Delay discounting, genetic sensitivity, and leukocyte telomere length

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In a graying world, there is an increasing interest in correlates of aging, especially those found in early life. Leukocyte telomere length (LTL) is an emerging marker of aging at the cellular level, but little is known regarding its link with poor decision making that often entails being overly impatient. Here we investigate the relationship between LTL and the degree of impatience, which is measured in the laboratory using an incentivized delay discounting task. In a sample of 1,158 Han Chinese undergraduates, we observe that steeper delay discounting, indexing higher degree of impatience, is negatively associated with LTL. The relationship is robust after controlling for health-related variables, as well as risk attitude—another important determinant of decision making. LTL in females is more sensitive to impatience than in males. We then asked if genes possibly modulate the effect of impatient behavior on LTL. The oxytocin receptor gene (*OXTR*) polymorphism rs53576, which has figured prominently in investigations of social cognition and psychological resources, and the estrogen receptor β gene (*ESR2*) polymorphism rs2978381, one of two gonadal sex hormone genes, significantly mitigate the negative effect of impatience on cellular aging in females. The current results contribute to understanding the relationship between preferences in decision making, particularly impatience, and cellular aging, for the first time to our knowledge. Notably, oxytocin and estrogen receptor polymorphisms temper accelerated cellular aging in young females who tend to make impatient choices.

telomere length | delay discounting | risk attitude | oxytocin receptor | estrogen receptor

With an increasing percentage of the world's population "graying," the determinants of successful aging are of paramount importance in public health planning and policy across the globe (1). In the last decades, there has been a surge in the epidemiological research body suggesting that telomere length, indexing cellular aging, serves as an early predictor of onset of disease and earlier mortality (2–4). Telomeres are nucleoprotein structures capping the ends of chromosomes functioning to prevent their fusion and degradation (5). In humans, telomeres consist of TTAGGG repeats. Each division of a cell erodes telomere length, and when telomeres reach a critical short length, the cell enters senescence and no longer divides (6), although it may remain metabolically active and functioning. Critically short telomeres will trigger DNA damage responses that inhibit cell cycle progression. Intriguingly, the seeds of biological aging are widely thought to be planted early in life (7), even as far back as in the womb (8). Beyond the fetal period, other factors, such as the early family environment, lifestyle, and stress, also have considerable impact on cellular aging (2, 9–13).

In addition to these factors, we suggest that economic preferences characterized as overly impatient or impulsive may also correlate with cellular aging. Behavioral studies on decision making have examined the individual's preference in choosing between a more future-oriented alternative (e.g., healthy snacks) and a more tempting, but ultimately inferior, option (e.g., junk foods) (14). Although impatience can be a virtue when individuals are facing survival risks (15), the tendency to devalue future outcomes relative to the present outcomes, coined as delay discounting, has been negatively associated with a wide spectrum of life domains essential to successful aging. These include unhealthy behaviors such as substance abuse (16) and physical inactivity (17). Beyond these relationships, impatience is linked to cognitive and social incompetence, inability to cope with life frustration and stress (18), and risk of mental disorders (19, 20). These untoward effects associated with impatience suggest that steeper delay discounting may be negatively correlated with telomere length, a process potentially mediated by inflammatory response and oxidative stress (12, 13).

Drawing on these observations, in the current study, we sought to clarify the link between delay discounting and leukocyte telomere length (LTL), an emerging marker of aging at the cellular level. We examined a large group of 1,158 nominally healthy Singaporean university undergraduates, and probed the relationship between LTL with delay discounting measured by behavioral economic tasks (Fig. 1, *SI Materials and Methods*, and Table S1). In this study, subjects made a series of choices between receiving a $100 reward tomorrow and larger rewards in 30 d. By varying the monetary value of the delayed rewards, we could observe the minimum acceptable amount (MAA) for the subjects to be willing to delay the $100 reward for 30 d. Higher MAA indicates a higher degree of impatience in response to

