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Born to be wild: Second-to-fourth digit length ratio and risk preferences

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ABSTRACT

The second-to-fourth digit length ratio of an individual's hand (digit ratio) is a putative biomarker for prenatal exposure to testosterone. We examine the hypothesized negative association between the digit ratio and the preference for risk taking within a large U.S. population survey. Our statistical framework provides a cardinal proxy for the true digit ratio based on ordinal digit ratio measurements and accounts for measurement error under the assumptions of Gaussianity and time-invariant true digit ratios. Our empirical findings support the hypothesis and suggest a meaningful biological basis for risk preferences.

1. Introduction

Risk preferences are fundamental building blocks of models of economic and health behavior (Beauchamp et al., 2017; Schildberg-Hörisch, 2018), and their biological roots have been examined with data on twins and with genetic data (Benjamin et al., 2012; Cesarini et al., 2009; Cronqvist et al., 2015; Linnér et al., 2019). We contribute to the literature on the biological roots of risk preferences by investigating the hypothesized negative association between the second-to-fourth digit length ratio of an individual's hand (the digit ratio) and the individual's preference for risk taking. This association is assumed to follow from (prenatal) testosterone's positive association with the preference for risk taking (Coates et al., 2010; Cronqvist et al., 2015; Nofsinger et al., 2018) and the digit ratio's status as a retrospective biomarker of prenatal testosterone exposure; higher exposure is thought to decrease the digit ratio (Manning et al., 1998; Manning et al., 2003; Manning, 2011; Voracek, 2014).[1] These assumed relationships have been questioned (Hönekopp et al., 2007; Voracek, 2014; Van Leeuwen et al., 2020; Warrington et al., 2018) and empirical evidence of the digit ratio's association with risk preferences has thus far proved inconclusive (Neyse et al., 2020).

In economics, interest in the relationship between the digit ratio and risk preferences was triggered by Coates and Herbert (2008), who found that financial traders' levels of circulating testosterone were positively related to their profits on trading days, and subsequent studies that partly explained this by finding digit ratios to be negatively associated with risk taking (Coates et al., 2009; Brañas-Garza and Rustichini, 2011). While some studies have confirmed the negative association between the digit ratio and the preference for risk taking (Garbarino et al., 2011; Stenstrom et al., 2011; Apicella et al., 2015), most studies could not confirm it, despite often having used similar research designs (Apicella et al., 2008; Candelo and Eckel, 2018; Drichoutis et al., 1998; Neyse et al., 2020; Parslow et al., 2019).

The lack of replicability of the association between the digit ratio and risk preferences could be due to the absence of a relationship between the digit ratio and the preference for risk taking (Neyse et al., 2021), small sample sizes in combination with a small effect size (Apicella et al., 2015; Dupont and Plummer 1998; Van Leeuwen et al., 2020), or measurement error in the elicited digit ratio (Ribeiro et al., 2016). To date, sample sizes in the literature have ranged from around 50–700 observations (Neyse et al., 2020), except in Neyse et al. (2021) who used a sample of 3431 respondents.[2] Brañas-Garza et al. (2018) used the second largest sample size to date (704) and show that a lab-experimental measure of the preference for financial risk taking, but not a

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[1] Online Appendix 1 provides background information on the assumed relationship between prenatal testosterone exposure and the digit ratio.

[2] Larger sample sizes have been used when studying the relation between the digit ratio and other personal characteristics. For instance, Manning and Fink (2011) use the BBC Internet study comprising more than 140,000 responses from 23 countries and concentrate on national differences in personality.

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self-reported measure of a general preference for risk taking, is significantly and negatively associated with the digit ratio. Thus, they could replicate some of the earlier findings, but could not replicate the findings of Stenstrom et al. (2011) and Bönte et al. (2016) who find a significant negative association between the digit ratio and the response to a question about the general preference for risk taking, albeit for the right hand only and not for women separately. Further, Van Leeuwen et al. (2020) and Neyse et al. (2021), who used the largest sample to date (3431 respondents), found no significant association between the digit ratio and general risk preferences. Gaining insights into the digit ratio's association with a general risk preference measure is of particular interest because recent studies have argued that compared to, e.g., lab-experimental measures of financial risk taking, a general risk preference measure has a higher validity for real-world risky choices (Charness et al., 2019; Kapteyn and Teppa, 2011; Verschoor et al., 2016). Also, while previous studies have acknowledged the issue of measurement error in elicited digit ratios, they have not accounted for measurement error bias when estimating the association of the digit ratio with general risk preferences, which can attenuate the estimated association (Bound et al., 2001).

