High variability in vital rates with positive autocorrelation negatively affects humans' capacity to buffer against the variable inflation environment

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Introduction

Humans are risk averse and prefer reducing intertemporal inequalities in vital rates to minimise variability in long-term growth rates within the fluctuating inflation environment. Indeed, we invest in survival based on the value of a statistical life, *i.e.,* how individuals value their remaining life years and are willing to pay for mortality reduction (Aldy and Viscusi 2004, 2008; Bommier 2006, 2008; Johansson 2002; Rosen 1988; Tolley et al. 1994; Viscusi 1993; Viscusi and Aldy 2003). Existing literature suggests that time discounting, *i.e.,* the investment in future survival over present consumption, measures the value of a statistical life (Edwards 2013; Fuchs 1982). Interestingly, the value of a statistical life varies systematically with time because of variation in income, consumption, and inflation (Edwards 2013; Ehrlich 2000). In the case of fertility, temporary unemployment shocks associated with fluctuating inflation reduce the wages forgone due to maternity, making the unemployment period a favourable time for fertility (Adsera and Menendez 2010; Butz and Ward 1979; Galor and Weil 1993; Schultz 1985; Ward and Butz 1980). Whereas, persistently high inflation resulting in permanent unemployment lowers the household permanent income (income effect) and subsequently reduce fertility (Adsera 2005; Adsera and Menendez 2010; Becker 1960; Ben-Porath 1973; Comoli 2017; Goldstein et al. 2013; Silver 1965; Sobotka et al. 2011). Therefore, humans can adjust variability in fertility and survival to reduce fluctuation in long-term population growth within the variable inflation environment.

The vital rates response to variability in the inflation environment can be studied using the demographic buffering hypothesis (DBH, hereafter; Morris and Doak 2004). A key result of stochastic modelling of population dynamics is that the vital rates with the highest sensitivities are expected to be under strong selection for a reduction in temporal variation, a phenomenon called demographic buffering (Hilde et al. 2020; Pfister 1998; Tuljapurkar and Haridas 2006). Therefore, DBH can explain how the human life-history strategy of reducing the variability in fertility and survival to adapt to the fluctuating inflation environment ultimately maximises long-term fitness (Fisher 1999; Saether and Engen 2015). The framework applies the hypothesis that human demographic preferences are at evolutionary equilibrium, and any mutation changing these preferences is selectively disadvantageous (Orzack 1985; Rogers 1994). However, quantifying demographic buffering in humans against the variable inflation environment needs three key considerations. First, we need to define the inflation environment, representing economic uncertainty and affecting temporal variation in vital rates (Hilde et al. 2020). Second, we should account for the lagged effect in the vital rates response to variability in inflation (Adsera and Menendez 2011; Juselius and Takats 2015, 2018). Finally, we need to incorporate the population (age) structure as the reaction norms between humans' vital rates and variability in inflation environments vary over age (Adsera and Menendez 2011; Edwards 2013; Ehrlich 2000; Murphy and Topel 2006; Orzack 1985; Rogers 1994).

Here, we test the effects of environmental autocorrelation, variability of vital rates and their joint effect on humans' capacity to buffer against variability in the inflation environment. We use high-resolution economic (Ha et al. 2023) and demographic data (United Nations 2024) from 76 countries over 1971-2024 to test the hypothesis on structured demographic buffering against the variable inflation environment. We expect that (H1) a population's capacity to buffer against a variable inflation environment depends on the joint effect of variance-covariance and autocorrelation in vital rates. Specifically, an increase in variance in vital rates affects the sum of stochastic elasticities, $\Sigma E^{S\sigma}_{a_{ij}}$ negatively for positive autocorrelation. Whereas, the opposite effect is observed for negative autocorrelation, as predicted by Tuljapurkar's small noise approximation (1982a, 1982b, 1989). Therefore, as the environment becomes more variable and positively autocorrelated population will become less buffered.

Data and Methods

Inflation data

To explore the impact of variability in inflation on human capacity to remain buffered, we extracted inflation data from the World Bank's Global Database on Inflation (Ha et al. 2023). This comprehensive database provides the estimates of trend inflation, using a univariate component stochastic volatility model, for 76 countries from 1971-2022 on a quarterly frequency. These estimates can be used to describe economic dynamics (Ascari and Sbordone 2014). Therefore, our analyses of the impact of trend inflation on population dynamics use the trend inflation data for the 76 countries for which estimates are available in Ha et al. (2023).