Significance

This paper makes a singular contribution to understanding the association between biological aging indexed by leukocyte telomeres length (LTL) and delay discounting measured in an incentivized behavioral economic task. In a large group of young, healthy undergraduates, steeper delay discounting is significantly associated with shorter LTL, while controlling for risk attitude and health-related behaviors. Notably, we found that delay discounting and risk attitude—two fundamental determinants of economic preferences—are independently associated with LTL. Moreover, for the first time to our knowledge, the effects of well-studied oxytocin and estrogen receptor polymorphisms are shown to specifically moderate the impact of impatience on LTL. Our work suggests a path to integrate behavioral economic methodology to supposed biological mechanisms associated with health outcomes.

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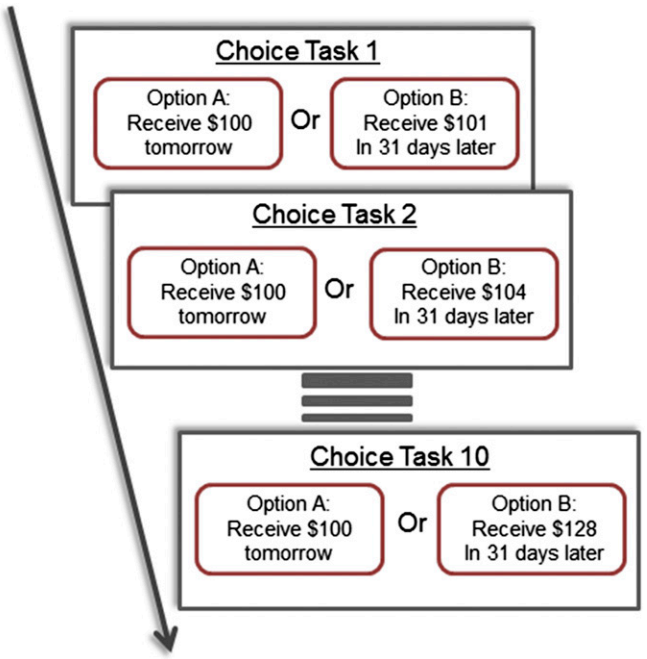

Fig. 1. Experimental tasks in measuring delay discounting. In the delay discounting task, subjects were asked to choose between receiving $100 tomorrow (option A) and a larger amount of money in 31 d later (option B). In a series of tasks, the amount in option B was increased from $101 to $128 in steps of $3. If the subject was willing to choose option B at a lower stake, for instance, $104, she would be willing to choose option B at a higher stake, for instance, $107. The task enables us to observe the MAA for the subjects to choose option B, the delayed reward.

proximate reward. We hypothesized that a higher degree of impatience would be associated with shorter LTL.

To better understand the role of impatience, we also investigated a delayed discounting task pertaining to tradeoffs in the distant future. Instead of choosing between two rewards in the near future (tomorrow versus in 31 d), subjects chose between receiving $100 in 351 d and receiving a larger amount in 381 d. Similarly, we elicited MAA for the subjects to be willing to delay the earlier reward in 351 d to a more distant future—381 d. Intriguingly, earlier neuroscience research suggested that making the tradeoff in the near future and distant future involves differential activation of separate neural systems (21). Delay discounting in the near future is driven by the limbic system, which is a neural network related to attention deficit hyperactivity disorder (22), drug dependence (23), and emotions regulation (24), whereas delay discounting in the distant future is mediated by the lateral prefrontal cortex, which is associated with deliberation and evaluating abstract rewards (25). Hence, we hypothesize that LTL is more likely to be negatively associated with MAA in the near future (MAAN)—evoking impulsive responses—but less likely to be associated with MAA in the distant future (MAAD)—involving deliberative responses.

