

University of Groningen

Climate and creativity

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Published in:
Creativity Research Journal

DOI:
[10.1080/10400419.2018.1411571](https://doi.org/10.1080/10400419.2018.1411571)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2018

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Van de Vliert, E., & Murray, D. R. (2018). Climate and creativity: Cold and heat trigger invention and innovation in richer populations. *Creativity Research Journal*, 30(1), 17-28.
<https://doi.org/10.1080/10400419.2018.1411571>

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Climate and Creativity: Cold and Heat Trigger Invention and Innovation in Richer Populations

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To cite this article: Evert Van de Vliert & Damian R Murray (2018) Climate and Creativity: Cold and Heat Trigger Invention and Innovation in Richer Populations, *Creativity Research Journal*, 30:1, 17-28, DOI: [10.1080/10400419.2018.1411571](https://doi.org/10.1080/10400419.2018.1411571)

To link to this article: <https://doi.org/10.1080/10400419.2018.1411571>



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Climate and Creativity: Cold and Heat Trigger Invention and Innovation in Richer Populations

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Nobel laureates, technological pioneers, and innovative entrepreneurs are unequally distributed across the globe. Their density increases in regions toward the North Pole, toward the South Pole, and very close to the Equator. This geographic anomaly led us to explore whether stressful demands of climatic cold and climatic heat (imposed necessities) interact with economic wealth resources (available opportunities) in modulating creative culture—defined here as including both inventive idea generation and innovative idea implementation. Controlling for societal intellectualization, industrialization, and urbanization, results indicated that higher thermal demands, primarily cold stress and secondarily heat stress, hinder creativity in poorer populations but promote creativity in richer populations. Complementing their direct wealth-dependent effects, colder and hotter temperatures also exert indirect wealth-dependent effects on creative culture through lower prevalence of human-to-human transmitted parasitic diseases. Across 155 countries, the resulting ecotheory of creativity accounts for 79% of the variation in creative culture. The findings open up valuable perspectives on the creativity-related consequences of thermal climate—and climate change—in poor and rich populations.

Both climate and creativity distinguish human life. Throughout human evolution, climatic problems and difficulties—how to stay warm and dry, how to acquire and retain food, how to handle extreme weather—have required novel solutions and innovations. Not infrequently, these climatic threats and challenges seem to have been insurmountable. Especially in arctic and desert climates, the

creative responses required to survive and thrive has been so overwhelming that few ancestors migrated there. There is, indeed, a long and influential history of geographic differences in the amount of cold and heat to be handled imaginatively as human niche constructions (Van de Vliert, 2016). Perhaps, then, it should not come as a surprise that there is still worldwide variation in the prevalence of individual and cooperative creativity among contemporary inhabitants of differentially cold and hot habitats.

As reported herein, colder latitudes at a greater distance from the equator are home to higher rates of creativity—defined culturally here as including both inventive idea generation and innovative idea implementation. This link holds true in each of the Earth's four hemispheres. For example, in the northern hemisphere, Swedes and Swiss top the rankings for novelty in science, business, and arts; in the southern hemisphere, Australians and New Zealanders shine in similar creative achievements. Intriguingly, several populations at hotter latitudes including Barbadians, Bruneians, Ecuadorians, Malaysians, Seychellois, and Singaporeans do not tend to have much lower creativity rates. The ensuing

For helpful suggestions and critical comments on earlier versions of this article, we thank Elizabeth Cashdan, Serge Daan, Ellen Giebels, Onne Janssen, Maciej Karwowski, Evy de Koning, Izabela Lebeda, and Mark Schaller.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/HCRJ.

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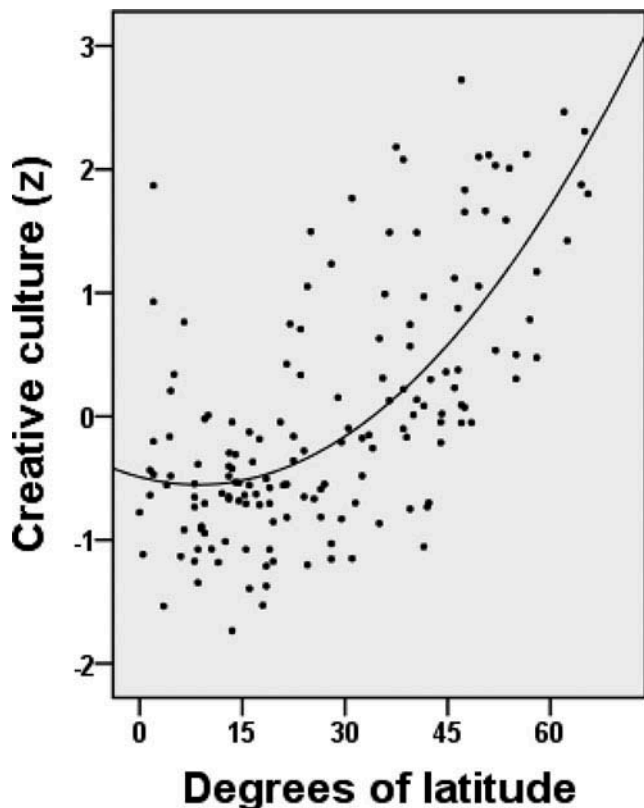


FIGURE 1 The latitudinal variation of creative culture across 155 countries (based on five cross-national measures of invention and innovation detailed in Electronic Supplement 1). Midrange distance from the equator accounts for 40% of the variation in creativity ($\Delta R^2 = .381$, $b = .439$, $n = 125$, $p < .001$ for the northern hemisphere; $\Delta R^2 = .345$, $b = .486$, $n = 109$, $p < .001$ for the eastern hemisphere; $\Delta R^2 = .293$, $b = .777$, $n = 30$, $p < .001$ for the southern hemisphere; $\Delta R^2 = .558$, $b = .542$, $n = 46$, $p < .001$ for the western hemisphere). The curvilinear tendency toward the equator accounts for an additional 6% of the variation in creativity ($\Delta R^2 = .067$, $b = .296$, $p < .001$ for the northern hemisphere; $\Delta R^2 = .057$, $b = .262$, $p < .01$ for the eastern hemisphere; $\Delta R^2 = .076$, $b = .361$, $p < .10$ for the southern hemisphere; $\Delta R^2 = .072$, $b = .250$, $p < .01$ for the western hemisphere).