Inflation Environment

To examine the capacity of humans to buffer against variability in inflation environments, we defined the environments based on the level of inflation at one time step (year). We defined four environmental states, E_r based on the level of inflation in each country as, $E_1 = 0 - 3\%, E_2 = 3 - 10\%, E_3 = 10 - 50\%, E_4 = > 50\%$, based on established classification (Frisch, 1977; Lim and Sek, 2015; Machlup, 2020; Wolozin, 1959). We assume that environmental conditions change between $r = 4$ possible states according to a Markov chain with a $r \times r$ environmental transition matrix **P**, which is primitive, and its columns sums to one. The transition probability matrix **P** has eigenvalues ordered as $1 > |\nu_1| \geq \ldots \geq |\nu_{r-1}|$, with corresponding left and right eigenvectors $\boldsymbol{\pi}_x$, $\boldsymbol{\psi}_x$, $x = 1, \ldots, r-1$ (Tuljapurkar 1982a, 1982b; Tuljapurkar and Haridas 2006).

Matrix Population Models

To quantify the response of vital rates to variability in the inflation environments, we used a derivative-based approach. Specifically, we constructed Leslie matrices (Leslie 1945, 1948) projecting human populations across a one-year timestep, using age-specific vital rates from the World Population Prospects 2024 for 76 countries over 1971-2024 (United Nations, 2024). We adopted the survival probabilities from the abridged life tables from WPP 2024 as the subdiagonal entries of **B** and calculated fertility for the first row of **B** using the age-specific fertility rate and the sex ratio at birth from WPP 2024. Then we computed average projection matrix with respect to the stationary equilibrium distribution of the Markov chain as

$$\mathbf{A} = \sum_{x=0}^{r-1} \boldsymbol{\psi}_0\, \mathbf{B}_x \qquad (1)$$

(Cohen 1977; Hajnal 1976; Tuljapurkar 1982a, 1982b, 1989; Tuljapurkar and Haridas 2006). We denoted $\mathbf{v}_0$ and $\mathbf{u}_0$ as the $s \times 1$ left and right eigenvectors corresponding to the dominant eigenvalue λ_0 of the time-averaged matrix $\mathbf{A}$. Therefore, at each time step, the environmental state determines the projection matrix that applies, *i.e.*, if the environment at time t is in state i then $\mathbf{A}_t = \mathbf{B}_x$. However, we added a two-year lagged effect to consider the lag effect in the reaction norm between inflation and vital rates such that $\mathbf{A}_{t+2} = \mathbf{B}_x$.

Stochastic Population Growth

To examine the effect of environmental variability on humans' capacity to buffer through variability in vital rates, we calculated the stochastic growth rate. Specifically, we calculated the growth rate using a random sequence of $\mathbf{A}(t), \mathbf{u}(t)$, and $\mathbf{v}(t)$ by using a Markov chain simulation with 100,000 iterations. We discarded the first 500, adjusting for the transient dynamics (Haridas and Tuljapurkar 2005; Tuljapurkar et al. 2003). The growth rate approximation gives quantitatively accurate results when the coefficient of variation of vital rates is small, *i.e.,* ≤ 0.3 (Tuljapurkar 1989). However, the approximation describes the qualitative dependence accurately when the variability in vital rates is high.

Quantifying Demographic Buffering

To examine the response of the stochastic growth rate to the variability in vital rates, we calculated the stochastic elasticity with respect to variance in vital rates. Haridas and Tuljapurkar (2005) show that life history strategies to reduce the effect of variability in vital rates on the growth rate, $\log\lambda_s(\sigma) - \log\lambda_s(0)$, called demographic buffering, can be quantified by $\Sigma E_{a_{ij}}^{S^\sigma}$. Therefore, we computed $\Sigma E_{a_{ij}}^{S^\sigma}$ as a summary measure of proportional change in long-term stochastic growth rate due to change in variability of every matrix element, thus, directly quantifying the degree of demographic buffering.

