



OPEN Modernization, collectivism, and gender equality predict love experiences in 45 countries

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Recent cross-cultural and neuro-hormonal investigations have suggested that love is a near universal phenomenon that has a biological background. Therefore, the remaining important question is not whether love exists worldwide but which cultural, social, or environmental factors influence experiences and expressions of love. In the present study, we explored whether countries' modernization indexes are related to love experiences measured by three subscales (passion, intimacy, commitment) of the Triangular Love Scale. Analyzing data from 9474 individuals from 45 countries, we tested for relationships with country-level predictors, namely, modernization proxies (i.e., Human Development Index, World Modernization Index, Gender Inequality Index), collectivism, and average annual temperatures. We found that mean levels of love (especially intimacy) were higher in countries with higher modernization proxies, collectivism, and average annual temperatures. In conclusion, our results grant some support to the hypothesis that modernization processes might influence love experiences.

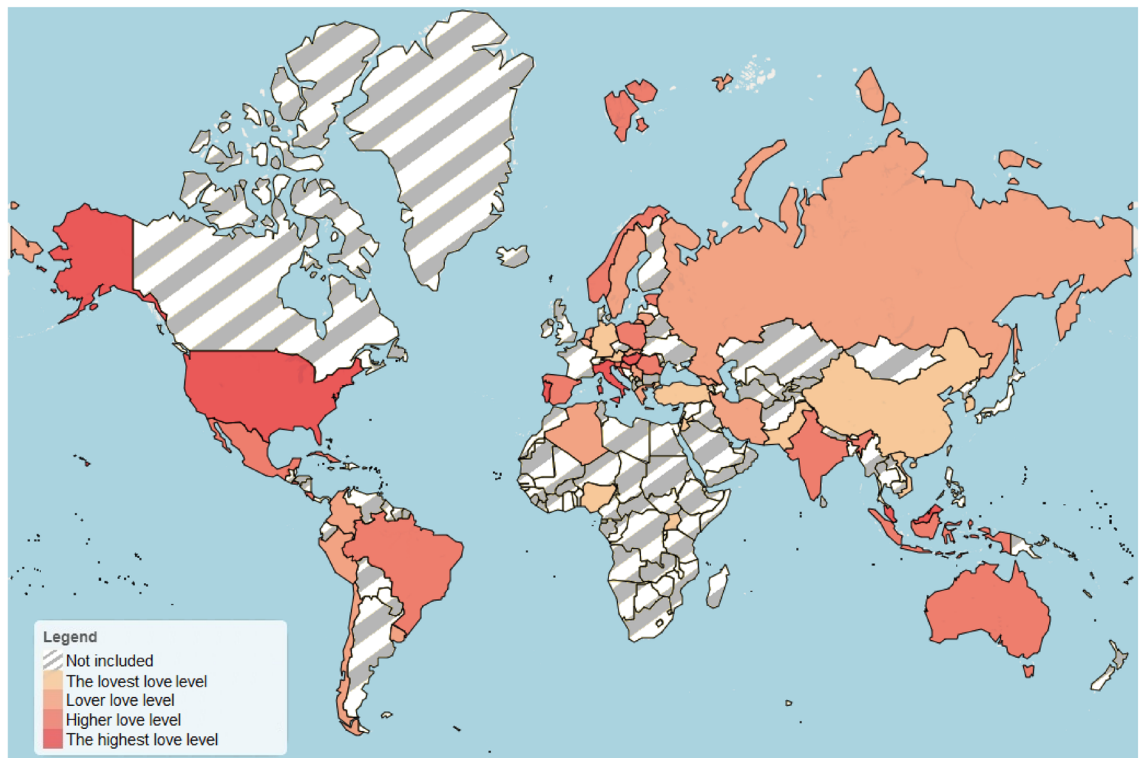
Many studies have attempted to describe the phenomenon of love. However, only a limited number of scholars have explored love feelings and experiences from a cross-cultural perspective (for notable exceptions, see, e.g.,^{1–4}). Even fewer scholars have focused on the observed differences in love levels across cultures (see, e.g.,^{5–7}). Yet, such studies provided firm evidence that love varies across cultures^{8,9}. Thus, in the present study, we aimed to investigate which cultural and environmental factors might be most pertinent to love experiences.

One of such factors may be the country's level of modernization^{10,11}. Modernization has many meanings, but in the present paper, we define it as a permanent process carried out through reform, education, and innovation, which today means a transition to an industrial and urbanized society^{12,13}. This hypothesis has been supported by theories and observations of classical humanists^{14,15} and a few empirical studies. For instance, Belsky et al.¹⁶ surmised that when children are exposed to harsh physical environments and economic hardships (as in cultures with lower modernization indexes), they tend to exhibit lower levels of romantic love in adulthood. Conversely, when children are provided with sufficient health care, education, and resources (as in cultures with higher modernization indexes), they may experience more intense love and be more emotionally engaged with their partners^{17,18}. Thus, it is possible that growing importance of romantic love in adulthood stems from changes in parental emotional investments and better living conditions. Baumard et al.¹¹ provided some evidence for such claims. Based on the refined literary analysis of almost 4000 years, Baumard et al. showed that incidences of love increased throughout history with economic development.

Another potential sociocultural factor that might influence love experiences is a classical construct in psychology, namely, individualism-collectivism. From a psychological perspective, collectivism is a value characterized by an emphasis on cohesiveness and prioritization of the group over the self^{19,20}. Some studies suggested that level of collectivism influences mate choice and acceptance of arranged marriages²¹, as well as understanding and endorsing the concept of romantic love in romantic relationships⁵. In more collectivistic countries (such as India²²), love before marriage can be considered a “disruptive element” motivated by selfish interest, which undermines loyalty to family. On the contrary, love is regarded as a basis for marriage among more individualistic Americans^{7,23}. Thus, the level of cultural individualism might relate to love patterns in the given society.