J-shaped latitudinal variation of creative culture is visualized in Figure 1. Given that geographic latitude is merely an abstraction, this finding raises the novel question: Can climatic cold and heat account for the robust J-shaped relationship between latitude and creativity?

Earlier work has attributed greater societal creativity to more intellectual talent, social tolerance, and technology (e.g., Florida, 2002). Other more value-based explanations assert that greater societal creativity is preceded by lower levels of xenophobia, traditionalism, and conformity (e.g., Herbig & Dunphy, 1998). But such proximal explanations tend to be overly endogenous and insufficiently contextualized. More contextualized explanations trace creative culture back to exogenous precursors such as wheat rather than rice agriculture (Talhelm et al., 2014), migratory diffusion of knowledge (Acemoglu, Johnson, & Robinson, 2001), urban

concentration and cross-fertilization of diverse ideas (Andersson, Andersson, & Mellander, 2011; Jacobs, 1961), and economic affluence (Beteille, 1977; Lee, Florida, & Acs, 2004). The most exogenous explanation to date speculates that disease-causing parasites tend to thrive in warm ecologies characteristic of low latitudes (Cashdan, 2014; Talhelm et al., 2014), and that lower disease prevalence—and its psychological implications—at higher latitudes tends to favor scientific invention and technological innovation (Murray, 2014).

Although these explanations have produced a richer view of the cross-cultural variation in creativity, the underlying pieces of evidence can perhaps be better understood as interdependent, rather than parallel, markers of difference. The cited studies tend to offer single-factor explanations that fail to consider how these social, economic, and ecological factors operate simultaneously to impact creativity. To begin to better understand the modifying conditions and mediating links of the latitude-related causes of creativity, a more nuanced and broader theory is developed and tested here. This *ecothery of creativity* emphasizes the causal interplay between thermal climate (Hsiang, Burke, & Miguel, 2013; Van de Vliert, 2009), economic wealth (Beteille, 1977; Lee et al., 2004), and parasitic diseases (Cashdan, 2014; Murray, 2014).

EXPLAINING THE GEOGRAPHY OF CREATIVITY

Effects of Thermal Climate

All species on Earth must navigate toward an optimal environment that has neither too much cold nor too much heat. Humans, as warm-blooded animals, have evolved not only a conscious and unconscious awareness of needs for thermal comfort, nutrition, and health, but have also created ecologically-specific strategies to help satisfy these basic needs (e.g., exploiting the seasonal availability of plants and animals). Consequences of shrinking environmental control in colder and hotter habitats (Burke, Hsiang, & Miguel, 2015; Gailliot, 2014) include cognitive demands and affective stresses, which in turn lead to conative attempts to turn these demands and stresses into tangible objects. Climatically more demanding and stressful regions require more inventive and innovative uses of natural and artificial resources. Inventions involve the generation of new goals, means, or outcomes to the system of need satisfaction (e.g., biogenetic discoveries in crop production), whereas innovations involve the implementation of new combinations of already existing goals, means or outcomes within the system (e.g., biotechnological modification of crops).

Effects of Wealth Resources

Creative efforts to restore shrinking environmental control in harsher habitats are usually facilitated by the availability

of wealth resources. Money has become an integral part of the climatic ecosystem, being able to turn potentially threatening cold and heat into challenging opportunities (Van de Vliert, 2009, 2013a). In poor populations, threat appraisals may trigger more creativity purely out of necessity (Karwowski & Lebuda, 2013); more commonly, however, the psychological effects of the threats—closed-mindedness and risk aversion—may tend to hinder invention and innovation (Richter & Kruglanski, 2004). In rich populations, by contrast, challenge appraisals are thought to leave more leeway to develop and nurture open-mindedness, risk seeking, and creativity as a result (cf. Frederickson, 2001; Ryan & Deci, 2011; Schaller & Murray, 2008).

Liquid cash and illiquid capital offer opportunities of free choice in setting and achieving goals, including creative choices in satisfying basic needs. Perhaps most important, financial transactions and trade enable people to inventively and innovatively manage thermal demands and environmental stresses by acquiring clothing, housing, warming and cooling devices, meals, medical cure and care, and numerous other temperature-related goods and services (Parker, 2000). The greater creativity triggered by seasonal challenges in rich populations, compared to seasonal threats in poor populations, presumably has been gradually generalized and sublimated into a wider variety of inventions and innovations, as well as higher investments in institutionalized research and development. A preliminary study of the climato-economic origins of nations' creativity (Karwowski & Lebuda, 2013), albeit one that made no distinction between cold deviations and heat deviations from 22°C, largely supports this speculative logic.

