlated with shorter telomeres. Restricting consideration to the reduced dataset, the associations remaining significantly less than zero were: smoking; anxiety; cardiovascular disease; diabetes; education; lower fruit, legume and vegetable consumption; lower meat, fish and egg consumption; and lower physical activity. In addition, the parental care correlation (receiving poorer care associated with shorter telomeres), which had not been significantly different from zero in the full dataset, became so in the reduced dataset.

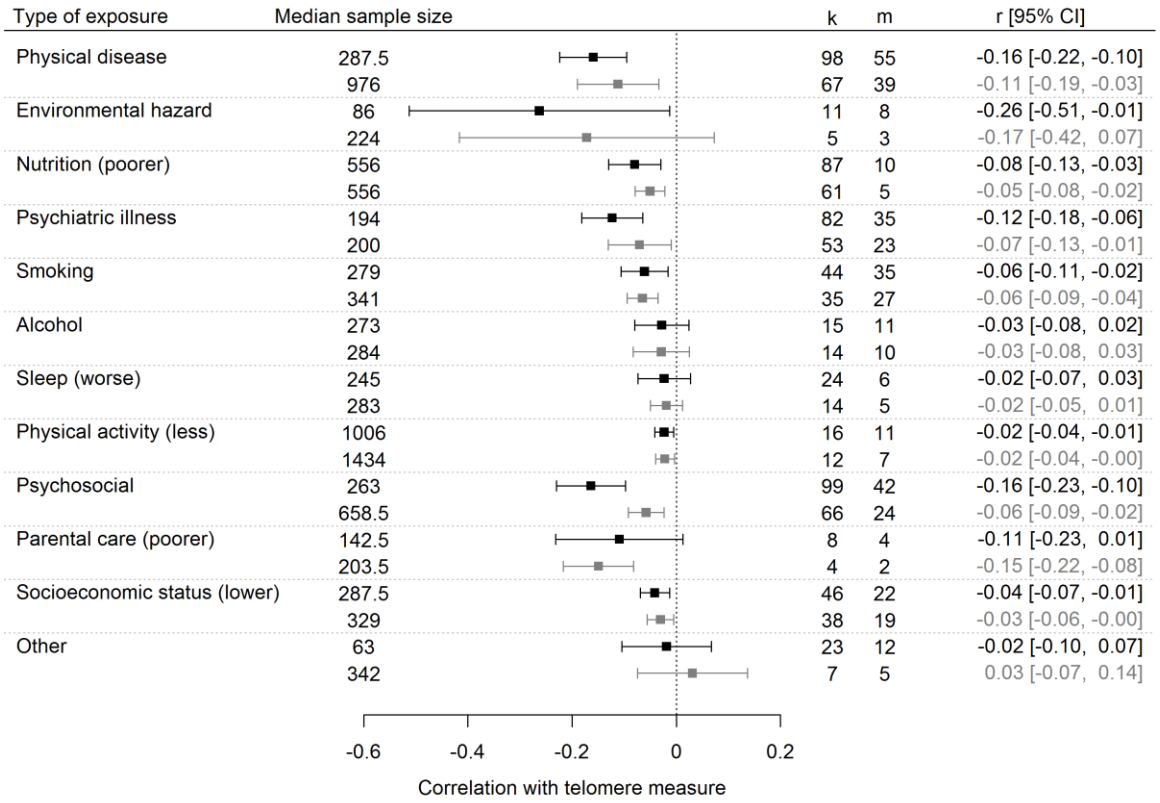

Figure 2. Forest plot showing central estimates of correlation and 95% confidence intervals from meta-analytic models for each broad category of exposure separately. For each category, the first row represents the full dataset, and the second, the reduced dataset (only sample sizes of 100 or greater). The *k* column represents the numbers of correlations and the *m* column the number of unique studies.