Joint effect of variability and autocorrelation

To examine (H3) the joint effect of variance and autocorrelation on humans' capacity to buffer, we computed the sensitivity of the growth rate to variance-covariance and autocorrelation. Tuljapurkar (1982b) shows that the effect of positive autocorrelation is increasingly greater than negative correlation as $|\rho|$ approaches unity. Additionally, the effect is modulated by the damping ratio to make an effective autocorrelation always less than ρ (Tuljapurkar 1982b; Tuljapurkar and Haridas 2006). Therefore, to capture the effect of variability and autocorrelation, we have computed the growth rate, in terms of the sensitivities of λ_0, as

$$log\lambda_s \approx log\lambda_0 - \frac{1}{2\lambda_0^2}\sum_{m,n=1}^{s}\sum_{p.q=1}^{s} s_{mn}s_{pq}cov(mn,pq) + \frac{\rho}{2\lambda_0^2}\sum_{m,n=1}^{s}\sum_{p.q=1}^{s} S_{mn,pq}^{c}cov(mn,pq) \quad (2)$$

(Tuljapurkar and Haridas 2006). We have considered ρ as ν_1, the leading subdominant eigenvalue of **P,** which gives the longest environmental memory. Using the sensitivity matrix,

$\mathbf{S}^c$ we tested (H1) how sensitive λ_s is to autocorrelated variability in the vital rates. Large diagonal sensitivities $\mathbf{S}^c(mn, mn)$ identify the effect of variability in the presence of autocorrelation; off-diagonal elements give the effect of covariation.

Expected Findings

Here we tested the hypothesis that increasing variance with environmental autocorrelation has a negative effect on humans' capacity to buffer against variability in inflation (H1). To do so, we ran simulations of projection matrices for each of 76 examined countries across the parameter space of autocorrelation and stationary frequencies of inflation environment. Then we calculated long-term stochastic population growth rate, $log\lambda_s$ and sum of stochastic elasticities of growth rate with respect to variability in matrix elements, $\Sigma E^{\sigma^2}_{a_{ij}}$. Supporting our hypothesis, we find evidence for a negative effect of variance in vital rates on humans' capacity to buffer against variance in the inflation environment, measured as $\Sigma E^{\sigma^2}_{a_{ij}}$, in most countries. To examine the impact of autocorrelation we compared the simulation estimates of growth rate, $log\lambda_s$ for the autocorrelation, ν_1 values from -0.99 to $+0.99$ with increasing frequency. In support of our hypothesis, we found that the stochastic growth rate, $log\lambda_s$ increases with increasing stationary frequency and negative autocorrelation, in most of the 76 examined countries. This finding indicates that the effect of autocorrelation on growth rate and capacity to buffer is nonlinear across the environmental autocorrelation and stationary frequency space of the inflation environment.

We further test if the effect of positively autocorrelated variability in the inflation environment negatively affects the demographic buffering, and vice versa. To do so we measured the effect of interannual variability in matrix element on the demographic buffering as W_1, and the effect of autocorrelation as W_2. Specifically, we computed the summed effect of W_1 and W_2 as a function of stationary frequency of environment and autocorrelation. We observe that high negative autocorrelation with increasing variance in vital rates positively impacts the buffering capacity and long-term growth rate. Whereas positive autocorrelation with increasing variance in vital rates has a negative effect. Interestingly, we found that, as autocorrelation, ν_1 approaches -1 the effect of autocorrelation with increasing vital rates variance shows a small but positive impact on buffering and growth rate. However, as ν_1 approaches $+1$ the effect increases sharply. This finding indicates that the limits of the impact of positive autocorrelation being enormously greater than that of negative, especially as the absolute magnitude of autocorrelation approaches unity.

Our analysis provides an accurate approximation of the stochastic growth rate, $log\lambda_s$ and the structured demographic buffering in a Markovian inflation environment. In our empirical analysis, we showed the effect of variance in vital rates and environmental autocorrelation on humans' capacity to buffer against a wide range of variability patterns in the inflation environment. Our analytical approach can be applied to study the structured demographic buffering in a wide range of species and for all possible drivers of environmental variability. Therefore, this study makes a unique contribution to comparative and evolutionary demography.