Effects of Parasitic Diseases

Lower prevalence of infectious or pathogenic diseases is another component of the climatic ecosystem that may help counteract shrinking control over everyday life in colder and hotter habitats. Core suppositions are that: (a) Disease-causing pathogens tend to thrive in warm or temperate climates (Cashdan, 2014; Epstein, 1999; Murray, 2013; Talhelm et al., 2014), whereas both much colder and much hotter environments than 22°C are suboptimal because, just like humans, parasites can be easily frozen or burned to death; and (b) wealth resources are often used to control the incidence of pathogens. Core corollaries are that: (c) Lower prevalence of pathogens in colder and hotter habitats may increase creativity due to less illness, increased social interaction, and less conformity (Epstein, 1999; Fincher & Thornhill, 2012; Murray, 2014); and (d) this higher creativity is further strengthened in colder and hotter environments with wealthier inhabitants.

This research tested the possibility that a lower parasitic disease burden mediates the beneficial impact of thermal demands and wealth resources on invention and innovation. In a threatening context of stressful thermal demands and

financial poverty, the lower disease threat is expected to serve as a weakly positive or negative mediator between climate and creativity, overpowered as it is by closed-mindedness and risk aversion. In a challenging context of stressful thermal demands and financial wealth, however, the lower disease threat is expected to serve as a strongly positive mediator between climate and creativity, empowered as it is by open-mindedness and risk seeking. These expectations are specific to nonzoonotic or human-to-human transmitted diseases (such as measles, cholera, leishmaniasis, and leprosy) rather than zoonotic or animal-to-human transmitted diseases (such as lyme disease, rabies, and tularemia). This is so because nonzoonotic diseases are pre-eminently the ones that motivate people to avoid potentially infectious contacts with others (Fincher & Thornhill, 2012), thus inhibiting social network structures that are conducive to creative processes and outputs.

The Ecotheory of Creativity

The overarching idea is that the climatic ecosystem—consisting of thermal necessities, monetary opportunities, and their parasitic repercussions—shapes interdependent pressures on creativity. The visual integration of the proposed relationships in Figure 2 shows two pathways of wealth-dependent influence from climate to creativity—direct effects and indirect parasite-mediated effects of stressful thermal demands on creative culture. In contrast to oversimplified main-effect explanations (e.g., Acemoglu et al., 2001; Andersson et al., 2011; Florida, 2002; Lee et al., 2004; Murray, 2014; Talhelm et al., 2014), Figure 2 deliberately emphasizes interactive relationships between climatic, economic, and parasitic pressures on creative culture.

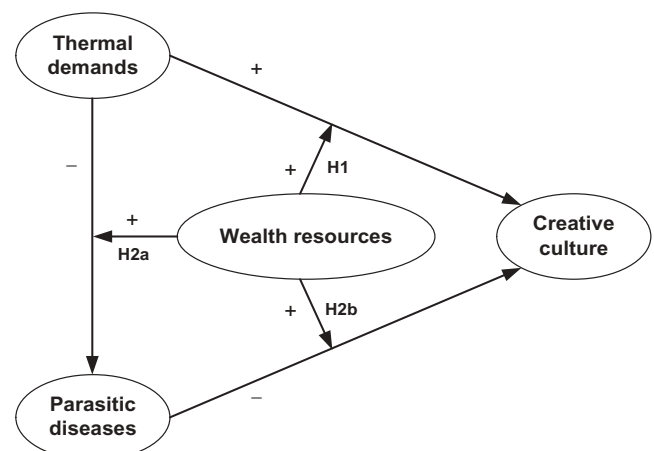


FIGURE 2 The ecotheory of creativity. The central hypotheses are that wealth resources strengthen the direct positive influence of stressful thermal demands of cold and heat on creative culture (H1), the direct negative influence of stressful thermal demands on parasitic diseases (H2a), and the parasite-mediated positive influence of stressful thermal demands on creative culture (indirect 2a-2b path of H2).

METHODS

Comparing Country-Level Data

A rigorous longitudinal test of the causal hypotheses in Figure 2 was not feasible because of the negligible changes in the relative geographic distribution of atmospheric temperatures over the previous centuries (Ditlevsen, Svensmark, & Johnsen, 1996). The next-best option, adopted here, was to analyze cross-sectional data under the plausible assumption that climatic constraints and their repercussions for the prevalence of parasitic diseases help modulate creative culture predominantly in a unidirectional way. In regression-based analyses of country-level data due attention was given to potential problems of countries as units of comparative analysis (see electronic supplement 2).

Sample of Countries

For the 155 countries listed in electronic supplement 1, data on latitude, creative culture, thermal demands, wealth resources, and parasitic diseases were freely collected from scientific publications and international sources. One-sample *t*-tests suggested that heat demands ($t = .322, n.s.$) and wealth resources ($t = .990, n.s.$) in this sample are representative of heat demands and wealth resources across all of the world's 232 independent and dependent territories. By contrast, a slight overrepresentation of countries with cold demands ($t = 2.590, p < .05$) enabled us to better identify the impact of cold conditions below 22°C.

Dependent Variable: Creative Culture

The following overlapping measures of invention and innovation were standardized and then additively combined: (a) Cornell University's global innovation index comprising five input pillars of creative goals and means, and two output pillars (<http://www.globalinnovationindex.org>); (b) the technology achievement index of the UN, which combines rates of patents and licenses, diffusion of innovation, and the like (<http://hdr.undp.org/en/reports/global/hdr2002>); (c) the World Economic Forum's survey assessment of less creative innovation versus more creative inventions (<http://www.weforum.org/issues/global-competitiveness>); (d) the rate of patent applications per country reported by the World Intellectual Property Organization (<http://www.wipo.int/ipstats/en/statistics/patents>); and (e) Nobel Prize laureates per capita, by country of birth (http://www.nobelprize.org/nobel_prizes).

Electronic supplement 3 contains an extended discussion of the aforementioned components of the index of creativity, and ample evidence of its internal consistency ($.642 < r < .932, p's < .001$), its representativeness ($.852 < r < .955, p's < .001$), and the equivalence of its meaning across cultures ($.636 < r_s < .928, p's < .01$).