Gender equality is the third country-level aspect that is vastly hypothesized to differentiate love experiences across cultures. De Munck and Korotayev²⁴ analyzed Rosenblatt's²⁵ data, which consisted of 75 societies, and found that societies in which premarital sex and/or adultery are permitted for both men and women rate romantic love as a more important prerequisite of marriage than do societies in which either one is prohibited. Thus, when women are treated more equally, it might entail their higher agency in choosing with whom they would like to get married (most likely, with someone they love). Furthermore, based on the archival descriptions of traditional societies, the same authors²⁶ showed that various factors, possibly related to relationships' intimacy (e.g., spending leisure time together), significantly predict female status in society. Both analyses are intriguing, but they face similar shortcomings. Authors utilized archival data, which might not reliably represent explicit love levels in analyzed societies. Hence, testing the above hypotheses in contemporary societies that differ on the gender equality continuum could shed more light on the role of gender equality in the love landscape.

To test predictions about cultural differences in love experiences, we conducted a large-scale study of romantic relationships in 45 countries and territories. We tested if country-level modernization indexes, including the Human Development Index (HDI), World Modernization Index (WMI), Gender Inequality Index (GII), and level of collectivism, are related to levels of love across different countries. Many well-known theories of love in the social sciences highlight that love consists of passionate (intense and arousing) and companionate (tender and affective) elements. Such a distinction can also be found in Sternberg's Triangular Theory of Love²⁷.



Note: gray strips represent countries not included in the study, the lightest orange—countries with the lowest love levels (scores between 6.49 to 7.35), lighter orange—countries with lower love levels (scores between 7.36 to 7.61), darker orange—countries with higher love levels (scores between 7.62 to 7.78), the darkest orange—countries with the highest love levels (scores between 7.79 to 7.94) on a scale 1–9. The map was generated using Heatmapper (<http://heatmapper.ca/geomap>; Creative Commons Attribution-ShareAlike 2.0 Generic).

Figure 1. Levels of love (comprised of 45 items from the Triangular Love Scale) across the countries.

Sternberg has stated that love consists of intimacy, passion, and commitment. We decided to follow Sternberg's theory because at least two of its components (i.e., intimacy and passion) perfectly align with our aims. The first component—intimacy—refers to closeness, connectedness, communication, and caring. The second component—passion—pertains to romance, excitement, and physical arousal. Furthermore, as previous studies have shown that environmental variation in temperature induces greater social proximity²⁸, influences preferred interpersonal distance²⁹, interpersonal touch in close relationships³⁰, and affects emotional expressiveness³¹, we decided to control for each country's average annual temperature. Because relationship length can affect the intensity of the love components³, and the average lengths of relationships varied across the countries we surveyed, we controlled for it in the analyses. We also controlled for sex, as men and women tend to experience love differently^{32,33}.

Results

Figure 1 presents levels of composite love scores (mean love comprised of 45 items) across countries. The analyses of skewness and kurtosis of the love scales did not provide evidence for the violation of the normality assumptions for large samples. Correlations between variables of interest are presented in Table S1 in the Supplementary Material (SM). Next, we proceeded with multilevel models. Based on the high multicollinearity ($VIFs > 5$) when computing models with subscales of love as outcome variables and modernization indexes (WMI, GII, and HDI) as predictor variables (raw correlations between these variables ranged from $r = 0.86$ to $r = 0.93$, suggesting that, despite different names, they all might fall under the same umbrella of modernization), we decided to run three separate models for each of the love components. In each of these models, we entered either WMI, GII, or HDI and the remaining variables of interest (country-level collectivism, annual average temperatures, and participants' sex and relationship length) as predictor variables. The outcome variables were the composite TLS-45 score (a mean of 45 items) and a composite score (a mean of 15 corresponding items) of each of the love subscales (i.e., intimacy, passion, and commitment). Here, we present the results of the models that explained the most variance (see Table S2 in the Supplementary Material for a comparison of explained variance), that is, models with HDI (see Table 1).

The results showed that HDI and country-level average annual temperatures were positively related to the STLS-45, intimacy, passion, and commitment, while country-level collectivism was positively related to the STLS-45, intimacy, and commitment. That would mean that inhabitants of more modernized countries with higher

	STLS-45				Intimacy				Passion				Commitment			
	β	SE	95% CI	<i>p</i>	β	SE	95% CI	<i>p</i>	β	SE	95% CI	<i>p</i>	β	SE	95% CI	<i>p</i>
Fixed effects																
HDI ^a	0.233	0.043	[0.043, 0.148]	<0.001***	0.312	0.046	[0.046, 0.221]	<0.001***	0.143	0.049	[0.049, 0.047]	0.004**	0.215	0.039	[0.039, 0.139]	<0.001***
Collectivism ^b	0.074	0.033	[0.033, 0.010]	0.023*	0.094	0.035	[0.035, 0.026]	0.007**	0.054	0.037	[0.037, -0.018]	0.145	0.059	0.029	[0.029, 0.001]	0.045*
Temperature ^c	0.099	0.035	[0.035, 0.031]	0.004**	0.084	0.037	[0.037, 0.012]	0.023*	0.118	0.039	[0.039, 0.041]	0.003**	0.077	0.031	[0.031, 0.016]	0.014*
Sex ^d	-0.016	0.011	[0.011, -0.038]	0.152	0.027	0.011	[0.011, 0.006]	0.012*	-0.042	0.011	[0.011, -0.064]	<0.001***	-0.022	0.011	[0.011, -0.043]	0.055
Relationship length ^e	-0.01	0.011	[0.011, -0.032]	0.363	-0.025	0.011	[0.011, -0.046]	0.021*	-0.076	0.011	[0.011, -0.098]	<0.001***	0.081	0.011	[0.011, 0.059]	<0.001***
Random effects																
Variance	0.030				0.035				0.042				0.023			
Variance SD	0.174				0.188				0.205				0.150			
ICC	0.035				0.043				0.045				0.026			
Pseudo r^2	0.032				0.065				0.021				0.035			
df _{residuals}	7532				7532				7524				7459			
Deviance	20,192				19,720.7				20,612.6				20,081.5			

Table 1. Results of the multilevel linear models regressing love components (i.e., STLS-45, intimacy, passion, and commitment) on countries' levels of Human Development Index (HDI), Collectivism level, annual average temperature, and participants' sex and length of relationship (in months), with participants nested within countries. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. ^aHuman Development Index, ^bCollectivism-in-group favoritism, ^cTemperature–Average annual temperatures, ^dParticipants' sex with men as a reference group, ^eParticipants' relationship length in months.

average annual temperatures would, on average, experience higher levels of all love components. Furthermore, more intimacy and commitment would be experienced by those from more collectivistic countries. We also found evidence that, controlling for other factors in the model, women had a higher mean level of intimacy but a lower mean level of passion than men. Furthermore, the longer the relationship, the lower the mean level of experienced intimacy and passion, but the higher the mean level of commitment.