The underlying mechanisms by which impatience is translated into telomere erosion are undoubtedly complex. Risk proneness (preference to choose riskier options) can often be a confounding factor toward understanding the role of impatience in the decision-making process. If individuals are averse to the risk inherent in delay, they may also prefer the immediate smaller rewards to the later larger reward. The degree of risk proneness is also reported to be negatively correlated with subjects' healthy behaviors (26). In this study, we elicited subjects' risk attitude by asking the subjects to decide how much to invest on an experimental stock (*SI Materials and Methods* and Table S2). Higher amount of investment in the stock indicates higher proneness to take risk. We also collected subjects' socioeconomic status (SES), approximated by family monthly income, as well as health-related variables such as body mass index (BMI) and healthy behaviors (see Tables S3 and S4 for the descriptions). Earlier studies also suggested that SES (27) and health-related behaviors (16, 17) could correlate with impatience as well as LTL (9, 10, 12). Hence, our design enables us to minimize the impact of confounds toward better understanding the relationship between delay discounting and LTL.

In addition to characterizing the behavioral processes underlying impatience and cellular aging, we investigate a number of important factors that may moderate this relationship. First, prior research suggests that early life adversity has a larger impact on females' cellular aging (28, 29). Moreover, young females tend to be more susceptible than males to stress, an effect partially explained by the inhibitory role of testosterone in males on hypothalamic pituitary axis (HPA) cortisol secretion (30, 31). Additionally, psychological stress is related to oxidative DNA damage [responsible for telomere shortening (32)] in females but not in males (33). Given these observations, we expect that females are more sensitive to impatience than males in telomere erosion.

Second, we also implement a neurogenetic strategy to further explore the biological pathways between impatience and LTL. The genetic markers we investigate in this study are known to affect inflammatory response and steroid hormone function, as well as physiological responses to psychological stress. We first genotype GST pi 1 (*GSTP1*) single-nucleotide polymorphism (SNP) rs1695, which is extensively linked to inflammatory response (34) and DNA damage (35). As earlier research suggests, inflammatory and oxidative agents play a critical part in telomere shortening, suggesting that such factors may mediate many of the adverse stressors that impinge LTL (36, 37). Additionally, we examine two well-studied estrogen receptor gene SNPs, *ESR1* rs3798577 and *ESR2* rs2978381, which are associated with endocrine abnormalities and cancer (38–42). Interestingly, telomerase is also modulated by steroid hormones such as estrogen (43, 44), potentially due to estrogens' antioxidant neuroprotective effects (45). Because its neuroprotective action is dependent on estrogen receptor activity (45), we conjecture that estrogen receptor genes may moderate the correlation between impatience and LTL. Last, we genotype the oxytocin receptor (*OXTR*) SNP rs53576 that is linked to a considerable range of cognitive and social cognitive processes (46–59). Prior evidence shows that individuals possessing the rs53576 G allele, relative to those with the A allele, are less affected by psychological stress, indicated by lower cortisol response (51) and greater psychological resources (52). Imaging studies of rs53576 (60) suggest underlying neural mechanisms of action for rs53576. We hypothesized that individuals with the G allele will be less susceptible to the deleterious effect of impatience in cellular aging.

Results

In our sample, the mean age of male university students is 1.5 y older than that of females [$M_{male} = 22$ vs. $M_{female} = 20.5$, $t(1,131) = 18.3$, $P < 0.001$], due to male subjects' 2-y compulsory military service. Females have longer LTL than males [$M_{male} = 1.01$ vs. $M_{female} = 1.06$, $t(1,026) = 3.44$, $P < 0.001$]. The age-adjusted regression confirms that females have significantly longer LTL than males ($\beta = 0.05$, $P < 0.01$). When controlling for sex, age is not significantly correlated with LTL, potentially due to the narrow age range in our sample ($M_{age} = 21.21$, SD = 1.54). These results are consistent with previous findings showing that, generally, males have shorter telomeres and higher erosion rates (61). In investigating the relationship between delay discounting and LTL, we consider sex and age as controls in the subsequent regression models.