Electronic supplement 3 also provides evidence of the external validity of the creativity measure using societal individualism and political democracy as criteria. Creative culture consistently increases with increasing individualism in autocratic polities ($b = .308, p < .01$), increasing individualism in democratic polities ($b = .553, p < .001$), increasing democracy in collectivist societies ($b = .218, p < .02$), and increasing democracy in individualist societies ($b = .462, p < .001$).

Predictors

Thermal demands

In this investigation, 22°C (~72°F) was adopted as a point of reference because 22°C is the approximate midpoint of the healthy thermoneutral zone, where the metabolic rate required for the clothed individual to maintain a core body temperature of 37°C is both minimal and independent of the ambient temperature (Gailliot, 2014; Parsons, 2003), and where abundant flora and fauna facilitates nutrition (Cline, 2007; Parker, 2000). Demands and stresses of atmospheric cold and heat differ qualitatively in downward versus upward direction of deviation from 22°C, and quantitatively in absolute degrees of deviation from 22°C. Qualitatively, heating and eating may necessitate more creativity in colder environments, whereas creativity regarding the mitigation of disease transition due to substances, germs, bacteria and insects may be more of a necessity in warmer environments (Cashdan, 2014; Talhelm et al., 2014). Quantitative modeling was used as it allows the integration of climatic, economic, and parasitic predictions of creativity, and the exclusion of confounding influences.

Climatic demands were operationalized across each country's major cities, weighted for population size, as degrees of deviation from 22°C. Specifically, cold demands are the sum of the downward deviations from 22°C for the average lowest and highest temperatures in the coldest month, and the average lowest and highest temperatures in the hottest month; heat demands are the sum of the upward deviations from 22°C for these four average temperatures (Van de Vliert, 2013b). Climatic cold and heat are distinct variables ($r = -.582, p < .001$). The country scores in electronic supplement 1 reveal that there are more cold demands ($M = 36.271, SD = 26.272$) than heat demands ($M = 21.497, SD = 8.039; t = 5.815, p < .001$), and more countries with prevailing cold demands ($n = 92$) than with prevailing heat demands ($n = 63$; binomial test, $z = 2.249, p < .02$).

Wealth resources

National income per capita was measured as the average log-transformed capacity of a country's currency to buy a given basket of basic goods and services in 2000, 2002, and 2004 (United Nations Development Programme [UNDP], 2002, 2004, 2006). Electronic supplement 1 gives mean

country scores; test-retest reliabilities, $r > .991$). Wealth resources had only a moderate overlap with cold demands ($r = .406, p < .001$) and heat demands ($r = -.312, p < .001$), thus minimizing the potential problem of multicollinearity in regression analysis.

Parasitic diseases

The prevalence of nonzoonotic and zoonotic diseases (Fincher & Thornhill, 2012; country scores in electronic supplement 1) were mutually related, yet distinct, variables ($r = .495, p < .001$).

Control Variables

Current points of historical trajectories of societal intellectualization, industrialization, and urbanization were controlled for as these processes are so entwined with increasing material wealth (see Table 1) that they might unintentionally confirm the ecotheory of creativity.

Intellectualization

Cognitive ability is an obvious antecedent condition of inventive idea generation and innovative idea implementation. There are differentially evolving increases in the average intelligence of a country’s inhabitants relative to other countries’ inhabitants (Lynn, 2007; Lynn & Vanhanen, 2006)—herein referred to as *intellectualization*. Despite some debate about the origins and comparative validity of national intelligence quotients, agreement exists that intellectualization is confounded with economic development (Hunt, 2012; Rindermann, 2012; Rindermann & Thompson, 2011). Consequently, intellectualization was controlled. National intelligence quotients, ranging from 64 in Mozambique to 108 in Hong Kong, were available for all countries in the sample ($M = 85.680, SD = 11.531$; Lynn & Vanhanen, 2006).

Industrialization

The industrializing past, too, may have sparked creativity that happens to covary with the climatic ecosystem. Each country’s position on the historical continuum from agriculture to industrial and service employment was approximated by the national percentages of employment in the agrarian sector (agriculture, fishing, and hunting), the industrial sector (manufacturing, mining, building, and public utilities), and the service sector (trade, transport, restaurants, hotels, finances, communications, and community and personal services; UNDP, 2004, 2007). The three employment percentages loaded on a single factor that accounts for 72% of the common variation. National factor scores were saved as a new variable to represent the extent to which each country is engaged in industrial and service activities. Industrialization scores range from 7 in Burundi to 99 in the United Kingdom ($M = 63.370, SD = 27.201$).

Urbanization

Cities function as creative sinks that concentrate human capital and diverse perspectives, which stimulate synthesis of ideas and subsequent inventive and innovative thinking (Andersson et al., 2011; Jacobs, 1961). As a consequence, the current degree of urbanization is a relevant control variable because the effects of the three components of the climatic ecosystem on creative culture might be confounded or mediated by it. The percentage of the total population living in urban areas, as defined by the country’s government (Parker, 1997), ranges from 6 in Burundi to 100 in Singapore ($M = 51.130, SD = 23.609$).