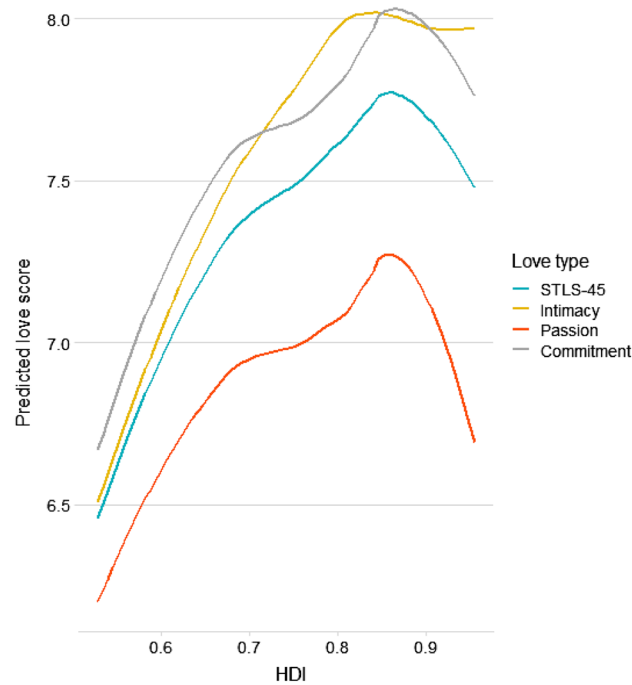
A similar pattern of results was yielded in the case of the two other proxies of countries' modernization levels. World Modernization Index was positively and Gender Inequality negatively related to the STLS-45 ($\beta = 0.181$, $p < 0.001$, pseudo $r^2 = 0.018$, $\beta = -0.138$, $p < 0.001$, pseudo $r^2 = 0.011$, respectively), intimacy ($\beta = 0.264$, $p < 0.001$, pseudo $r^2 = 0.046$, $\beta = -0.178$, $p = 0.002$, pseudo $r^2 = 0.024$, respectively), and commitment ($\beta = 0.169$, $p = 0.007$, pseudo $r^2 = 0.022$, $\beta = -0.142$, $p < 0.002$, pseudo $r^2 = 0.019$, respectively), see Tables S3–S4 in the SM for detailed results. We have also tested the above models with participants' age as a control variable. However, because participants' age and relationship length were highly correlated ($r = 0.83$), we did not introduce age simultaneously but rather interchangeably with relationship length. The patterns of results between love components and cultural and environmental variables remained the same, except for country's collectivism level, which ceased to be significantly related to intimacy (see Tables S5–S7 in the Supplementary Material).

As we observed stronger effects for intimacy than passion, in an explorative vein, we also tested for models with passionate love (i.e., passion to intimacy ratio) as an outcome variable. We found that the amount of passion to intimacy ratio was lower in countries with higher modernization indexes (see Tables S3, S4 and S8 in the SM for details).

In the last step, we tested for non-linear relationships between the outcome and predictor variables. As became evident from the scatterplots (see Fig. 2 and Figs. S1–S4 in the SM), after a certain threshold of modernization (e.g., ~ 0.85 in the case of HDI), mean levels of STLS-45, passion, and commitment tended to decrease. These conclusions were further confirmed by the results of the multilevel models, which included the squared term of modernization indexes (see Tables S9–S11 in the SM for detailed results).

Discussion

Many descriptive works show how love experiences may change with various levels of modernization^{34,35}. Other study supported such claims based on the analysis of incidences of love in narrative fiction throughout centuries¹¹. However, based on quantitative, cross-cultural data, our study is the first to provide evidence on how love experiences vary concerning different levels of human development and modernization indexes. We observed that, in general, participants from countries with higher (compared with countries with lower) levels of HDI, World Modernization Index, and gender equality experienced more love with their partners, controlling for participants' sex, relationship length, countries' average annual temperatures, and collectivism level. However,



Note. HDI—Human Development Index.

Figure 2. A graphical representation of the non-linear relationship between predicted love scores and Human Development Index (controlling for country's collectivism, average annual temperature, and participants' sex and relationship length).

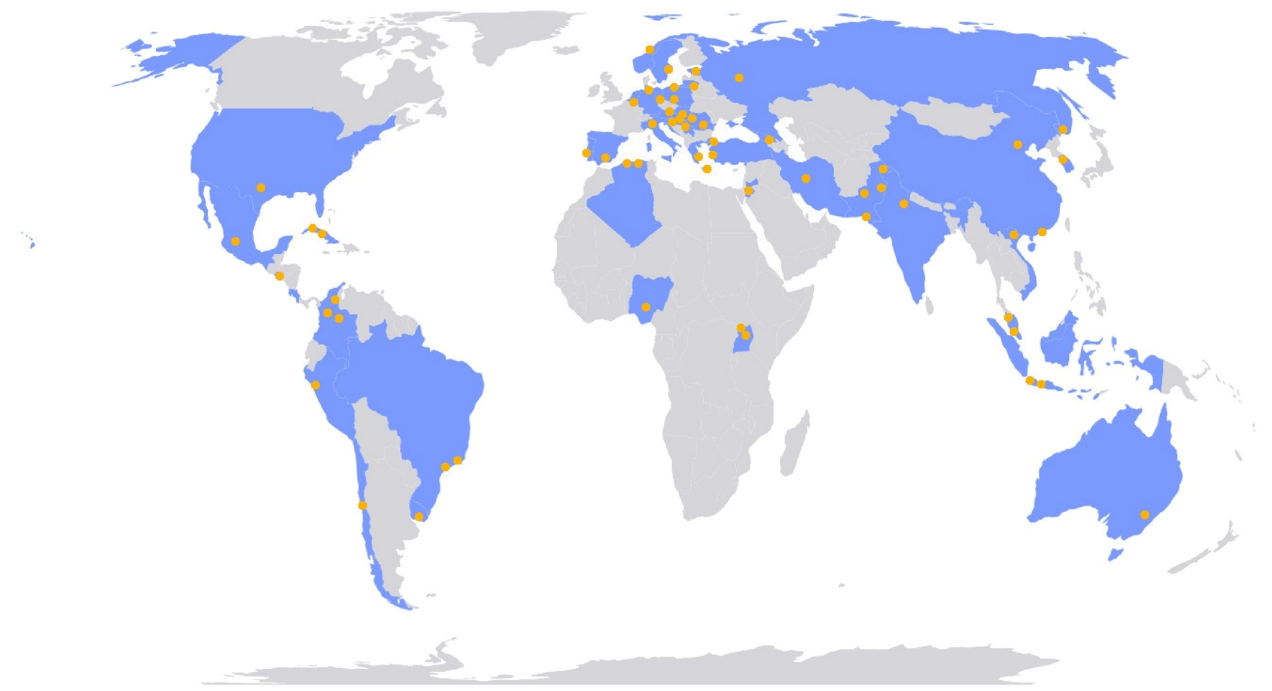
after reaching a certain, relatively high threshold of modernization (e.g., in the case of HDI—0.85), mean love levels tend to drop. Overly simplifying, we can conclude that more modernized countries have a higher level of all love subscales (though this effect is more pronounced for intimacy than passion), but the highest levels of modernization do not promote intense love experiences.