Relationship Between Delay Discounting and LTL. The mean MAAN is $111.47 (SD = 10.42), indicating that the subjects need about $111.47 to be willing to delay a $100 reward for 30 d. There is no gender difference in MAAN [$M_{male} = 111.48$ vs. $M_{female} = 111.5$, $t(1,131) = -0.04$, $P > 0.9$]. MAAN is highly correlated with MAAD (Pearson's $\rho = 0.53$, $P < 0.001$). MAAD is significantly lower than MAAN [$M_{near} = 111.45$ vs. $M_{distant} = 108.63$, $t(1,136) = 9.4$, $P < 0.001$], suggesting that the subjects are more impatient

for the tradeoffs in the near future than the tradeoffs in the distant future. The discrepancy of impatience in the distant future and in the near future is often labeled as hyperbolic discounting (14).

We conduct linear regression analyses to test the association between MAAN (the focal independent variable) and LTL (the dependent variable) (see *SI Results* and Table S6 for full sets of model specifications and results). A significant correlation between MAAN and LTL is observed ($\beta = -0.00167$, $P < 0.05$). The sign of the coefficient is negative, indicating that higher MAAN, indicating steeper delay discounting, is associated with shorter LTL. As shown in Table 1, we further test the relationship by in turn adding two sets of control variables. In model 1, we add MAAD, sex, and age as control variables. In model 2, we add the second set of control variables consisting of risk proneness, SES, and health-related variables that are potentially confounding factors with respect to impatience and LTL. As can be seen, the association between MAAN and LTL is robust after controlling for other factors (model 1 and model 2). In contrast to MAAN, the regression models show no correlation between MAAD and LTL, consistent with our hypothesis that delay discounting in the near future, in comparison with the distant future, is related to telomere erosion.

As Table 1 model 2 shows, there is a significant correlation between LTL and risk proneness ($\beta = -0.0024$, $P < 0.05$), suggesting that the higher amount of investment, reflecting higher degree of risk proneness, is associated with shorter LTL. In the investment task, the expected rate of return on investment is 25%, i.e., it is profitable to invest money in the experimental stock. The mean investment amount in the experimental stock was \$13.27 (SD = 7.06), about half of the initial endowment \$27, which indicates that the subjects exhibit a considerable degree of risk aversion. Males, on average, invest significantly more than females [$M_{male} = \$13.96$ vs. $M_{female} = \$12.54$, $t(1,140) = 3.4$, $P < 0.001$], indicating that males are more risk-prone than females.

Among the set of control variables in model 2, low SES (family monthly income < \$2,300) and BMI are negatively correlated with LTL, which is consistent with earlier studies (10, 62). We do not find that other health-related variables we measure in this student population are significantly associated with LTL. Importantly, the relationship between MAAN and LTL is robust by controlling for these health-related variables.

The Role of Sex in Moderating the Relationship Between Delay Discounting and LTL. We hypothesized that impatience may have a sex-specific influence on LTL. We find a significant interaction effect between MAAN and sex on LTL after controlling for age [$\beta = -0.003$, $t(998) = -2.02$, $P < 0.05$]. Marked gender differences in risk and LTL shown above, as well as the differential effects of sex on stress (30, 31), led us to stratify our analyses by gender. Hence, we further analyze the data separately by sex (Table 1 model 3 for males and model 4 for females). We observe that the correlation between MAAN and LTL is significant in females ($\beta = -0.0039$, $P < 0.001$) but not in males ($\beta = -0.0015$, $P > 0.3$). We plot this relationship between LTL and MAAN in Fig. 2*A*. As can be seen from the estimated regression lines, females' LTL is more sensitive to the change in impatience than males'. By stratifying the sample by sex, other covariates are also gender sensitive. For instance, risk proneness is only negatively correlated with LTL in females but not in males (see Table 1 models 3 and 4, and Fig. 2*B*). SES and BMI are correlated with LTL in males but not in females.

Genetic Markers, Delay Discounting, and LTL. None of the genetic markers are correlated with MAAN (Pearson's correlation $P > 0.33$). Table 2 presents the estimated coefficients from the model testing the association between genetic marker and LTL (models 1 and 3), as well as the model testing the interaction effect between genetic marker and impatience on LTL (models 2 and 4) (see *SI Results* for detailed information and results for the full sample). As can be seen in Table 2 (models 1 and 3), none of the genetic markers are correlated with LTL, except *GSTP1* rs1695 (in males). The correlation between *GSTP1* and LTL is likely due to its role in modulating inflammatory response and detoxifying potentially mutagenic and toxic DNA-reactive electrophiles suggested by earlier research (34, 35).