The aim of our paper is to provide empirical evidence regarding the existence and strength of the hypothesized negative association between the digit ratio and the preference for risk taking. Empirical evidence in favor of such an association would be further support for a biological basis for risk preferences. It would also suggest the use of digit ratio elicitation in population surveys to facilitate research on the biological roots of risk preferences and of, e.g., education, personality traits, and health (Klimek et al., 2014; Manning and Fink, 2011; Nye et al., 2017a, 2017b).

We contribute to the literature by introducing a methodology for easily collecting self-reported digit ratio measurements. This allows us to use a large population representative sample for investigating the digit ratio's association with risk preferences and facilitates replication studies in similar population-based surveys. We have elicited the digit ratio with a short survey question that asks, for each hand, whether the ring finger is shorter than, longer than, or equal in length to, the index finger (Buser, 2012). Risk preferences were elicited with a general question that measures the preference for risk taking on a Likert scale (Falk et al., 2018). Further, each hand's digit ratio was elicited twice, in a pair of surveys spaced about seven months apart. This longitudinal design makes it possible to account for measurement error in the reported digit ratios, using a modified version of the estimator proposed by Kimball et al. (2008). This two-step estimator first uses the ordinal digit ratio reports from our surveys to obtain a cardinal proxy for the expected true digit ratio. The proxy is then used in a second-step linear regression model for risk preferences (see Section 3). An important advantage of the statistical model is that it reduces the multiple ordinal measurements of the digit ratio to a one-dimensional measure and provides estimates of the associations with the true digit ratio. Our empirical analysis uses a population survey of about 6000 adults from the Understanding America Study (see Section 2).

The empirical results, discussed in Section 4, support the hypothesized negative association between the digit ratio and the preference for risk taking. This association is about the same for both genders and remains when accounting for characteristics at birth, such as race and mother's education, to control for possible hereditary or intergenerationally transmittable factors, and for education and health characteristics, which represent possible causal pathways. In terms of effect size, the estimated difference in the preference for risk taking associated with a one-standard deviation change in the digit ratio equals on average about 18 % of the estimated gender difference in the preference for risk taking. Our findings, therefore, suggest a meaningful biological basis for risk preferences. Section 5 discusses the main findings and concludes.

2. The data

Our empirical analysis is based on a sample of about 6000 adults from the Understanding America Study (UAS; https://uasdata.usc.edu). The UAS is a probability-based internet panel, which at the time of the survey comprised about 7000 respondents (age 18+) who are representative of the U.S. population (Alattar et al., 2018). The UAS oversamples Native Americans and residents of Los Angeles County. All data used for this study is self-reported.

We have twice fielded a module to all UAS panel members, which elicited individuals' digit ratios and their risk preferences.[3] Of the 6554 panel members invited in November and December of 2018, 4966 (76 %) completed the module, and of the 7259 panel members invited in June and July of 2019, 5393 (74 %) completed the module. We included in our analysis sample respondents who completed the module in one or both years. We excluded 185 observations with missing values for gender, race, or age, and, subsequently, excluded 66 observations with missing values for the digit ratio or risk preferences. A further 132 observations were dropped because the digit ratios could not be measured because of physical impairment of either the left or right hand, or because respondents were under the age of 20.[4] The final analysis sample therefore comprised 9976 observations for 5898 unique respondents (2496 men and 3402 women), of whom 4078 were observed twice. Respondents' educational attainment, mother's education, cognitive skills, and health-related characteristics were elicited by other UAS questionnaires before the digit ratio questionnaires were fielded, making these time-invariant covariates in our analysis. Summary statistics of all variables for the analysis are in Table A.1 (Online Appendix 2).

2.1. The digit ratio

The lengths of the ring and index fingers can be measured by using a (digital) caliper or ruler, either directly or indirectly based on a photocopy, scan, or radiographic image of the hands (Jeevanandam and Muthu, 2016; Neyse et al., 2021). Alternatively, one can use software designed to measure digit lengths (Huang et al., 2014). See Ribeiro et al. (2016), Kim and Cho (2013), and Mikac et al. (2016) for a discussion of these methods of measurement. The UAS is a large internet population survey, which makes these methods impractical. We have therefore asked respondents to compare their index and ring fingers and to report which one is longer.[5] The survey also includes illustrations showing hands with different digit ratios to clarify the possible responses (see Online Appendix 3). The exact wording of the digit ratio question (for the left hand) is:

> *Please turn your left hand with the palm towards you, fingers next to each other. Keeping your fingers straight, look to see which finger is longer on your left hand: the index finger or the ring finger?*
>
> *On my left hand...*

1. *My index finger is longer than my ring finger (Picture included)*

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[3] Our study has not been pre-registered. All UAS participants have received the digit ratio and risk preferences questionnaires and all responses have been included for our study.