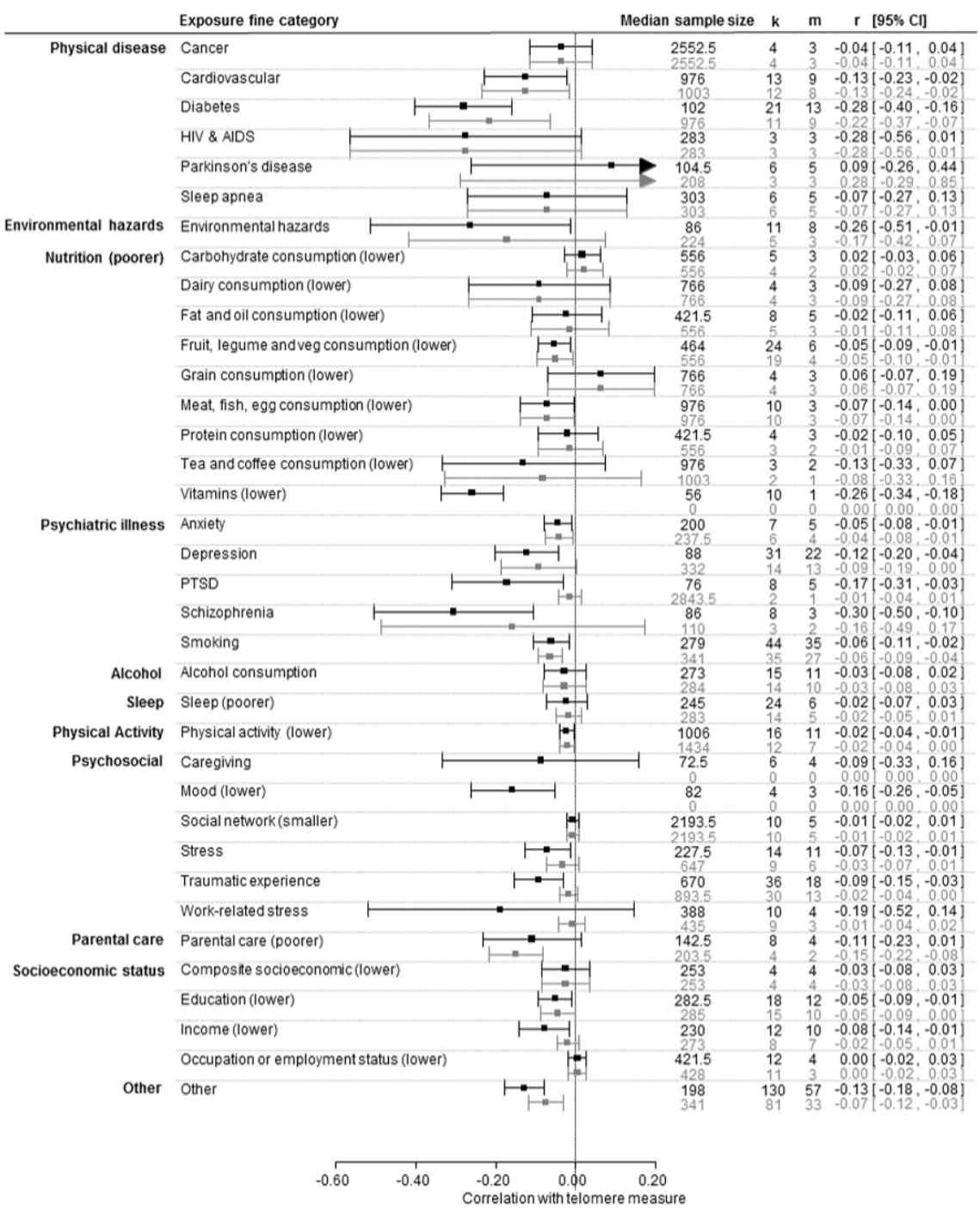

Figure 3. Central estimates of correlation and 95% confidence intervals for separate meta-analytic models for each fine category of exposure. For each fine category, the first row represents the full dataset, and the second, the reduced dataset (only sample sizes of 100 or greater). The *k* column represents the numbers of correlations and the *m* column the number of unique studies. Note that all nutritional fine categories are treated as if more of the food category equalled better nutrition, and hence less adversity. Fine categories are grouped by broad category.