As observed in Table 2 (models 2 and 4), *GSTP1* and *ESR1* rs3798577 do not moderate the relationship between MAAN and LTL. However, we found that the *ESR2* rs2978381 AA genotype buffers the relationship between MAAN and LTL in females (Table 2 model 4) but not in males (Table 2 model 2), as might be expected of a female gonadal hormone receptor. Fig. 2*C* illustrates the interaction effect of impatience and *ESR2* rs2978381 in females. Impatience significantly affects LTL only among females with the AG/GG genotype [$F(1,530) = 7.46$, $P < 0.01$]. There is no significant difference in LTL between patient and impatient females with the AA genotype [$F(1,530) = 0.074$, $P > 0.3$]. The findings lend some support to the notion that estrogen, perhaps due to its role as an antioxidant, can serve to protect women in response to the wear and tear evoked by chronic impatience.

As shown in Table 2, *OXTR* rs53576 GA/GG genotype, which is associated with greater psychological resources (52) in managing stress (51), buffers the impact of impatience on LTL in females ($\beta = 0.0054$, $P < 0.05$, model 4) but not in males ($P > 0.6$, model 2). We illustrate the interaction effect of impatience and *OXTR* rs53576 in females in Fig. 2*D*. Notably, impatience significantly affects LTL only among females with AA genotype

Table 1. Regression results of delay discounting on LTL

Variables	Model 1	Model 2	Model 3 (male)	Model 4 (female)
MAAN	−0.0019**	−0.0024**	−0.0015	−0.0039***
MAAD	0.0004	0.0008	0.0005	0.0011
Sex	0.0502***	0.0404**	—	—
Age	−0.0024	−0.0024	−0.0100	0.0028
Risk proneness		−0.0024**	−0.0005	−0.0034*
Low SES		−0.0726**	−0.1083***	−0.0597
BMI		−0.0095***	−0.0121***	−0.0066
Other variables on health	no	yes	yes	yes
Observations	1,000	748	344	404
R-squared	0.018	0.054	0.076	0.042

The dependent variable is LTL for all models. MAAN indexes delay discounting in the near future. We control for variables such as MAAD (indexing delay discounting in the distant future), sex, age, risk proneness, low SES (family monthly income <\$2,300), BMI, and other variables on health (physical activity, physical activity intensity, drug completion, frequency of flossing, eating healthy food, overeating, frequency of dentist visits, and smoking behavior); "yes" indicates that we included these health-related variables as controls in the model. The number of observations varies because of attrition of the participants in different waves of studies. Robust SEs corrected for heteroscedasticity were used and reported in *SI Results* and Table S6; *$P < 0.1$; **$P < 0.05$; ***$P < 0.01$ (two-tailed).