[4] Gillam et al. (2008) show that women's digit lengths attain their maxima around the ages 12–15 while for men it is around 17–20 years of age.

[5] An alternative elicitation method is to ask respondents to measure the lengths of their index and ring fingers with a ruler, as done in the BBC Internet Study (Reimers, 2007). We decided against that possibility, as it could negatively affect response rates (it requires more effort and not everyone has a ruler).

2. *My ring finger is longer than my index finger (Picture included)*
3. *My ring and index finger are the same length (Picture included)*
4. *I am physically unable to do this*

Following this, the same question was asked for the right hand. Buser (2012) reports test statistics suggesting a high correlation between a digit ratio measure based on scans and an elicitation like ours. Compared to using scans or radiographic images, the main advantage of our survey question for eliciting information on individuals' digit ratios is that it takes much less time and can easily be incorporated into any survey, and hence facilitates replication studies. A disadvantage is that it yields a less accurate measure of the digit ratio, which is already an assumed proxy for prenatal testosterone exposure, and therefore adds measurement error to the analysis (Brañas-Garza and Kovarik, 2013). Additional measurement error may also be present due to the use of a self-reported measure instead of a measure taken by a trained interviewer (Manning et al., 2007). In support of using a self-reported measure, Manning et al. (2007) showed that the means of the digit ratio for a sample in which finger lengths were self-reported and for a sample in which these were measured by a trained observer were close and that the standard deviations were also close after having removed outliers in the self-reported sample.

Further, our elicitation of the digit ratio is, arguably, related to measuring the relative distal extent of the ring and index fingers (Peters et al., 2002), as some respondents may compare their fingertips rather than the lengths of their ring and index fingers. Peters et al. (2002) do an extensive comparison of the tip ratio based on relative distal extent measurements (for the ring and index fingers) with the finger lengths ratio (2D:4D) and showed that the tip ratio and finger lengths ratio are positively correlated for both hands.

In line with most previous studies (Swami et al., 2013), the reported digit ratios in (Table 1 (Panel A), show the sexually dimorphic nature of the digit ratio for each hand: women reported, on average, a higher digit ratio than men. The null hypothesis of independence of the digit ratio and gender is, for each hand and for each year, rejected with a p-value close to zero (these test results are not reported in the table). For both genders, the reported digit ratio is on average somewhat higher for the left hand than for the right hand. Further, the percentage of respondents who answered that their index finger is shorter than their ring finger (and hence have a digit ratio smaller than 1), is somewhat lower than what can be expected based on the findings of, e.g., Hönekopp and Watson (2010) that (true) digit ratios are, on average, smaller than 1 for both genders. This finding can be explained by our elicitation method for the digit ratio which has a similarity with measuring the relative distal extent of the ring and index fingers: Peters et al. (2002) reported a higher percentage of respondents being classified as having a longer index than ring finger when based on the relative distal extent of the ring and index fingers than when based on relatively finger lengths.

Although the Cronbach's alpha of 0.80 in Panel B suggests that the same construct was measured for both hands (Sijtsma, 2009), the differences between the ordinal digit ratio reports for the left and right hands are substantial. For instance, among respondents who reported that the index finger was shorter than the ring finger of their left hand, 80.2 % reported the same of their right hand, 11.7 % reported that their right index and ring fingers were about equal, and 8.1 % reported that their right index finger was longer than their right ring finger. Similar patterns are observed by gender (not reported).

For both hands, there are substantial differences between the ordinal digit ratio reports in 2018 and in 2019 (Panel C). For instance, respondents who reported that their index finger was shorter than their ring finger of their left hand in 2018, 65.5 % reported the same for their left hand in 2019. The Cronbach's alphas are 0.65 for the left hand and 0.67 for the right hand, which are still acceptable, but the correlations over time of the digit ratios are about 0.5 for both hands and suggest low reliability. Overall, Table 1 suggests substantial measurement error in the ordinal digit ratio reports.

Table 1
Ordinal digit ratio reports.