Other moderators

We tested whether a series of different methodological features explained any significant amount of heterogeneity between associations (table 2; we were unable to simultaneously include exposure category and all the methodological variables in a single model for reasons of statistical power). There was no strong evidence that the life stage of the participants (either at exposure or telomere measurement), the study design, the type of tissue, or the sex of the participants explained a significant amount of the heterogeneity, either in the full or reduced datasets.

Table 2. Tests of potential moderators of the association strength between exposure variables and telomere length or telomere attrition. For reasons of statistical power, potential moderators were added one at a time.

	Whole dataset		Reduced dataset	
Moderator	Test of moderation	p-value	Test of moderation	p-value
Longitudinal design	$Q_1 = 0.06$	0.80	$Q_1 = 0.01$	0.97
Experimental study	$Q_1 = 2.91$	0.09	$Q_1 = 3.26$	0.07
Life stage at exposure	$Q_3 = 0.40$	0.94	$Q_3 = 0.83$	0.84
Life stage at telomere measurement	$Q_3 = 1.98$	0.58	$Q_3 = 5.70$	0.13
Tissue type	$Q_2 = 1.76$	0.42	†	
Technique	$Q_3 = 9.78$	0.02*	$Q_2 = 0.11$	0.94
Sex	$Q_2 = 0.16$	0.92	$Q_2 = 0.89$	0.64

* $p < 0.05$

† Cannot be tested because there is only a single study in any tissue type other than blood / white blood cells in the reduced dataset.

There was some evidence for variation in association strength by telomere measurement technique in the full dataset. Fluorescent in situ hybridization (FISH) techniques produced significantly stronger negative associations than the dominant qPCR technique (B = -0.22, 95% CI -0.36 to -0.07, $p < 0.01$). Southern blot (B = -0.05, 95% CI -0.14 to -0.04, p = 0.30) and TelSeq (B = 0.09, 95% CI -0.31 to 0.48, p = 0.66) associations did not differ significantly from qPCR, though TelSeq was represented in just one study. However, measurement technique was confounded with sample size in the data: FISH was used in small-sample studies (median 49); Southern blot in intermediate-sample studies (median 197), TelSeq in one very large study (sample size 11670), and qPCR in a range of sample sizes including large ones (median 761). We have already established that correlations were weaker in larger samples, and the order of central correlation estimates for the four techniques (FISH: r = -0.29, 95% CI -0.43 to -0.16; Southern blot: r = -0.17, 95% CI -0.24 to -0.10; qPCR: r = -0.13, 95% CI -0.17 to -0.09; TelSeq: r = -0.04, 95% CI -0.08 to -0.01) exactly mirrored their median sample sizes. Including sample size (square-root transformed) in the model as an additional moderator, the overall moderating effect of measurement technique became marginally non-significant ($Q_3 = 7.76$, p = 0.051). However, the 95% confidence interval for the parameter estimate for FISH still did not cross zero (B = -0.19, 95% CI -0.33 to -0.05, $p < 0.01$). Moderation by measurement technique was non-significant in the reduced dataset ($Q_2 = 0.11$, p = 0.94), though 95% of the associations in the reduced dataset used qPCR; there were no FISH associations at all, and only 15 instances of Southern blot.

Discussion

Telomere length or attrition has been proposed as a common currency 'psychobiomarker' of the impact of many different types of stress and adversity on the individual. Here, we meta-analysed an exceptionally large and diverse data set consisting of 553 associations from 142 studies featuring over 400,000 human participants. The results confirm that, in the published literature, telomere length is indeed significantly associated, in the predicted directions, with a wide range of exposures including environmental hazards, smoking, psychiatric illness, psychosocial factors, socioeconomic factors, parental care, poor nutrition, and physical activity. The large heterogeneity estimate even after controlling for exposure type suggests that there is more variation in results between different studies of the same exposure than between different types of exposure.