National culture

Societal institutionalization, social inequality versus equality, collectivism versus individualism, and similar socio-behavioral covariates of affluence (Hofstede, 2001; Lynn & Vanhanen, 2006; Triandis, 1995; Van de Vliert, 2009) were

TABLE 1
Correlations among the predictors, the control variables, and the dependent variable of creative culture.^a

Variables	1	2	3	4	5	6	7	8
1. Cold demands								
2. Heat demands	-.582 ^b							
3. Wealth resources	.406	-.312						
4. Non-zoonotic diseases	-.599	.384	-.682					
5. Zoonotic diseases	.045 ^c	.061 ^c	-.203 ^d	.495				
6. Intellectualization	.600	-.421	.715	-.670	.008 ^c			
7. Industrialization	.475	-.346	.848	-.764	-.248 ^d	.790		
8. Urbanization	.435	-.352	.767	-.583	-.165 ^d	.660	.828	
9. Creative culture	.547	-.430	.801	-.609	-.116 ^c	.717	.697	.665

^a $n = 155$.

^b p 's < .001 unless a superscript indicates otherwise.

^c $p > .15$.

^d $p < .05$.

not controlled for, as these cultural dimensions are considered too viciously close to the dependent variable of creative culture (for evidence, see electronic supplement 3).

RESULTS AND DISCUSSION

Conditional Process Analysis

The relatively complex ecotheory of creativity predicts that direct effects and indirect parasite-mediated effects of thermal demands on creative culture are modified by wealth resources. Regression-based conditional process analysis (Hayes, 2013; Preacher, Rucker, & Hayes, 2007) can handle this complexity. Specifically, Hayes's (2013) path diagram 59, an exact statistical representation of the conceptual path diagram in Figure 2, was used to estimate the predicted modulation of creative culture.

As detailed in electronic supplement 4, creative culture was regressed on the standardized measures of thermal demands and parasitic diseases, and their interactions with wealth resources. The 12-term regression equation included two ultimate predictors (cold and heat demands), the modifier (wealth resources), two mediators (nonzoonotic and zoonotic diseases), four two-way interactions (cold by wealth, heat by wealth, nonzoonotic by wealth, and zoonotic by wealth), and the three control variables—societal intellectualization, industrialization, and urbanization. This analysis produced bootstrap confidence intervals for making integrated inferences about direct effects and parasite-mediated effects of thermal demands on creative culture at the 10th, 25th, 50th, 75th, and 90th percentile of the distribution of wealth resources.

Confirmatory Testing

Correlations among all study variables are presented in Table 1. Table 2 reveals four effects of thermal demands on creative culture. First, there was a direct wealth-dependent path from cold demands to creativity (Table 2A, Figure 3A; H1 in Figure 2). This pathway suggests that colder temperatures lead to more invention and innovation only if greater wealth resources offer more challenging opportunities for necessary creativity. One narrow interpretation of this result is that only in conjunction with wealth resources does awareness of cold problems—cognitive demands, affective stresses, and conative efforts to restore control—nurture cold-based creativity. A broader interpretation is that climatic necessities interact with economic opportunities in modulating numerous cultural elements characterized by open-mindedness, risk seeking, and creativity.

There was also a direct poverty-dependent path from heat demands to creativity (Table 2B, Figure 3B; H1 in Figure 2). Hotter temperatures tend to produce less

invention and innovation where greater poverty is more threatening and prone to evoke stronger closed-mindedness and risk aversion. A plausible interpretation of this finding is that scorching summers overwhelmingly threaten poor populations, leading to greater levels of cognitive closure, affective seclusion, and suppressed creative potential for strategically mitigating heat demands and stresses.

The third path leads from cold demands through parasitic diseases to creative culture. This path is of special interest as it reincarnates the interaction effects on creativity of climate and wealth (Figure 3A) and climate and poverty (Figure 3B), but, as predicted, does so only through nonzoonotic diseases (Table 2C, Figure 3C) and not through zoonotic diseases (Table 2E). Countries with colder winters and cooler summers, and especially richer countries in such climates, have lower prevalence of nonzoonotic diseases (plotted in electronic supplement 5; H2a in Figure 2). The cumulative interaction of much lower disease prevalence and greater wealth-enabled challenges of cold demands further leads to more invention and innovation (right side of Figure 3C; H2b in Figure 2). By contrast, the cumulative interaction of somewhat lower disease prevalence and greater poverty-induced threats of cold demands reduces invention and innovation (left side of Figure 3C; H2b in Figure 2).

Finally, heat demands and wealth resources also had an interaction effect on creative culture via non-zoonotic (Table 2D, Figure 3D) rather than zoonotic (Table 2F) parasitic diseases. Countries with hotter summers and warmer winters, and especially richer countries in such climates, have lower prevalence of nonzoonotic diseases (plotted in Electronic Supplement 5; H2a in Figure 2), but only the cumulative interaction of much lower disease prevalence and greater wealth-enabled challenges of heat problems leads to more invention and innovation (right side of Figure 3D; H2b in Figure 2). A comparison of Figure 3B and 3D illustrates the conclusion that the threatening combination of heat and poverty reduces creativity directly without the help of parasitic diseases, whereas the challenging combination of heat and wealth tends to increase creativity in two steps—a lower disease burden, followed by higher creativity.

Together, the three components of the climatic ecosystem ($\Delta R^2 = .792$) and the control variables ($\Delta R^2 = .019$) accounted for 81% of the cross-national variation in creative culture (Table 2). This predictive power is all the more impressive as it is reached with synchronously measured variables, which exclude the detection of time-lagged effects. The results seem also convincing because the wealth-dependent pathways of influence, both the direct effects and the parasite-mediated effects, generalize from relatively large cold demands (Figure 3A and 3C) to relatively small heat demands (Figure 3B and 3D).