Furthermore, the results provided tentative evidence that higher mean levels of intimacy and commitment are positively related to countries' level of collectivism. It is especially interesting, considering that previous studies highlighted the importance of romantic love in relationships established in more individualistic cultures^{7,23,26} as opposed to more collectivistic cultures, in which, historically, arranged rather than love marriages have been more prevalent^{36,37}. On the other hand, collectivistic values promote a more relational view of romantic relationships³⁸. Thus, individuals from more collectivistic countries might be more altruistic towards their partners^{5,39}, which could naturally lead to more intimate and stronger bonds between the lovers⁴⁰. However, the observed relationships ceased to be significant when controlling for participants' age. Also, we did not observe any links between passion level and country's collectivism index. Considering the most recent cultural changes in collectivistic values in various countries⁴¹, future studies could investigate whether individual levels of collectivistic beliefs might be more related to experiences love than country-levels of collectivism.

Relatively modest relationships between modernization indexes and passion suggest that passion is rather stable across different modernization levels, and that what carries the relationship between the passionate love (i.e., passion to intimacy ratio) and modernization indexes is higher intimacy in countries with higher modernization indexes. A growing body of research provides evidence for biological antecedents of passion and its role in reproduction (see, e.g.,^{42–44}), and thus, the stability of passionate experiences across various countries seems unsurprising. Furthermore, in line with previous works^{3,44,45}, we observed lower levels of passion and intimacy, and higher levels of commitment among participants with longer relationship duration.

However, questions regarding the mechanisms behind the observed patterns of changes in intimacy/commitment are more challenging to answer. The simplest explanation might be that people from countries with higher modernization indexes tend to emphasize the friendship aspect of relations with their partners⁴⁶. Indeed, some studies provided evidence that individuals from countries with higher modernization indexes expect love to be based on mutual attraction and emotional closeness^{31,47}. Apart from the environmental and economic factors already tackled in the introduction (i.e., the growing importance of romantic love in adulthood possibly resulting from changes in parental emotional investment and better living conditions^{11,16,48,49}), we can also hypothesize other possible explanations.

For instance, cultural changes stem from processes of democratization, emancipation of love^{34,50,51}, gender shifts, and increasing gender equality^{52,53}. Because love becomes increasingly dependent on the capitalist market, such processes may also promote specific love patterns (that is, more intimate love but not that much of sexual love^{47,54}). We might also consider social changes in terms of cultural perception of reproduction or, in general, postponed reproduction in countries with higher modernization indexes^{55,56}. Several of these factors may be



Country: Cities where the data was collected		
Algeria: Algiers, Setif	Greece: Crete, Athens	Portugal: Lisbon
Australia: Canberra	Hungary: Pécs, Budapest, Várpalota, Székesfehérvár, Veszprém, Zalaegerszeg	Romania: Bucharest
Austria: Vienna	India: Delhi	Russia: Moscow, Ussuriisk
Belgium: Luovain la Neuve	Indonesia: Yogyakarta, Jakarta	Serbia: Nis
Brazil: Rio de Janeiro, São Paulo	Iran: Shiraz	Slovakia: Trnava, Nitra
Chile: Santiago	Italy: Milan	Slovenia: Ljubljana, Maribor
China: Hong Kong, Beijing	Jordan: Ma'an	South Korea: Seoul
Colombia: Bogota, Cucuta, Tunja	Lithuania: Vilnius	Spain: Granada
Costa Rica: San José	Malaysia: Kuala Lumpur	Sweden: Stockholm
Croatia: Zagreb	Mexico: Morelia	the Netherlands: Amsterdam
Cuba: Havana, Verda Nueva, Consolacion del Sur	Nigeria: Nsukka	Turkey: Izmir, Istanbul
El Salvador: San Salvador	Norway: Trondheim	Uganda: Kampala, Gulu
Estonia: Tartu	Pakistan: Lahore, Dera Ghazi Khan, Istambad, Karachi	United States: Austin
Georgia: Tiblisi	Peru: Lima	Uruguay: Montevideo
Germany: Dresden	Poland: Brzeg, Wrocław, Gdańsk	Vietnam: Hanoi

Note: The map was generated using the react-simple-maps library, which allows open use, copying and modification (including sale). Made available under the MIT license (<https://github.com/zcreativelabs/react-simple-maps/blob/main/LICENSE>). The author of the library is Richard Zimmerman.

Figure 3. Locations of data collection. Countries (in blue) with corresponding study sites (cities in orange).

responsible for the observed increasing role of intimacy in societies with higher modernization indexes. Future research should focus on disentangling modernization components, which would shed more light on which specific factors drive the observed patterns.