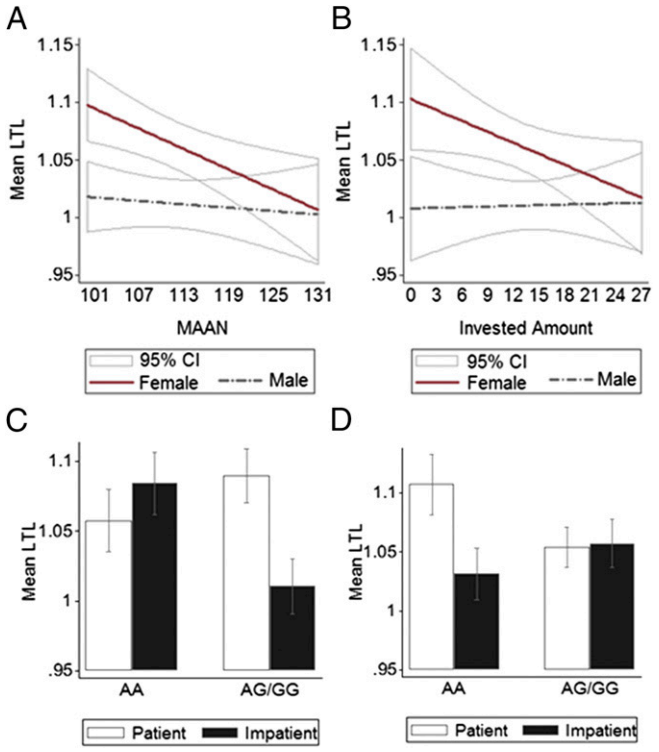

Fig. 2. (*A*) Estimated regression lines for impatience and LTL. From the estimated regression lines in the figure, females' LTL appears more sensitive to the change in impatience (indicated by MAAN) than males'. Along the regression lines, 95% confidence intervals are presented. (*B*) Estimated regression lines for risk proneness and LTL. From the estimated regression lines in the figure, females' LTL appears more sensitive to the change in risk proneness (indicated by larger amount of investment) than males'. Along the regression lines, 95% confidence intervals are presented. (*C*) Interaction between ESR2 and impatience. Subjects are categorized as "patient" if their MAA is smaller than \$110 (the median); otherwise, they are "impatient." Impatience affects LTL only for females with the G genotype for ESR2 rs2978381. There is no significant difference in LTL between patient and impatient females if they lack the G allele. Error bars represent ±1 SE. (*D*) Interaction between OXTR and impatience. Subjects are categorized as "patient" if their MAA is smaller than \$110; otherwise, they are "impatient." Impatience affects LTL only for females with the AA genotype for OXTR rs53576. There is no significant difference in LTL between patient and impatient females if they possessed the G allele. Error bars represent ±1 SE.

$[F(1, 531) = 5.45, P = 0.02]$. There is no significant difference in LTL between patient and impatient females if they are carriers of the GA/GG genotype $[F(1,531) = 0.01, P > 0.9]$. The results suggest that the G allele modulates the deleterious impact of impatience and that this allele plays the role of a protective buffer.

Discussion

Our results indicate that shorter LTL is associated with steeper delay discounting as measured in a behavioral economic task. The additional task measuring risk attitude allows us to disentangle the impact of delay discounting and risk attitude on LTL, and minimize the potential confound of these two variables. As we show, the correlation between delay discounting and LTL is robust to adjustments for sex, age, SES, risk proneness, and an array of lifestyle behaviors in this young sample. The results are consistent with prior findings that early life stress can already have a deleterious impact on telomere length at a young age (2, 9–13).

Notably, we found that gender moderates the relationship between impatience and cellular aging. When the sample in this study is stratified by sex, the association between delay discounting and LTL is observed in females but not in males. Our findings are in agreement with earlier evidence that females are more sensitive to social adversity and stress (28, 29, 63) with respect to cellular aging. Overall, shortened LTL mirrors the cell's mitotic history and replicative history of hematopoietic stem cells, and is further subjected to the effects of inflammation and oxidation (36, 37, 64). Interestingly, as prior reports show, there are gender-specific effects of oxidative stress and inflammation markers in response to psychological stress, lifestyle, and disease (33, 65, 66). Although estrogen was shown to have antioxidant neuroprotective effects in response to stress for females (45, 67), young women may be more sensitive to psychological stress (30). Higher susceptibility in response to psychological stress could potentially "trump" the positive impact of estrogen in modulating oxidative stress. Importantly, during the early years of development, psychological challenges appear to preferentially increase the risk for affective disorders in females, especially during their reproductive years, reflecting their greater vulnerability to psychological stress (30). Studies in rodents and humans point to an increased susceptibility to stress in females during the peripubertal and pubertal window of maturation, a period suggested to be critical for programming of long-term risk for stress-related affective disorders (68).