For several of the exposure variables in our dataset, there are published specialist meta-analyses covering just that exposure type. In many cases, these have appeared since we began data collection for this paper. Where such a specialist meta-analysis exists and we had more than 5 associations in our dataset, we compared the by-category results from our figure 3 with the key results of the corresponding specialist meta-analyses (table 3). There was, overall, a high degree of agreement. We would not expect the results to be identical, since the specialist meta-analyses had search strategies suited to their specific purposes, whereas our objectives were deliberately broader. The specialist meta-analyses are generally better-powered than the present dataset for answering their particular questions. We view the good agreement between the specialist reviews and subsets of our dataset as confirmation that the search strategy we used yielded a representative transect of the telomere epidemiology literature as it currently stands, and as independent corroboration of the conclusions of several of the specialist meta-analyses.

In detecting significant negative associations between telomere variables and a wide variety of different exposures, our findings appear to support the contention that telomeres are a useful integrative 'psychobiomarker' [1,4]. Nonetheless, they bring to the fore a number of important caveats. The first caveat is that the observed correlations are in the range that would conventionally be considered weak or small [33]. This has methodological implications for the use of telomere measures in research. A correlation coefficient of $r = -0.14$ (our central estimate from the whole dataset) requires a sample size of 398 to be detected as significant ($p < 0.05$) with 80% power. Only 37% of the associations had this sample size. Using the central correlation estimate from the reduced dataset ($r = -0.08$), the required sample size rises to 1224 (which was met by 15% of associations). Thus, significance tests from individual small-*n* studies should not be taken as strong evidence that a given exposure variable does or does not associate with telomere length, or associates differently from other variables. Moreover, with correlations typically of small magnitude, telomere length measures are of limited value as indicators of adversity exposure or welfare in individual people.

The weakness of observed associations may be related to the fact that the extant literature relies almost entirely (over 93% of associations) on cross-sectional studies using telomere length measured at a single point in time. This is almost bound to produce weak associations with environmental factors, since the individual variation in telomere length at birth, which is substantially heritable, dwarfs the amount by which telomeres shorten over the life-course [34,35]. Thus, any environmental signal in cross-sectional telomere studies will be diluted by a large component of irrelevant individual variability. Longitudinal studies that examine lifetime attrition, rather than telomere length, thus effectively controlling for different individual telomere starting lengths, are potentially much more powerful for detecting possible environmental influences (see [36] for discussion and [37,38] for examples of animal studies using this type of design). However, in the present dataset, we were not able to confirm that the few human longitudinal studies that exist produce stronger correlations than

Table 3. Comparison of the present findings by fine category with key results of specialist meta-analyses, where available. Represented are central meta-analytic estimates with 95% confidence intervals. Note that we have reversed the direction of our correlations compared to figure 3 where this is necessary for the comparison.