Furthermore, we observed a distinctive drop in the mean levels of love among participants from countries that reached a relatively high level of modernization (e.g., in the case of HDI, the threshold was 0.85). This suggests that, although country's economic development generally promotes more intense love experiences, reaching a certain developmental point might reverse these beneficial love effects. Such hypotheses have been indirectly laid by ethologists studying animal behaviors^{57,58}. For instance, in a classical study, Calhoun⁵⁷ observed that mice thrived when granted unlimited access to all necessary resources. However, mice started to lose interest in mating and reproduction when the situation was too good for too long. We can only speculate to which extent such an animal model might apply to humans.

Interestingly, research on the role of temperature in social interactions evokes heated discussions. We found some evidence that a country's average temperature is positively related to love experiences. When controlling for other factors, we found that participants from countries with higher annual temperatures reported higher levels of love (though this effect was the strongest for passion). However, raw correlations showed the opposite patterns, meaning that participants from countries with higher temperatures experienced lower intimacy and commitment levels. As results of previous studies also yielded contradictory conclusions^{28,29}, future investigations might attempt to deepen our understanding of the role of climate and temperature on humans' feelings and behaviors.

Although the current study sheds new light on the cultural evolution of love, it is not free of limitations. First, despite recruiting a relatively large number of participants from various cultures, one needs to bear in mind that the studied sample was not representative of any of the 45 countries. Moreover, our participants were relatively

well-educated and from urban areas (see Fig. 3), which makes them even less representative of less modernized countries. Second, although we used one of the most famous love scales, the Triangular Love Scale²⁷, the scale has been criticized for high correlations between love components^{59,60}. Furthermore, the TLS might not reliably distinguish participants with high levels of love⁶¹. As love measures are not perfectly correlated (their correlations tend to vary from 0.00 to even 0.83, see^{62,63}), it would be interesting to test the present results' robustness using different love measures. Third, we have focused on cultural and environmental variables at the country-level. Future studies could investigate whether individual-level factors identified in the present study contribute to love experiences in a similar vein. There is some evidence that, for instance, psychological collectivism might impact love patterns differently⁶⁴.

In conclusion, our study—one of the largest studies on cross-cultural differences in love experiences to date—provided evidence that, at least at the beginning of the twenty-first century, love is a near universal human experience. The results of the present investigation offer valuable insight into cultural and environmental factors related to countries' variability of love experiences. Although our research is correlational and no causal conclusions can be made, one may hypothesize that cultural changes in the level of a country's modernization index may affect patterns of love (i.e., may increase experiences of intimacy and commitment). More studies conducted in countries with lower levels of modernization using a longitudinal design might address this hypothesis.

Our study showed that love experiences differ across cultures. The results corroborate previous research findings on similarities and differences in how people chose their love partners⁶⁵ and how their choices affect their relationship satisfaction^{66,67}. However, as a concluding remark, we would like to highlight that we believe there is no better or worse way to experience love. On the contrary, understanding different love patterns may be crucial in studying the vast phenomenon of love. Exploring how love differs across cultures may result in identifying the love hardships of couples from different cultural backgrounds, which may, *inter alia*, promote developing more accurate and effective strategies in couple counseling.

Methods

Ethical statement. All participants gave written informed consent to participate. The study protocol was approved by the Institutional Ethics Committee at the Institute of Psychology at the University of Wrocław. Furthermore, all methods were performed in accordance with the guidelines of the Declaration of Helsinki. The other co-authors acquired ethical consent at their institutions when necessary. Russian data were collected in line with the state assignment # 01201730995 of the Institute of Ethnology and Anthropology (MB and DD).

Participants. Data for the present study were obtained from our published dataset³, which reported a large-scale study of sexual and romantic relationships conducted in 45 countries and territories in 2018 (see, e.g.,^{3,30,68}).

Only participants 18 years old or above were invited to participate in the study. Approximately half of the sample was recruited from outside of the university community. The original sample comprised 11,422 participants from 45 countries. Herein, we analyze data only from participants who reported being in a relationship (i.e., dating, engaged, or married) and completed all information about their relationship (i.e., type and length). As eight countries had small sample sizes (Colombia $n = 22$, El Salvador $n = 42$, Germany $n = 57$, Greece $n = 49$, Indonesia $n = 23$, Iran $n = 22$, Jordan $n = 28$, Nigeria $n = 36$), and the sex disproportion was substantial (i.e., below 40% of men or women) in 17 countries (Austria, Chile, Colombia, El Salvador, Germany, Greece, Iran, Italy, Nigeria, Peru, Portugal, Slovakia, Spain, Uganda, USA, Uruguay, Vietnam), we recruited additional participants so that at least 70 individuals would represent each country and so that the proportion of each sex would be no more imbalanced than 40% to 60%. New participants (18 years or older, currently in a relationship: dating, engaged, or married) were recruited in two ways: first, by posting the invitation to participate in the study in various groups on social media ($n = 134$) and with the use of an outsourcing company ($n = 462$). We increased the sample size to increase the number of analyzed countries and to ensure that the observed relationships were not spurious due to the impact of variability stemming from the abovementioned reasons. Importantly, increasing the sample size ($n = 596$) did not change any of the main results in our study (see Tables S12–S14 for results of the analyses based on the original dataset). All additional participants were distinguished in the database (which can be found in the Supplementary Material, under the link: <https://figshare.com/s/25d3cc3ec48e6b5a6d64>). The final sample consisted of 9,474 participants (56% women) from 45 countries (mean age = 30.53, $SD = 10.95$), with average relationship length of 87.46 ($SD = 104.56$) months. Detailed information about the participants and concerning the countries can be found in the SM (Table S15). Figure 3 shows an overview of countries and sites where the data were primarily collected.

Procedure. The data from the large-scale study were collected simultaneously across all study sites. We exercised great care to ensure similar recruitment methods in all countries. Before the data collection, each collaborating researcher got acquainted with detailed study protocols. In countries where English was not a primary language, collaborating researchers performed a forward-back translation by separate translators when possible⁶⁹. Participants were not compensated for their participation in the study. The study was conducted before the COVID-19 pandemic. After providing informed, written consent to participate in the study, participants were given a set of questionnaires, including the current love scale and several unrelated questionnaires about romantic relationships (see, e.g.,^{68,70}). Additional online data were collected in 2021 by the two first authors (via social media and the outsourcing company).