We also document that specific genetic polymorphisms moderate the impact of impatience on biological aging. The well-studied *OXTR* SNP rs53576 buffers the impact of impatience on LTL in the expected direction: Individuals with AG/GG genotype are less sensitive to the negative impact of impatience on LTL. This moderating effect is statistically significant in females but not in males, which is consistent with early studies showing that rs53576 has gender-specific effects on modulating stress (69) and anxiety-related temperament (70). We observe that *ESR2* rs2978381 AA genotype mitigates the impact of impatience on LTL for females but not for males. The effect we observe is only with *ESR2* consistent with a recent study showing a relationship between this receptor and anxiety (71). Altogether, our neurogenetic results indicate that oxytocin and estrogen receptors modulate the relationship between delay discounting and telomere length, an effect that is particularly pronounced in one gender.

Given the nature of the data in our study, we are unable to conclusively disentangle two potential underlying mechanisms, namely, impatience leads to shortened LTL or, alternatively, shortened telomeres lead to impatience (state-dependent model) as in Bateson et al. (72), who documented a similar phenomenon regarding the association between delay discounting and telomere length in European starlings (*Sturnus vulgaris*). Some results in our study are suggestive that impatience leads to shortened telomeres in contrast to the notion suggested by Bateson et al. (72) that shorter telomeres somehow lead to impatient behavior. For example, we would expect that if a state-dependent model is involved as Bateson et al. suggest (72), then shorter LTL would also be correlated with delay discounting in the distant future. However, if shorter telomeres are the consequence of impatient behavior as we suggest, only delay discounting in the near future should be significantly associated with the erosion of telomeres. We do not find any association between LTL and delay discounting in the distant future, implying that the correlation between impatience and LTL in our study is less aligned with the state-dependent decision-making model. The neurogenetic results are also consistent with our argument, because it is difficult to understand how a state-dependent decision-making model would predict the interaction effects of moderating variables such as *OXTR* or *ESR2* polymorphisms on LTL. Nevertheless, we emphasize that, regardless of the causal direction, the important notion is that the correlation between shorter telomeres and impulsive behavior is reproducible remarkably across boundaries of taxonomic species and even class. In addition to strengthening our findings, a similar observation in birds and humans further suggests that both findings may point to a shared evolutionary biological origin for an untoward relationship between impatient decision making and aging at the biological level.

An important limitation of our study pertains to its cross-sectional design, and therefore the results can only be interpreted as correlational. Whether or not shorter LTL is the consequence of

Table 2. Regression estimates of gene delay discounting interaction effect on LTL

	Male		Female	
Variables	Assoc. (model 1)	Interact. (model 2)	Assoc. (model 3)	Interact. (model 4)
MAAN	−0.0017	−0.0013	−0.0040***	−0.0051***
GSTP1	0.0786***	0.2094	0.0316	−0.3446
GSTP1 × MAAN		−0.0012		0.0034
MAAN	−0.0016	−0.0007	−0.0039***	−0.0039*
ESR1	0.0373	0.1798	0.0164	0.0213
ESR1 × MAAN		−0.0013		−0.0000
MAAN	−0.0015	−0.0022	−0.0039***	−0.0007
ESR2	0.0040	−0.1283	−0.0037	0.6461**
ESR2 × MAAN		0.0012		−0.0058**
MAAN	−0.0015	−0.0023	−0.0039***	−0.0073***
OXTR	−0.0067	−0.1551	−0.0327	−0.6489**
OXTR × MAAN		0.0013		0.0055**

The dependent variable is LTL for all models. The genetic markers we investigate are *GSTP1* rs1695, *ESR1* rs3798577, *ESR2* rs2978381, and *OXTR* rs53576. For all of the SNPs, we assumed a dominant model, and G-allele is the dominant allele. To test the association (Assoc.) between specific genes and LTL, and the interaction effect (Interact.) between genetic markers and impatience on LTL, we include all of the other control variables in the regression model, including MAAD, age, risk proneness, SES, and other health-related variables, but we omit these coefficients and R-squared in the table (see *SI Results* and Table S7 for fuller results). We add one genetic marker each time to the model. In models 1 and 3, we report the coefficients on MAAN and the genetic marker. In models 2 and 4, we report the coefficients on MAAN, the genetic marker, and the interaction between genetic marker and MAAN. Robust SEs corrected for heteroscedasticity were used (see *SI Results* and Table S7); $^{*}P < 0.1$; $^{**}P < 0.05$; $^{***}P < 0.01$ (two-tailed).