One limitation of the research methods used is that the seven largest countries in the sample—Australia, Brazil, Canada, China, India, Russia, and the United States—

TABLE 2

Effects of demands of climatic cold and heat on the prevalence of creative culture at five levels of wealth resources, based on the regression equation in the bottom-most section (155 countries). There is simultaneous support for the direct path of H1 in Figure 2 (sections A and B), and for the parasite-mediated 2a-2b path of H2 in Figure 2 (sections C and D)

A. Direct effects of cold demands on creative culture at five percentiles of wealth resources:						
	Wealth percentiles	<i>b</i>	<i>S.E.</i>	<i>95%-confidence interval</i>		
A	10th	-.028	.116	-.257	.201	
	25th	.039	.086	-.130	.209	
	50th	.139	.065	.011	.266	
	75th	.228	.084	.061	.395	
	90th	.290	.111	.070	.510	
B. Direct effects of heat demands on creative culture at five percentiles of wealth resources:						
	Wealth percentiles	<i>b</i>	<i>S.E.</i>	<i>95%-confidence interval</i>		
B	10th	-.148	.068	-.283	-.012	
	25th	-.106	.051	-.207	-.005	
	50th	-.045	.051	-.146	.055	
	75th	.010	.075	-.139	.159	
	90th	.048	.098	-.145	.241	
C. Indirect effects of cold demands through non-zoonotic diseases on creative culture at five percentiles of wealth resources:						
	Wealth percentiles	<i>b</i>	<i>Boot S.E.</i>	<i>95%-confidence interval</i>		
C	10th	-.156	.057	-.313	-.070	
	25th	-.087	.041	-.182	-.017	
	50th	.020	.042	-.053	.109	
	75th	.121	.060	.019	.256	
	90th	.193	.084	.064	.401	
D. Indirect effects of heat demands through non-zoonotic diseases on creative culture at five percentiles of wealth resources:						
	Wealth percentiles	<i>b</i>	<i>Boot S.E.</i>	<i>95%-confidence interval</i>		
D	10th	.039	.033	-.013	.114	
	25th	.003	.013	-.018	.038	
	50th	.005	.013	-.012	.040	
	75th	.063	.039	.008	.169	
	90th	.133	.068	.033	.308	
E. Indirect effects of cold demands through zoonotic diseases on creative culture at five percentiles of wealth resources:						
	Wealth percentiles	<i>b</i>	<i>Boot S.E.</i>	<i>95%-confidence interval</i>		
E	10th	-.005	.026	-.081	.027	
	25th	-.002	.027	-.058	.050	
	50th	.009	.033	-.052	.077	
	75th	.028	.053	-.089	.122	
	90th	.045	.078	-.136	.182	
F. Indirect effects of heat demands through zoonotic diseases on creative culture at five percentiles of wealth resources:						
	Wealth percentiles	<i>b</i>	<i>Boot S.E.</i>	<i>95%-confidence interval</i>		
F	10th	.003	.014	-.014	.054	
	25th	-.000	.005	-.013	.007	
	50th	.004	.012	-.019	.035	
	75th	.015	.029	-.033	.086	
	90th	.028	.048	-.061	.137	

(Continued)

TABLE 2
(Continued)

Conditional process analysis					
Predictors	<i>b</i>	<i>S.E.</i>	<i>p</i>	95%-confidence interval	
Cold demands	.136	.065	.037	.008	.264
Heat demands	-.047	.050	.354	-.146	.053
Wealth resources	.508	.078	< .001	.352	.663
Non-zoonotic diseases	-.044	.098	.653	-.237	.149
Zoonotic diseases	.017	.061	.778	-.104	.139
Cold x Wealth	.113	.067	.091	-.018	.243
Heat x Wealth	.069	.048	.155	-.026	.165
Non-zoonotic x Wealth	-.329	.066	< .001	-.460	-.199
Zoonotic x Wealth	.029	.052	.579	-.073	.131
Intellectualization	.021	.006	< .001	.009	.033
Industrialization	.003	.004	.444	-.004	.010
Urbanization	.000	.003	.909	-.006	.006
Total effect ^a			$R^2 = .811, F(12, 142) = 5.652, p < .001$		

^aThere is no problematic multicollinearity ($VIFs < 7.176$), and there are no outliers (Cook's $Ds < .175$).

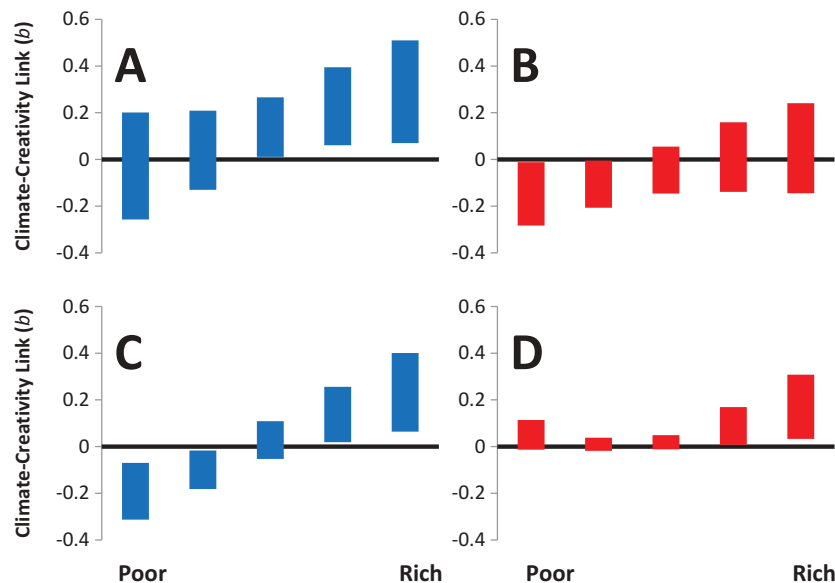


FIGURE 3 Visualization of the effects of demands of climatic cold and heat on creative culture. Shown are 95%-confidence intervals of the regression coefficients for thermal demands predicting creative culture at five percentiles of wealth resources. Results are broken down for direct effects of cold (A) and heat (B), and parasite-mediated effects of cold (C) and heat (D).