Variables. In the present study, we used the 45-item version of the Sternberg's Triangular Love Scale (STLS)²⁷. It consists of 15 items about intimacy (e.g., *I share deeply personal information about myself with...*), 15 items about passion (e.g., *Just seeing... excites me*), and 15 items about commitment (e.g., *I have confidence in*

the stability of my relationship with...). Answers range from 1—*Not at all*, to 9—*Extremely*. The scale was highly reliable: Cronbach's α for the STLS-45 = 0.97, $\alpha = 0.94$ for intimacy, $\alpha = 0.94$ for passion, and $\alpha = 0.95$ for commitment. A detailed description of the equivalence of invariance across countries can be found in Sorokowski et al.³.

To test the level of modernization in each country, we used the World Modernization Index (WMI)⁷¹. This measure was based on World Development Indicators (published by World Bank) and Statistical Yearbook (published by, inter alia, United Nations). The World Modernization Index reflects the composite levels of modernization in the economy, society, knowledge, and environment. The WMI consists of First Modernization, a classical modernization index that typically features industrialization, urbanization, and democratization, and Second Modernization, a new modernization that typically features knowledge, innovation, and transmission⁷¹. In the present study, we used an integrated modernization index, a combination of these two indexes (i.e., First Modernization and Second Modernization).

As scholars use various proxies to control for the level of modernization across countries^{72–75}, we additionally tested our hypothesis using the Human Development Index, obtained from the United Nations Development Programme⁷⁶.

We used Gender Inequality Index (GII), which measures gender inequality in several contexts (e.g., inequalities in reproduction health or force participation and labor market rate of men and women over 15 years). The data on GII was obtained from United Nations Development Programme⁷⁶.

Collectivism (in-group favoritism) levels were received from van de Vliert⁷⁷. This scale highly correlates with the classical Hofstede individualism-collectivism scale but, contrary to the Hofstede scale, contains data on all countries included in the present analyses.

The data on the annual average temperature of each country were obtained from the Tyndall Centre for Climate Change Research⁷⁸.

Statistical analyses. In the first step, mean levels for the STLS-45 (45 items), intimacy (15 items), passion (15 items), and commitment (15 items) across participants were calculated. In the second step, the normality assumptions of love subscales were investigated, adhering to commonly recommended thresholds for large sample data (i.e., $|2|$ for skewness and $|7|$ for kurtosis⁷⁹).

Pearson correlations were then computed. Next, country-level variables were grand-mean centered and individual-level variables were group-mean centered. Further, multilevel analyses with a maximum likelihood estimator were conducted. Participants were nested within countries to account for the non-independence between the inhabitants of the same geographical territories. In these models, STLS-45, intimacy, passion, and commitment, were introduced as outcome variables and World Modernization Index, Gender Inequality Index, Human Development Index, Collectivism level, and annual average temperature, participants' sex and length of relationship (in months), as predictor variables. Next, the amount of multicollinearity was investigated using the Variance Inflation Factor (VIF), and models fit with the amount of explained variance. The recommended guidelines were adhered to, that is, $VIF > 5$ indicating possible issues with collinearity^{80,81}. In the final step, visual representations of non-linear relationships between the outcome variables and predictor variables were inspected. All the analyses were performed in R (version 4.2.0).

Data availability

All data and the Supplementary Material can be found under the link: <https://figshare.com/s/25d3cc3ec48e6b5a6d64>.

Received: 27 April 2022; Accepted: 19 December 2022

Published online: 14 January 2023

References

- Agey, E., Morris, A., Chandy, M. & Gaulin, S. J. C. Arranged marriage often subverts offspring mate choice: An HRAF-based study. *Am. Anthropol.* **123**, 861–878 (2021).
- Jankowiak, W. & Fischer, E. F. A cross-cultural perspective on romantic love. *Ethnology* **31**, 149 (1992).
- Sorokowski, P. et al. Universality of the triangular theory of love: Adaptation and psychometric properties of the triangular love scale in 25 countries. *J. Sex Res.* **58**, 106–115 (2021).
- Watkins, C. et al. Men say 'I love you' before women do: Robust across several countries. *J. Soc. Pers. Relat.* **2022**, 026540752210752 (2022).
- Dion, K. K. & Dion, K. L. Individualistic and collectivistic perspectives on gender and the cultural context of love and intimacy. *J. Soc. Issues* **49**, 53–69 (1993).
- de Munck, V. C., Korotayev, A., de Munck, J. & Khaltourina, D. Cross-cultural analysis of models of romantic love among U.S. residents, Russians, and Lithuanians. *Cross Cult. Res.* **45**, 128–154 (2011).
- Levine, R., Sato, S., Hashimoto, T. & Verma, J. Love and marriage in eleven cultures. *J. Cross Cult. Psychol.* **26**, 554–571 (1995).
- Feybesse, C. & Hatfield, E. Passionate love. In *The New Psychology of Love* (eds Sternberg, R. J. & Sternberg, K.) 183–207 (Cambridge University Press, 2019).
- Karandashev, V. & Karandashev, V. Cultural and interdisciplinary approaches to romantic love. In *Romantic Love in Cultural Contexts* (ed. Karandashev, V.) 35–50 (Springer, 2017). https://doi.org/10.1007/978-3-319-42683-9_2.
- Musiał, M. Intimacy and modernity: Modernization of love in the western culture. *Stud. Eur. Gnesn.* **7**, 157–168 (2013).
- Baumard, N., Huillery, E., Hyafil, A. & Safra, L. The cultural evolution of love in literary history. *Nat. Hum. Behav.* **6**, 506–522 (2022).
- Groh, A. *Theories of Culture* (Routledge, 2019).
- Goorha, P. *Modernization Theory. Oxford Research Encyclopedia of International Studies*2 (Oxford University Press, 2010).
- Foucault, M. História da sexualidade I: A vontade de saber. *Edições Graal* **1**, 67–81 (1988).
- Malinowski, B. *The Sexual Life of Savages in North-Western Melanesia* Isis Vol. 13 (Kegan Paul Trench, Trubner, 1929).
- Belsky, J., Steinberg, L. & Draper, P. childhood experience, interpersonal development, and reproductive strategy: An evolutionary theory of socialization. *Child Dev.* **62**, 647–670 (1991).