Panel A: Digit ratios by hand, year, and gender					
Cells: %	Year	2018	2018	2019	2019
	Gender	Female	Male	Female	Male
Left hand	index<ring (low digit ratio)	33.6	49.3	31.8	48.8
	index = ring	24.7	20.9	24.0	24.3
	index>ring (high digit ratio)	41.7	29.9	44.2	26.9
	Total	100.0	100.0	100.0	100.0
Right hand	index<ring (low digit ratio)	35.2	51.9	32.4	50.1
	index = ring	25.8	23.6	27.4	24.7
	index>ring (high digit ratio)	39.1	24.5	40.3	25.2
	Total	100.0	100.0	100.0	100.0
Panel B: Digit ratios for the right hand, given those for the left hand					
Cells: %	Cronbach's alpha = 0.80	Right hand			
	Correlation = 0.66	index<ring	index = ring	index>ring	Total
Left hand	index<ring (low digit ratio)	80.2	11.7	8.1	100.0
	index = ring	21.0	65.8	13.2	100.0
	index>ring (high digit ratio)	12.8	14.6	72.7	100.0
Panel C: Digit ratios for the left and right hand in 2019, given those in 2018					
Cells: %	Cronbach's alpha = 0.65	Left hand	2019		
	Correlation = 0.48	index<ring	index = ring	index>ring	Total
Left hand 2018	index<ring (low digit ratio)	66.5	16.6	17.0	100.0
	index = ring	25.6	45.0	29.5	100.0
	index>ring (low digit ratio)	20.1	17.1	62.8	100.0
	Cronbach's alpha = 0.67	Right hand	2019		
	Correlation = 0.50	index<ring	index = ring	index>ring	Total
Right hand 2018	index<ring (low digit ratio)	67.6	16.5	15.9	100.0
	index = ring	23.8	50.7	25.5	100.0
	index>ring (high digit ratio)	20.8	17.0	62.3	100.0

Notes. 'Index' refers to index finger length (second digit length) and 'ring' refers to ring finger length (fourth digit length). Survey weights are used for constructing this table. Rank order correlation coefficients are reported and for each case the null hypothesis of the correlation being equal to zero is rejected with a p-value close to zero.

2.2. *The digit ratio and risk preferences*

Individual risk preferences in a large population survey are, for reasons of feasibility, often elicited with a question about general risk preferences, with answer categories on a Likert scale. Validation tests for such a question are presented in Falk et al. (2016). Charness et al. (2018, 2019), Kapteyn and Teppa (2011), and Verschoor et al. (2016) provide further support for using a question about general risk preferences.[6] We followed Falk et al. (2018) for the elicitation of risk preferences:

> *Are you generally a person who tries to avoid taking risks or one who is fully prepared to take risks? Please rate yourself from 0 to 10, where 0 means "not at all willing to take risks" and 10 means "very willing to take risks."*

In line with previous studies (e.g., Dohmen et al., 2011), on average men have a higher preference for risk taking than women (Table 2, Panel

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[6] Also, Kreuter et al. (2008) show that self-administered surveys, like the UAS, are much less subject to social desirability bias than surveys administered by an interviewer.

Table 2
Risk preferences and the ordinal digit ratio reports.

Gender	Males	Females	Total
Number of observations	4294	5682	9976
Panel A: Preference for risk taking (0–10 scale with 10 Very willing to take risks)			
Mean	6.09	5.42	5.74
(Standard deviation)	(2.15)	(2.31)	(2.26)
Answer category	Percentage	Percentage	Percentage
0 (Not at all willing to take risks)	1.55	2.55	2.07
1	1.28	3.36	2.35
2	2.14	5.13	3.68
3	8.02	8.99	8.52
4	7.11	11.43	9.33
5	17.8	19.88	18.87
6	15.64	15.2	15.41
7	21.18	16.11	18.57
8	14.48	9.46	11.9
9	4.27	2.47	3.34
10 (Very willing to take risks)	6.52	5.41	5.95
Panel B: Average of preference for risk taking by digit ratio categories			
Left hand	mean	mean	mean
Index<ring (low digit ratio)	6.14	5.52	5.89
Index = ring	6.06	5.45	5.74
Index>ring (high digit ratio)	6.01	5.32	5.58
Correlation, digit ratio and risk-taking preference	-0.02	-0.04***	-0.06***
Right hand	mean	mean	Mean
Index<ring (low digit ratio)	6.16	5.43	5.86
Index = ring	5.98	5.46	5.70
Index>ring (high digit ratio)	6.04	5.38	5.62
Correlation, digit ratio and risk-taking preference	-0.04***	-0.02	-0.05***

Notes. $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.005$. 'Index' refers to index finger length and 'ring' refers to ring finger length. Survey weights are used for this table's statistics. Rank order correlation coefficients are reported.

A). Panel B presents evidence in favor of a negative correlation between the digit ratio and the preference for risk taking. On average, men or women who reported that their index finger is shorter than their ring finger had a relatively higher preference for risk taking. These correlations are, however, low. For men and women combined, for both hands the findings are in support of a negative correlation. By gender, for either the left or right hand, but not for both hands, the findings are in support of a negative association.