violated the requirement of reliable averages of cold demands, heat demands, and parasitic diseases (Cline, 2007). Another limitation is that the assumption of independent observations may be violated, not only in 31 small and geographically adjacent countries with similar prevalence levels of thermal demands and parasitic diseases (Cashdan, 2014; Cline, 2007), but also in 23 landlocked populations interacting with many surrounding neighbors. However, removing these 61 countries from the analysis produces nearly identical patterns of the 12 coefficients in the regression equation ($r_s = .94, p < .001$) and of the 40 confidence intervals in the effect estimation ($r = .91, p < .001$). This

supplementary analysis tentatively suggests that imperfect sampling has biased the results only to a trivial extent.

The detailed regression equation underlying the results does lead to a better understanding of the J-shaped relationship in Figure 1. Neither countries' midrange distance from the geographic equator ($\Delta R^2 = .00$), nor their midrange distance squared ($\Delta R^2 = .01$) predict any residual variation in creative culture from the model in Table 2. Conversely put, the ecotory of creativity fully accounts for the latitudinal variation of invention and innovation. Promising extensions of this line of research may lie in the interactive impact of necessities other than latitude-characteristic thermal demands (e.g., genetic

survival over time) and opportunities other than latitude-characteristic wealth resources (e.g., ecosystem services across geographies) on creative culture.

Disconfirmatory Testing

In addition to controlling for zoonotic parasitic diseases, intellectualization, industrialization, and urbanization, the possible influence of climatic precipitation was examined, but there was no evidence for differing cultural consequences of dry and wet environments (such as desert vs. wet climates). Average annual precipitation and its interactions with stressful cold demands and stressful heat demands did not improve the predictive power or otherwise inferentially change the regression equation for wealth-dependent effects of climatic cold and heat (electronic supplement 6, model 2).

A further robustness analysis investigated the effects of *informal* income through concealed activities to avoid taxes and other liabilities (Schneider, Buehn, & Montenegro, 2010). Informal income per capita did not interact with thermal demands in influencing creativity, at least not when controlling for the main and interactive effects of the formal wealth resources (electronic supplement 6, model 3). Repeating this analysis with income inequality instead of informal income as an extra predictor yielded inferentially similar results (electronic supplement 6, model 4). Reverse causation is implausible as creative culture and thermal demands show no interaction

effect on wealth resources. More parsimonious causation, too, is unlikely. The predictability of creativity drops from 79% to 56% if the influence of thermal demands is completely excluded, to 18% if wealth resources are excluded, and to 26% if parasitic diseases are excluded (electronic supplement 7). Thus, it is unlikely that the proposed explanation is too complex; each of the four effects contributes substantially to the explanatory power of the model.

Validatory Testing

The geographic distribution of our sample provides an opportunity for spatial cross-validation of the results. The analysis for the 104 countries from the northern hemisphere above the biological equator at 10°N (Aschoff, 1981) was run again and the resulting regression equation used for the prediction of creativity in the countries from the southern hemisphere below the biological equator ($n = 51$). Predictions were based on the following equation: $creativity = (.198 \times cold) + (-.033 \times heat) + (.587 \times wealth) + (.092 \times nonzoonotic) + (-.038 \times zoonotic) + (.085 \times cold \times wealth) + (.024 \times heat \times wealth) + (-.282 \times nonzoonotic \times wealth) + (.056 \times zoonotic \times wealth) + (.021 \times intellectualization) + (.004 \times industrialization) + (.000 \times urbanization)$. In support of the ecotheory of creativity, a clear positive relationship exists between the predicted creativity and the validation criterion of measured creativity in the southern hemisphere (see Figure 4).

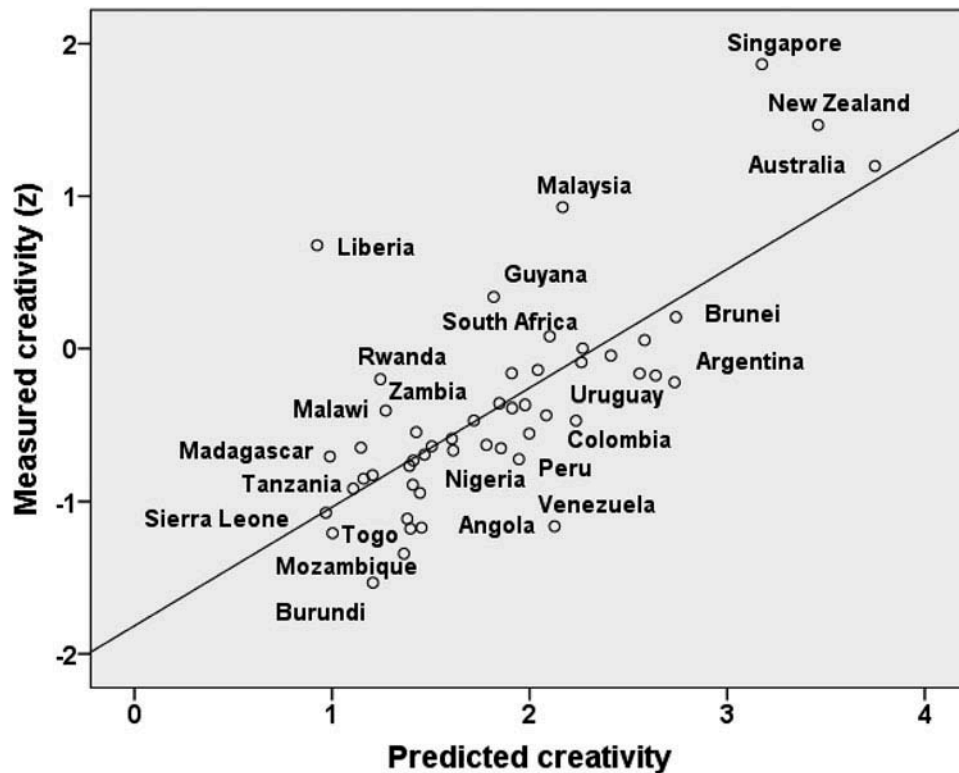


FIGURE 4 Cross-validation of the ecotheory of creativity. The explanatory power of the theory is apparent from the correspondence between predicted and measured creativity in 51 southern hemisphere countries ($r = .726, p < .001$).