17. Li, H. & Zheng, L. Associations between early life harshness, parents' parenting style, and relationship quality in China. *Pers. Relat.* **28**, 998–1016 (2021).
18. Gangestad, S. W. & Simpson, J. A. The evolution of human mating: Trade-offs and strategic pluralism. *Behav. Brain Sci.* **23**, 573–587 (2000).
19. Triandis, H. C., McCusker, C. & Hui, C. H. Multimethod probes of individualism and collectivism. *J. Pers. Soc. Psychol.* **59**, 1006–1020 (1990).
20. Hofstede, G. *Culture's Consequences: International Differences in Work-Related Values* (Sage, 1984).
21. Bejanyan, K., Marshall, T. C. & Ferenczi, N. Associations of collectivism with relationship commitment, passion, and mate preferences: Opposing roles of parental influence and family allocentrism. *PLoS ONE* **10**, e0117374 (2015).
22. Gupta, G. R. Love, arranged marriage, and the Indian social structure. *J. Comp. Fam. Stud.* **7**, 75–85 (1976).
23. Sprecher, S. *et al.* Love: American style, Russian style, and Japanese style. *Pers. Relat.* **1**, 349–369 (1994).
24. de Munck, V. C. & Korotayev, A. Sexual equality and romantic love: A reanalysis of rosenblatt's study on the function of romantic love. *Cross-Cult. Res.* **33**, 265–277 (1999).
25. Rosenblatt, P. C. Marital residence and the functions of romantic love. *Ethnology* **6**, 471 (1967).
26. de Munck, V. C. & Korotayev, A. V. Wife-husband intimacy and female status in cross-cultural perspective. *Cross-Cult. Res.* **41**, 307–335 (2007).
27. Sternberg, R. J. Construct validation of a triangular love scale. *Eur. J. Soc. Psychol.* **27**, 313–335 (1997).
28. Ijzerman, H. & Semin, G. R. Temperature perceptions as a ground for social proximity. *J. Exp. Soc. Psychol.* **46**, 867–873 (2010).
29. Sorokowska, A. *et al.* Preferred interpersonal distances: A global comparison. *J. Cross Cult. Psychol.* **48**, 577–592 (2017).
30. Sorokowska, A. *et al.* Affective interpersonal touch in close relationships: A cross-cultural perspective. *Pers. Soc. Psychol. Bull.* **47**, 1705–1721 (2021).
31. Pennebaker, J. W., Rimé, B. & Blankenship, V. E. Stereotypes of emotional expressiveness of northerners and southerners: A cross-cultural test of Montesquieu's hypotheses. *J. Pers. Soc. Psychol.* **70**, 372–380 (1996).
32. Hendrick, C., Hendrick, S., Foote, F. H. & Slapion-Foote, M. J. Do men and women love differently?. *J. Soc. Pers. Relat.* **1**, 177–195 (1984).
33. Meskó, N., Zsidó, A. N., Láng, A. & Karádi, K. Sex and relationship differences on the short love attitude scale: Insights from the Hungarian adaptation. *Sex Cult.* **25**, 1249–1272 (2021).
34. Giddens, A. *The Transformation of Intimacy: Sexuality, Love, and Eroticism in Modern Societies* (Stanford University Press, 1992).
35. Yan, Y. *Private Life Under Socialism: Love, Intimacy, and Family Change in a Chinese Village 1949–1999* (Stanford University Press, 2003).
36. Chu, G. C. & Ju, Y. *The Great Wall in Ruins* (State University of New York Press, 1993).
37. Chu, G. C. The changing concept of self in contemporary China. In *Culture and Self: Asian and Western Perspectives* (eds Marsella, A. J. *et al.*) 252–277 (Tavistock, 1985).
38. Dion, K. K. & Dion, K. L. Culture and relationships: The downside of self-contained individualism. In *Culture and Social Behavior: The Ontario Symposium* (eds Sorrentino, R. M. *et al.*) 77–94 (Erlbaum, 2005).
39. Dion, K. L. & Dion, K. K. Gender and ethnocultural comparisons in styles of love. *Psychol. Women Q* **17**, 463–473 (1993).
40. Sternberg, R. J. & Sternberg, R. H. *Triangle of Love* (Basic Books, 1988).
41. Yan, Y. Courtship, love and premarital sex in a North China Village. *China J.* **48**, 29–53 (2002).
42. Sorokowski, P. *et al.* Love influences reproductive success in humans. *Front. Psychol.* **8**, 1922 (2017).
43. Bode, A. & Kushnick, G. Proximate and ultimate perspectives on romantic love. *Front. Psychol.* **1**, 1088 (2021).
44. Hopcroft, R. L. Sex, status, and reproductive success in the contemporary United States. *Evol. Hum. Behav.* **27**, 104–120 (2006).
45. Sumter, S. R., Valkenburg, P. M. & Peter, J. Perceptions of love across the lifespan: Differences in passion, intimacy, and commitment. *Int. J. Behav. Dev.* **37**, 417–427 (2013).
46. Simoni, V. Ethnography, mutuality, and the utopia of love and friendship in touristic Cuba. *J. Anthropol. Soc. Oxford* **8**, 143–167 (2016).
47. Hochschild, A. R. *The Commercialization of Intimate Life: Notes from Home and Work* (University of California Press, 2003).
48. Prost, A. & Vincent, G. *A History of Private Life* (Harvard University Press, 1991).
49. Flandrin, J. *Familles: Parenté, Maison, Sexualité dans l'Ancienne Société* (Hachette, 1976).
50. McNair, B. *Mediated Sex Pornography and Postmodern Culture* (Hodder Education Publishers, 1996).
51. McNair, B. *Porno? Chic! How Pornography Changed the World and made it a Better Place* (Routledge, 2012).
52. Inglehart, R. & Norris, P. Rising tide: Gender equality and cultural change around the world. *Rising Tide* <https://doi.org/10.1017/CBO9780511550362> (2003).
53. Inglehart, R. & Baker, W. E. Modernization, cultural change, and the persistence of traditional values. *Am. Sociol. Rev.* **65**, 19–51 (2000).
54. Beck, U. & Beck-Gernsheim, E. *The Normal Chaos of Love Contemporary Sociology* Vol. 26 (Wiley, 2018).
55. Aengst, J. Representation and perception: Why reproduction matters in Ladakh. *Ladakh Stud.* **23**, 4–11 (2008).
56. Olaughlin, E. M. & Anderson, V. N. Perceptions of parenthood among young adults: Implications for career and family planning. *Am. J. Fam. Ther.* **29**, 95–108 (2001).
57. Calhoun, J. B. Population density and social pathology. *Sci. Am.* **206**, 139–149 (1962).
58. Jirotkul, M. Population density influences male–male competition in guppies. *Anim. Behav.* **58**, 1169–1175 (1999).
59. Aron, A. & Westbay, L. Dimensions of the prototype of love. *J. Pers. Soc. Psychol.* **70**, 535–551 (1997).
60. Hendrick, C. & Hendrick, S. A theory and method of love. *J. Pers. Soc. Psychol.* **50**, 392–402 (1986).
61. Kowal, M. *et al.* Validation of the Short Version (TLS-15) of the Triangular Love Scale (TLS-45) across 37 Languages. (2022).
62. Graham, J. M. Measuring love in romantic relationships: A meta-analysis. *J. Soc. Pers. Relat.* **28**, 748–771 (2011).
63. Masuda, M. Meta-analyses of love scales: Do various love scales measure the same psychological constructs?. *Jpn. Psychol. Res.* **45**, 25–37 (2003).
64. Dion, K. K. & Dion, K. L. Psychological individualism and romantic love. *J. Soc. Behav. Pers.* **6**, 17–33 (1991).
65. Buss, D. M. Sex differences in human mate preferences: Evolutionary hypotheses tested in 37 cultures. *Behav. Brain Sci.* **12**, 1–14 (1989).
66. Kowal, M., Groyecka-Bernard, A., Kochan-Wójcik, M. & Sorokowski, P. When and how does the number of children affect marital satisfaction? An international survey. *PLoS ONE* **16**, e0249516 (2021).
67. Sorokowski, P., Kowal, M. & Sokolowski, A. Religious affiliation and marital satisfaction: Commonalities among Christians, Muslims, and atheists. *Front. Psychol.* **10**, 2798 (2019).
68. Conroy-Beam, D. *et al.* Contrasting computational models of mate preference integration across 45 countries. *Sci. Rep.* **9**, 20 (2019).
69. Sechrest, L., Fay, T. L. & Zaidi, S. M. H. H. Problems of translation in cross-cultural research. *J. Cross Cult. Psychol.* **3**, 41–56 (1972).
70. Walter, K. V. *et al.* Sex differences in mate preferences across 45 countries: A large-scale replication. *Psychol. Sci.* **31**, 408–423 (2020).
71. Zhang, F. & He, C. World modernization indexes 1950 to 2010. In *Global Modernization Review: New Discoveries and Theories Revisited* 131–136 (World Scientific Publishing Co., 2015). https://doi.org/10.1142/9789814616072_0015.
72. Wucherpfennig, J. & Deutsch, F. Modernization and democracy: Theories and evidence revisited. *Living Rev. Democracy* **1**, 1–9 (2009).