Finally, a possible concern about using self-reported data is that the elicited risk preferences were influenced by first having answered the digit ratio questions (see Online Appendix 3). For instance, respondents could have conducted an internet search and learned about the digit ratio's hypothesized relationship with personal characteristics. Potentially, this could inflate the correlation between the digit ratio and self-reported risk preferences. However, on average, it took respondents 48 s to answer the digit ratio question for the left hand and 24 s to answer the question for the right hand. After that, they answered a question on handedness (which took, on average, 6 s) and subsequently answered the risk preferences question, which took an average of 18 s. These response times are short enough to exclude the possibility that respondents searched for information on the digit ratio and risk preferences while taking the survey.

2.3. *The digit ratio and risk preferences*

Using the ordinal responses to the digit ratio survey question, the estimated associations between risk pr–A of Table 3 are by and large in line with those of previous studies: men or women with a high digit ratio (index > ring) have a lower preference for risk taking than men or women with a low digit ratio (index<ring, which is the reference group).[7] Many of the associations in Panel A, however, are either borderline or not statistically significant (H_0: No DR). These results echo the conclusion of Brañas-Garza et al. (2018) that it is difficult to replicate previous findings concerning the associations between the digit ratios and risk preferences, and in particular to do so by gender and by hand.

The null hypothesis of the same digit ratio associations with risk preferences for the left and right hands (H_0: DR L = R) and the null hypothesis of the same digit ratio associations for both genders (H_0: DR M = W) are not rejected for any specification (Panel A). Under these two null hypotheses, the first column of Panel B shows a pattern in line with Panel A: a higher digit ratio is associated with a lower preference for risk taking. The results by gender show a similar pattern, albeit less precisely estimated.

It is likely there is measurement error in the ordinal digit ratio reports (Table 1) which attenuates the estimated associations between the digit ratio categories and the preference for risk taking (Table 3). The next sections, therefore, outline and employ an empirical strategy that collapses the ordinal digit ratio data for each hand into a single digit ratio proxy whose association with risk preferences is easily interpretable and not subject to such attenuation bias.

3. Empirical strategy

Our empirical strategy is based on Kimball et al. (2008) and relates risk preferences to the expected digit ratio, conditional on observables which include the ordinal digit ratio reports.[8] In a nutshell, a cardinal proxy for each hand's digit ratio is constructed based on the ordinal responses. This reduces the multiple, ordinal measurements of a hand's digit ratio to a one-dimensional cardinal measure that can be analyzed much as the digit ratio would be if it were observed directly. Furthermore, it exploits the repeated measurements of each hand's digit ratio to account for measurement error, under the assumption that the true digit ratio is constant over time. Our one-dimensional cardinal measure, referred to as the expected digit ratio, serves as a proxy of the unobserved true digit ratio, but the error structure does not lead to attenuation of estimated coefficients, as would be the case with classical measurement error. This error structure was first discussed by Berkson (1950).

To simplify notation, the model discussed below assumes respondents are observed in both years of the survey. The extension to our case, where some individuals are observed in only one wave, is straightforward.

3.1. *Empirical model*

The true, unobserved digit ratio of individual i's hand h, $d^{**}_{h,i}$, is not expected to change during adulthood (Garn et al., 1975; Galis et al., 2010; Gillam et al., 2008), so we assume it to be constant over time. We further assume it to be linearly related to the preference for risk taking, y_{it}, at time t:

$$y_{it} = \beta_0 + \sum_{h\in\{l,r\}} \beta_h d^{**}_{h,i} + \boldsymbol{X}_{it}\boldsymbol{\beta}_2 + \alpha_i + \varepsilon_{it}, \tag{1}$$

where l denotes the left hand and r the right hand, $i \in \{1..n\}$, n is the number of respondents, and $t \in \{1, 2\}$. $\boldsymbol{X}_{it}$ is a vector of covariates with corresponding parameter vector $\boldsymbol{\beta}_2$, α_i is an individual-specific random effect, and ε_{it} is an idiosyncratic error term. While the true digit ratio,

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[7] Based on linear models estimated with least squares. The main findings remain when based on ordered probit models (see Online Appendix 6).

[8] Kimball et al. (2008) have a different application: they use the reported preference for risk taking as an independent variable and account for measurement error bias in its association with asset allocation.

Table 3
Estimated associations of gender and the ordinal digit ratio reports with the preference for risk taking.