impatience remains an open question. Future work can be carried out longitudinally to more tightly determine the factors that modulate telomere change over time. In addition, the absence of a physiological measure of stress in the current study prevents us from substantiating our conjecture that impatience leads to biological stress that in turn leads to shorter LTL. In the study, we attempted to explore whether *GSTP1* rs1695—a well-studied inflammatory marker—moderates the relationship between impatience and LTL. Although we did not find an interaction between *GSTP1* rs1695 and impatience on LTL, our finding of a main effect suggests that this inflammatory marker polymorphism may play an important role in telomere erosion. Future research can extend our investigation to consider direct measures of oxidative stress and inflammatory response or other genetic markers toward better understanding the relationship between impatience and cellular aging.

Notwithstanding these limitations, our research makes a number of salient contributions. First, our study links a fundamental determinant of decision making, delay discounting that is measured in an incentivized laboratory behavioral paradigm, to a molecular marker for cellular aging in humans. Hence, this study lays down a strategy toward integrating the crispness of behavioral economic tasks to biological mechanisms associated with health outcomes. We further show that the impact of impatience on LTL is gender-sensitive and impatient women are especially affected. Underlying biological pathways modulating the effect of impatience on LTL are revealed using a neurogenetic strategy. Specifically, a well-studied *OXTR* SNP rs53576 and an *ESR2* SNP rs2978381 interact with delay discounting to buffer the untoward effect of impatience on LTL in females. The results suggest that the trajectories by which impatience is translated into cellular aging depend on individual characteristics relating to gender and genotype, among others yet to be identified.

Materials and Methods

Participants. We recruited 1,158 (51.6% females; $M_{age} = 21.2$, SD = 1.5) Han Chinese undergraduate students at National University of Singapore to participate in an economic decision-making experiment. The study was approved by Institutional Review Board of National University of Singapore, and subjects gave written informed consent before participating. Subjects were reimbursed for participation in the project (Singapore $25 per hour on average).

The study consisted of three stages. In stage 1, we conducted an economic decision-making experiment measuring delay discounting and risk attitude. In stage 2 (a few days after stage 1), participants donated 10–20 mL of blood for extracting DNA information. In stage 3 (immediately after stage 2), participants received an email invitation for an online survey in which we administered questions on demographics (age, sex, and family monthly income), height, weight, and health-related variables (see *SI Materials and Methods*).

LTL Measurement and Genotyping. LTL was measured using techniques modified from Cawthon (73), which comprise distinct polymerase chain reactions (PCR) that are normalized to a single-copy gene, generating the relative telomere to single copy (T/S) gene ratio as a measure of relative LTL. Quantitative PCR were carried out on the CFX96 Real-Time PCR Detection System from Bio-Rad. The *GSTP1* rs1695, *ESR1* rs3798577, *ESR2* rs2978381, and *OXTR* rs53576 genotyping was carried out using a 5′-nuclease Taqman assay with primers and probes from Applied Biosystems (catalog number 4351379). PCRs were performed using Qiagen's HotStarTaq Plus DNA polymerase (catalog number 203601) on BioRad's CFX96 Real-Time PCR Detection System. Additional details are presented in *SI Materials and Methods* and Table S5.

Statistics. Most analyses were based on linear regression models. We reported both the coefficient from the regression and the significance level (two-tailed) of the coefficient. SEs corrected for heteroscedasticity were used and reported in *SI Results* and Tables S6 and S7. All of the statistics reported here are based on two-tailed tests. All analyses were conducted using Stata 12. See *SI Results* for detailed model specification and regression results.

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