Should the cross-sectionally valid ecotheory of creativity also have causal validity, it could be used to predict changes in creative culture in response to local changes of the climatic ecosystem (Van de Vliert, 2013a, 2013b). Cooling of already cold regions (Figure 3A and 3C), as well as warming of already hot regions (Figure 3B and 3D), may be expected to hinder creativity in poor populations but promote creativity in rich populations. If this forecast is correct, the availability of wealth resources becomes more instrumental for societal invention and innovation in thermally stressful environments. By contrast, cooling of hot regions around the equator and warming of cold regions at higher latitudes may be expected to reduce the creativity-related relevance of the resource disparity between poor and rich populations.

IMPLICATIONS

This study suggests that environmental precursors of creativity are operating in concert, rather than, as others have implicitly implied, in competition. The new understanding is that climatic cold and heat trigger inventiveness and innovativeness, that economic cash and capital serve as modifiers, and that nonzoonotic parasites serve as mediators who decrease disease burdens. And the ultimate implication of that understanding is that creativity as a core process of human functioning is in part dependent on incoming heat radiation from space. In an attempt to extend this advanced knowledge, a causal pyramid of creativity is proposed. It then generates the question whether climatic causation may also drive genetic causation of creativity.

A Causal Pyramid of Creativity

Trying to come to grips with the long chain of climato-economic and parasitic causes of creativity, it seems helpful to look to individuals, groups, national populations, and climatic environments of countries, hierarchically represented as a pyramid, with the layer of individuals at the bottom and climatic ecosystems at the apex. Each layer below the apex (a) has average baselines of invention and innovation, (b) gradually adjusts these baselines of creativity to stable environments, (c) treats higher social layers in the pyramid as moderately remote and moderately stable environments, and (d) treats the apex of climatic ecosystems of countries as the remotest and most stable environments. This top-down perspective on the baseline implications of the ecotheory of creativity has important theoretical, methodological, and practical implications.

Theoretically, the climatic ecosystem at the apex links the solar system to creativity at all cascaded layers and baselines of the pyramid, opening up new windows for psycho-behavioral scholars and practitioners. A timely and topical question, for instance, would be whether the climatic

ecosystem also links the solar system to the genetic make-up of creativity. Methodologically, an effect size in an individual-layer or group-layer investigation—i.e., a standardized deviation from the layer's baseline—holds only within the given climatic ecosystem at the apex. Consequently, results of creativity research can often not be generalized across individuals or groups inhabiting different habitats. A major leap forward might be made by developing statistical coefficients that report the geographic generalizability of locally established effect sizes. Practically, the country baselines of creativity in electronic supplement 1 can serve as fruitful anchors for multilevel research into individual-layer and group-layer creativity, and for contextualized interventions into creative processes.

Does Climatic Causation Drive Genetic Causation?

The proposed influences of the solar system on creativity are not at odds with the existence of genetic influences on invention and innovation (e.g., Runco, 2014; Vartanian, Bristol, & Kaufman, 2013). Rather, solar explanations place genetic explanations as ideal causal mediators between the ultimate influences of axial tilt and ecological variability, and the ultimately resulting creativity. A sticking point here is that many pit ecological explanations of human creativity against genetic ones. Solar and genetic explanations are not incompatible—to the contrary, they must be compatible, and they operate in tandem at different levels to produce variation in creativity.

Ecologically driven genetic selection—and between-group genetic variation due to region-specific environmental demands—is the cornerstone of many complex, uniquely creative human adaptations. One apt example is the selection for the ability to digest lactose beyond weaning in populations that had domesticated milk-producing animals (e.g., Cook, 2014; Durham, 1991). Notably, northwestern Europeans gained an adaptive advantage by gleaning a genetic mutation that allowed for lactose digestion driven by the preponderance of cows, sheep, and goats within their specific ecology. This particular phenotypic feature has been traced back to genotypic lactase persistence, and ultimately to insufficient ultraviolet-B radiation from the Sun at higher geographic latitudes (e.g., Curry, 2013; Durham, 1991; Itan, Powell, Beaumont, Burger, & Thomas, 2009).

Ecologically-driven selection for genes associated with creativity is similarly plausible, and future research into the causal chain that leads to local creativity may perhaps be modeled after research into the causal chain that leads to local milk consumption. Just like temperatures relate the solar system to genetic lactase persistence and cultural milk consumption, the climatic ecosystem may form genetic links between the solar system and creative culture. In the case of milk culture, climatic cold in northwestern Europe and climatic heat in Western Africa and Southern Asia have led to selection for different genes that mediate between the

solar system and societal culture (Bloom & Sherman, 2005; Curry, 2013). Similarly, climatic cold and climatic heat might trigger selection for distinct genotypes as mediators of the solar impact on invention and innovation in poor and rich populations.

SUPPLEMENTRY MATERIAL

Supplemental data for this article can be accessed on the [publisher's web site](#).

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