	Men & women	Men & women	Men & women	Men	Men	Women	Women
L = Left hand	Coef.	Coef.	Coef.	Coef.	Coef.	Coef.	Coef.
R = Right hand	(Std.Err.)	(Std.Err.)	(Std.Err.)	(Std.Err.)	(Std.Err.)	(Std.Err.)	(Std.Err.)
Panel A							
Male	0.523***	0.527***	0.531***				
	(0.055)	(0.054)	(0.054)				
Index = ring, L	-0.102	-0.134*		-0.12		-0.156	
	(0.070)	(0.060)		(0.086)		(0.084)	
Index>ring, L	-0.143	-0.178***		-0.104		-0.228***	
	(0.076)	(0.057)		(0.086)		(0.077)	
Index = ring, R	-0.057		-0.119*		-0.233**		-0.024
	(0.069)		(0.059)		(0.086)		(0.082)
Index>ring, R	-0.054		-0.147*		-0.177*		-0.108
	(0.076)		(0.057)		(0.087)		(0.077)
H_0: No DR†	0.021*	0.005***	0.023*	0.277	0.013*	0.011*	0.335
H_0: DR L = R†	0.811			0.316		0.113	
H_0: DR M = W†	0.113	0.537	0.215				
R^2	0.018	0.018	0.017	0.001	0.003	0.003	0.002
N	9976	9976	9976	4294	4294	5682	5682
Panel B: Estimates under the null hypothesis of the same associations by hand							
Male	0.523***						
	(0.055)						
Index = ring	-0.080*			-0.114*		-0.054	
	(0.034)			(0.049)		(0.049)	
Index>ring	-0.098***			-0.083		-0.102*	
	(0.031)			(0.047)		(0.042)	
H_0: No DR†	0.004***			0.037*		0.055	
H_0: DR M = W†	0.545						
R^2	0.018			0.002		0.003	
N	9976			4294		5682	

Notes. $^*p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.005$. The references categories are female respondents or respondents with 'Index<ring'. N = Number of observations. A year dummy for 2019 is included in all specifications. Weighted average marginal effects are computed and the standard errors are clustered at the individual level. † "H_0: No DR", "H_0: DR L = R" and "H_0: DR M = W" are the null hypotheses of the digit ratio (DR) associations being equal to zero, the same for both hands, or the same across gender, respectively. Entries shown are p-values.

$d^{**}_{h,i}$, is unobserved, we observe $d_{h,it}$, a variable indicating whether, at time t, individual i reported that the ring finger of hand h was shorter than, longer than, or equal in length to the index finger (see Section 2). We define $\boldsymbol{d}_i = (d_{l,i1}, d_{l,i2}, d_{r,i1}, d_{r,i2})$ and $\boldsymbol{X}_i = (\boldsymbol{X}_{i1}, \boldsymbol{X}_{i2})$, and assume $\mathbb{E}(\alpha_i|\boldsymbol{d}_i, \boldsymbol{X}_i) = \mathbb{E}(\varepsilon_{it}|\boldsymbol{d}_i, \boldsymbol{X}_i) = 0$. With the compound error $u_{it} = \varepsilon_{it} + \sum_{h\in\{l,r\}} \beta_h d^{**}_{h,i} - \sum_{h\in\{l,r\}} \beta_h \mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i\right)$, Eq. (1) can be transformed into

$$y_{it} = \beta_0 + \sum_{h\in\{l,r\}} \beta_h \mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i\right) + \boldsymbol{X}_{it}\boldsymbol{\beta}_2 + \alpha_i + u_{it}, \tag{2}$$

where the new error term u_{it} includes expectation errors in the digit ratios.

We use a two-step estimator that first estimates $\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i\right)$ and then, in a second step, plugs this into Eq. (2) and estimates the resulting equation using least squares. The first-stage estimates of $\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i\right)$ come from a panel data bivariate ordered probit model that relates the true, unobserved digit ratios to the reported digit ratios and covariates. The parameters of this "digit ratio model" fully characterize $\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i\right)$, so we estimate these true, unobserved digit ratio expectations by the corresponding expectations from the maximum likelihood estimate of the digit ratio model (see Online Appendix 4).

We develop our digit ratio model from a triplet of equations describing the generation of the digit ratio reports, $\boldsymbol{d}_i$. First, the true digit ratios, $d^{**}_{h,i}$, are assumed to be time-invariant, and associated with $\boldsymbol{Z}^{1}_i$, a time-invariant subset of the covariates $\boldsymbol{X}_{it}$.

$$d^{**}_{h,i} = \gamma^0_h + \boldsymbol{Z}^1_i \boldsymbol{\gamma}^1_h + \eta_{h,i} + \theta_i \tag{3}$$

The error components, $\eta_{h,i}$ and θ_i, capture hand- and individual-specific influences on the true digit ratio, including any effect of prenatal testosterone exposure. The true digit ratio is allowed to correlate between hands due to the presence of θ_i.