73. Young, S. C. *The emergence of ecological modernisation: Integrating the environment and the economy?* (Routledge, 2001). <https://doi.org/10.4324/9781315812540>.
74. Barclay, R., Weinandt, M. & Barclay, A. The economic impact of study abroad on Chinese students and China's gross domestic product. *J. Appl. Bus. Econ.* **19**, 30–36 (2017).
75. Ogihara, Y. Economic shifts and cultural changes in individualism: A cross-temporal perspective unique names view project temporal changes in individualism and self-esteem in Japan View project. *Socioecon. Environ Hum. Psychol.* **50**, 1–10 (2017).
76. UNDP. *Human Development Reports. Human Development Index (HDI)*. <http://hdr.undp.org/> (2019).
77. van de Vliert, E. Climato-economic origins of variation in ingroup favoritism. *J. Cross Cult. Psychol.* **42**, 494–515 (2011).
78. Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M. & New, M. A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100). *Geography* **55**, 30 (2004).
79. Kim, H.-Y. Statistical notes for clinical researchers: Assessing normal distribution (2) using skewness and kurtosis. *Restor. Dent. Endod.* **38**, 52 (2013).
80. Gareth, J., Witten, D., Hastie, T. & Tibshirani, R. *An Introduction to Statistical Learning: With Applications in R* (Springer, 2013).
81. Menard, S. *Applied Logistic Regression Analysis* (SAGE Publications, 2001).

Author contributions

Conception and design of the study: P.S. Drafting the original manuscript: P.S. and M.K. Statistical analyses: M.K. Further editing of the manuscript: R.S. Data collection, revisiting and approving the manuscript: P.S., M.K., R.J.S., T.A., G.A., M.M.A., C.A., N.A., A.A., K.A., C.S.A., D.A.D., R.A., D.C.B., M.Be., A.B., B.B., M.Bo., D.M.B., M.B., S.C., A.C., H.C., I.C., R.M.C., M.C., D.D., S.D., I.D., B.E., A.E., I.E., C.S.E., T.F., J.C.G., K.U.G., F.G., M.Ha., I.He., M.H., I.H., C.H., J.L.J., F.J., K.K., T.K., L.E.O.K., N.K., T.T.K.H., I.A.K., N.C.K., A.K., H.M.L., A.L., G.R.L., E.L., T.L., T.T.L., G.L., N.V.L., A.Ma., Z.M., R.M., S.L.M., N.M., M.M., G.M., C.M., E.C.M., A.M., B.M., J.C.N., G.N., E.O., A.O., M.S.O., I.E.O., B.Ö., A.F.P., V.P., M.P., F.P., A.P., K.P., E.P., C.P., P.P., M.R., M.S., S.Sal., R.Sar., I.S., S.Sc., A.Sh., S.S., R.S.S., F.S., M.T., C.V., L.D.V., K.V.W., D.A.W., G.Y., M.Za., M.Zu., and A.S.

Funding

Funding was provided by Narodowe Centrum Nauki (Grant No. 2014/13/B/HS6/02644). Uganda's study was supported by a grant: AH/S00402511.

Competing interests

The authors declare no competing interests.

Additional information

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