Exposure category	Specialist meta-analysis findings	Present findings
Cardiovascular disease	Significant association between CVD and short TL, OR = 1.54 [1.30, 1.83] [12]	Significant negative correlation between CVD and TL, *r* = -0.13 [-0.23, - 0.02]
Diabetes	Significant association between diabetes and short TL, OR = 1.29 [1.11, 1.50] [13]	Significant negative correlation between diabetes and TL, *r* = -0.28 [-0.40, - 0.16]
Parkinson's disease	No significant association between TL and disease, SMD = 0.358 [-0.247, 0.962] [14]	No significant association between TL and disease, *r* = 0.09 [-0.26, 0.44]
Sleep apnea	Significantly shorter TL in sleep apnea, SMD = -0.03 [-0.06, -0.00] [15]	Association between TL and disease negative but not significant *r* = -0.07 [-0.27, 0.13]
Anxiety	Significantly shorter TL in anxiety disorders, SMD = -0.53 [-1.05, -0.01] [16]	Significantly shorter TL in anxiety disorders, *r* = -0.05 [-0.08, -0.01]
Depression	Significantly shorter TL in depressive disorders, SMD = -0.55 [-0.92, -0.18] [16]; *d* = -0.21 [-0.29, -0.12] [56]; *r* = -0.12 [-0.17, -0.07] [55]	Significantly shorter TL in depressive disorders, *r* = -0.12 [-0.20, -0.04], becomes marginally non-significant in reduced dataset
PTSD	Significantly shorter TL in PTSD, SMD = -1.27 [-2.12, -0.43] [16]	Significantly shorter TL in PTSD, *r* = -0.17 [-0.31 to -0.03]; becomes non-significant in reduced dataset
Schizophrenia	No significant association between TL and psychosis/schizophrenia, SMD = -0.2 [-0.68, 0.21] [16]; SMD = 0.34 [0.77, 154] [57] Significantly shorter LTL in paranoid schizophrenia compared to controls SMD = -0.48 [-0.94, -0.03] [42]	Significant association between TL and schizophrenia, *r* = -0.50 [-0.30, -0.10]; becomes non-significant in reduced dataset
Smoking	Smokers significantly shorter TL than non-smokers, SMD = -0.17 [-0.24, -0.09] [17]	Smokers significantly shorter TL than non-smokers, *r* = -0.06 [-0.11, -0.02]
Physical activity	Significant positive association between physical activity and TL, SMD = 0.91 [0.48, 1.35] [19]	Significant positive association between physical activity and TL, *r* = 0.02 [0.01, 0.04]
Stress	Weak negative correlation between perceived stress and TL, r = -0.06 [-0.10, -0.01]; possible publication bias [18]	Weak negative correlation between perceived stress and TL, *r* = -0.07 [-0.13, -0.01]; becomes non-significant in reduced dataset
Socioeconomic status other than education	No significant association with TL, SMD = 0.10 [-0.03, 0.24] [20]	No significant association with TL for composite measures, *r* = 0.03 [-0.03, 0.08] or occupation, *r* = 0.00 [-0.02, 0.02]; Significant association between income and TL, *r* = 0.08 [0.01, 0.14], becomes non-significant in reduced dataset
Education	More education associated with significantly longer TL, SMD = 0.06 [0.00, 0.12] [20]	More education associated with significantly longer TL, r = 0.09 [0.05, 0.09]

Abbreviations: TL: telomere length; SMD: standardized mean difference; OR: Odds ratio; *d*: Cohen's d; *r*: Correlation coefficient

the cross-sectional ones. This may be because the follow-up tends to comprise a fairly short stretch of adult life in these human studies (mean 1576 days, s.d 882 days). A possible alternative to life-course longitudinal designs in some cases is the 'blood-muscle' model, where telomere length in adult muscle (where telomere length changes little) is used to estimate starting telomere length for blood [39].

The second caveat is that the literature may be affected by publication bias, a conclusion that echoes those of some narrower reviews [18]. We found evidence of stronger negative correlations in published studies with small samples, and removing these halved the strength of the overall association between exposure variables and telomeres. Directionally stronger associations in small samples is usually taken as evidence that small studies with null results or results contrary to prediction are being selectively withheld or rejected. Publication bias is not the only possible interpretation of this pattern, though. It could be that smaller studies measure stresses and adversities with greater precision, or use more selected participant samples so that the variation in exposure is greater, and as such genuinely detect stronger correlations with telomeres. Nonetheless, many of the strongest claims in the highest-profile journals, particularly regarding psychosocial associations with telomeres, are based mainly on small-*n* findings that need to be replicated in larger samples. The problem of selective appearance of associations into the literature may be worse than our findings suggest. For example, large-*n* epidemiological studies are likely to be published whatever the results, but authors often have degrees of freedom concerning which of many available predictor variables they report, and in how much detail. Even a slight bias towards including or providing detailed results preferentially for those measures that produced a significant or near-significant *p*-value would suffice to distort the meta-analytic conclusions considerably.

The third caveat is that it is hard, from the present literature, to make inferences about causality in the relationships between telomere variables and exposures to stress and adversity. This is because of the overwhelming reliance on cross-sectional and correlational designs. Several of the specialist meta-analyses have concluded with calls for more longitudinal research [18,19]. It is disappointing to note that in the course of this review, we have recurrently encountered correlational findings described as if they were causal (e.g. [7,19,40,41]), and cross-sectional findings described as if they were longitudinal (e.g. [9,16,40,42]) in article titles, abstracts and discussions.