Next, measurement error is assumed to enter respondents' perceptions of their digit ratios, owing to factors like variation in hand position during measurement or arthritis in the hands. The perceived digit ratio, $d^*_{h,it}$, equals the true values, plus a mean-zero "perception error" and systematic distortion associated with the subset of (potentially time-varying) covariates $\boldsymbol{X}_{it}$ not present in $\boldsymbol{Z}^1_i$. Denoting these covariates $\boldsymbol{Z}^2_{it}$, so that $\boldsymbol{X}_{it} = (\boldsymbol{Z}^1_i, \boldsymbol{Z}^2_{it})$, the perceived ratios are generated according to

$$d^*_{h,it} = d^{**}_{h,i} + \boldsymbol{Z}^2_{it}\boldsymbol{\gamma}^2_h + \zeta_{it} + \upsilon_{h,it} \tag{4}$$

The perception error has two components: $\upsilon_{h,it}$ is fully idiosyncratic, while ζ_{it} is specific to time, but not to hand. The inclusion of ζ_{it} allows correlation between the two hands' perception errors in a particular period.

Finally, individuals report the observed digit ratio, $d_{h,it}$, based on which of three bins the perceived ratio falls in.

$$d_{h,it} = \left\{ \begin{array}{lll} 1 & \text{if} & -\infty < d^*_{h,it} < \tau_1 \\ 2 & \text{if} & \tau_1 \leq d^*_{h,it} < \tau_2 \\ 3 & \text{if} & \tau_2 \leq d^*_{h,it} < \infty \end{array} \right\} \tag{5}$$

Note that the threshold parameters τ_1 and τ_2 are time- and hand-invariant.

For estimation, we substitute Eq. (3) into Eq. (4) to obtain the reduced-form equation

$$d^*_{h,it} = \gamma^0_h + \boldsymbol{X}_{it}\boldsymbol{\gamma}_h + \eta_{h,i} + \theta_i + \zeta_{it} + \upsilon_{h,it}, \tag{6}$$

where $\boldsymbol{\gamma}_h = (\boldsymbol{\gamma}^1_h, \boldsymbol{\gamma}^2_h)$. We further assume that the error components θ_i, $\eta_{l,i}$, $\eta_{r,i}$, ζ_{i1}, ζ_{i2}, $\upsilon_{l,i1}$, $\upsilon_{r,i1}$, $\upsilon_{l,i2}$, and $\upsilon_{r,i2}$ are mean-zero, mutually independent, independent of the covariates, and jointly normal with respective variances σ^2_θ, $\sigma^2_{l,\eta}$, $\sigma^2_{r,\eta}$, σ^2_ζ, σ^2_ζ, σ^2_υ, σ^2_υ, σ^2_υ, and σ^2_υ. We normalize the perception error to have unit variance (i.e., $\sigma^2_\upsilon + \sigma^2_\zeta = 1$) and normalize $\gamma^0_l = 0$ because only the between-hand difference of the intercepts $\gamma^0_r - \gamma^0_l$ is identified. The combination of Eqs. (5) and (6) with these assumptions gives us a panel data bivariate ordered probit model, which we estimate with maximum likelihood. Collecting the digit ratio model's parameters into the vector $\boldsymbol{\Gamma} = (\gamma^0_l, \gamma^0_r, \boldsymbol{\gamma}'_l, \boldsymbol{\gamma}'_r, \tau_1, \tau_2, \sigma^2_\theta, \sigma^2_{l,\eta}, \sigma^2_{r,\eta}, \sigma^2_\zeta, \sigma^2_\upsilon)'$, we denote the corresponding maximum likelihood estimator by $\widehat{\boldsymbol{\Gamma}}$.

Next, we define $\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i; \widehat{\boldsymbol{\Gamma}}\right)$ as the conditional expectation $d^{**}_{h,i}$ would have if the digit ratio reports were truly generated by the estimated digit ratio model (i.e., if $\boldsymbol{\Gamma} = \widehat{\boldsymbol{\Gamma}}$). This is our estimator of $\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i \quad\right)$. We refer to Online Appendix 4 for details on computation. $\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i\right)$ is identified only up to scale (determined by our model's normalization), so, using similar notation, we renormalize our estimate by $SD\left(d^{**}_{h,i}\middle|\boldsymbol{X}_i; \widehat{\boldsymbol{\Gamma}}\right) = \sqrt{\widehat{\sigma}^2_\theta + \widehat{\sigma}^2_{h,\eta}}$ for each hand. Where the context is clear, we will refer to the estimated renormalized conditional digit ratio expectation, $\frac{\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i; \widehat{\boldsymbol{\Gamma}}\right)}{SD\left(d^{**}_{h,i}|\boldsymbol{X}_i; \widehat{\boldsymbol{\Gamma}}\right)}$, simply as the expected digit ratio. Substituting this into Eq. (2), we obtain