A weak cross-sectional correlation between telomere length and an exposure could arise for three reasons: the exposure causes telomeres to shorten ('causality'); short telomeres cause the exposure ('reverse causality'); or some third variable is causally related to both telomeres and the exposure ('third variable'). Causality should not be assumed without further evidence. Reverse causality is plausible for many physical diseases. In some cases this is supported by longitudinal evidence (e.g. [39,43,44]) and Mendelian randomization studies [45,46]. Reverse causality may be possible for psychological and behavioural variables too, since short telomere length can change patterns of gene expression [47]. Third-variable explanations are plausible for many of the correlations described here. Childhood adversity, for example, is a third variable of potential general importance [21]. Childhood adversity is a known risk factor for a number of the variables considered here as exposures, such as poor physical and psychiatric health, smoking, and low socioeconomic status. Childhood adversity may also accelerate telomere shortening [48]. Since the highest rate of telomere shortening occurs early in life [49,50], it is perhaps more plausible that developmental conditions affect both the risk of the adult exposures and adult telomere length, than the adult exposures affecting adult telomere length directly. However, we did not find evidence in the present dataset that exposures during childhood produce significantly stronger correlations with telomere length than exposures during adulthood (though see [51] for a Cohen's *d* effect size of −0.35 in a specialist meta-analysis of early-life adversity and telomere length).

In relation to our objective of drawing conclusions about methodological sources of variation in measured associations, we were not able to reach any strong conclusions. Most of the methodological variables we recorded did not explain any significant fraction of the observed heterogeneity, but we cannot infer that they make no systematic difference. This is because many of the non-standard methodological choices in the dataset (e.g. longitudinal design, tissue other than blood, measurement technique other than qPCR) are rare in the data. Moreover, the different features of the methodology do not vary independently of one another, or of exposure type. We found some evidence suggesting fluorescent in-situ hybridization (FISH) might produce stronger correlations with predictor variables than other measurement techniques. However, the FISH studies also featured small samples, and small sample size was associated with stronger correlations. After controlling for sample size, the moderating effect of measurement technique was attenuated. To make progress on methodological questions such as whether, for example, qPCR produces weaker associations than other techniques due to greater measurement error [23,52,53], it will be necessary to take more homogeneous sets of studies, all focussing on the same relationship, in order to isolate the consequences of this single methodological factor. For example, in recent meta-analyses of telomeres and sex [54], and telomeres and depression [55], stronger associations were found by Southern blot and/or FISH than by qPCR.

We conclude with a plea to the field. Of the studies we identified as containing suitable evidence for our meta-analysis, 43% could not be used as they did not describe their data in enough detail. Common omissions were simple, such as not providing means and standard deviations per group, not providing sufficient detail of regression models, or providing only a *p*-value for the key result. Moreover, there may have been cases where researchers measured more variables than those they reported. These failings could easily be addressed by more carefully reporting of statistics, better refereeing, and, above all, fostering a culture in which all raw data are made freely available. Given the subtlety of any associations between telomere dynamics and environmental exposures, it is going to be necessary to pool our collective evidence in order to understand them. It is a great waste if two fifths of that evidence is not usable for meta-analysis.

Ethics statement

This study was based on secondary analysis of study-level data already in the public domain, and as such required no ethical approval.

Data accessibility

Raw data and the R scripts for converting and analysing them are freely available via the Zenodo repository: http://doi.org/10.5281/zenodo.1189538 .

Competing interests

We have no competing interests.

Authors' contributions

G.V.P. participated in the design of the study, carried out literature searches, extracted data from the literature, designed conversion algorithms, analysed the data, and drafted the manuscript. D.N. participated in the design of the study, carried out literature searches, extracted data from the literature, analysed the data, and helped draft the manuscript. M.B. participated in the design of the study, advised on statistical analyses, and revised the manuscript for intellectual content. All authors gave approval for publication.

Acknowledgements

We acknowledge the members of the COMSTAR lab group and other colleagues at Newcastle University for their advice and feedback.

Funding

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No AdG 666669, COMSTAR, to D.N.). Support to M.B. was received from National Centre for the 3Rs (grant NC/K000802/1).

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