$$y_{it} = \beta_0 + \sum_{h\in\{l,r\}} \widetilde{\beta}_h \frac{\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i; \widehat{\boldsymbol{\Gamma}}\right)}{\sqrt{\widehat{\sigma}^2_\theta + \widehat{\sigma}^2_{h,\eta}}} + \boldsymbol{X}_{it}\boldsymbol{\beta}_2 + \alpha_i + \widetilde{u}_{it}, \tag{7}$$

where the new error term $\widetilde{u}_{it}$ includes the estimation error in the digit ratio expectation. Owing to our renormalization, $\widetilde{\beta}_h$ is interpretable as the change in the dependent variable associated with a one-standard deviation change in the true digit ratio, conditional on $\boldsymbol{X}_i$. Further, we refer in our empirical analysis to $\widetilde{\beta}_h$ as the association of the digit ratio with risk preferences.

We also estimate a specification with equal digit ratio associations for the left and right hand imposed:

$$y_{it} = \beta_0 + \widetilde{\beta}\left[\sum_{h\in\{l,r\}} \frac{\mathbb{E}\left(d^{**}_{h,i}|\boldsymbol{d}_i, \boldsymbol{X}_i; \widehat{\boldsymbol{\Gamma}}\right)}{\sqrt{\widehat{\sigma}^2_\theta + \widehat{\sigma}^2_{h,\eta}}}\right] + \boldsymbol{X}_{it}\boldsymbol{\beta}_2 + \alpha_i + \widetilde{u}_{it}, \tag{8}$$

where $\widetilde{\beta} = \widetilde{\beta}_l = \widetilde{\beta}_r$. A one-standard deviation change in the true digit ratios for the left and right hand is associated with a $2 \times \widetilde{\beta}$ change in the dependent variable. The null hypothesis of equal associations with the digit ratio of the left and right hand (H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r$) is empirically tested. Should the null hypothesis not be rejected, imposing this equality can increase the precision of the estimated digit ratio association.

Our estimator's second step simply estimates Eqs. (7), or (8), by least squares.[9] In this respect, our estimation strategy differs from the one proposed by Kimball et al. (2008) whose GMM estimator in the second stage is required because they do not control in the first stage, Eq. (6), for all the covariates that are included in the second stage, Eqs. (7) or (8). We cluster standard errors at the individual level to account for serial correlation and heteroskedasticity. While we do not adjust these standard errors for the first-stage estimation of the digit ratio, they remain valid for tests of null hypotheses where all digit ratio associations (i.e., $\widetilde{\beta}_l$ and $\widetilde{\beta}_r$) are zero (Hansen, 2022, pp. 364–367).[10]

Further, our estimator of the digit ratios' second-stage coefficients, $\widetilde{\beta}_l$ and $\widetilde{\beta}_r$, is robust to how the time-invariant covariates are split between $\boldsymbol{Z}^1_i$, which is associated with the true digit ratio in Eq. (3), and $\boldsymbol{Z}^2_{it}$, which is associated with the misperceptions in Eq. (4).[11] This robustness is ensured by controlling for the same covariates in the first and second stage (see Online Appendix 4). Also, it allows us to be agnostic about whether associations between time-invariant covariates and the reported digit ratios represent systematic differences in digit ratios or in reporting behavior.

Finally, for interpreting our estimates of the digit ratio's association with risk preferences, we follow Benjamin et al. (2018) in treating statistical findings that are significant below the 0.5 % level as "significant" (i.e., plausibly replicable) and findings that are significant between the 0.5 % and 5 % levels as "suggestive."

3.2. *Empirical specifications*

We estimate three different specifications of the model presented above, differentiated by the control variables used. The first specification controls only for gender, placing it in the true digit ratio Eq. (3). The second specification controls also for survey year and the level and square of respondent age, placing these in the perceived digit ratio Eq. (4) because the true digit ratio is not expected to change during adulthood (Garn et al., 1975; Galis et al., 2010; Gillam et al., 2008). The inclusion of gender is strongly supported in the literature, with the average digit ratio being lower for men than for women (see, e.g., Phelps, 1952, and Swami et al., 2013, Table 9, for an overview). The inclusion of age can control for the inability to fully extend the digits at advanced ages, e.g., because of arthritis in the hands, which can affect the measurement of digit ratios (Haugen et al., 2011; Richards et al., 2017; Yaku et al., 2016; Zhang et al., 2008). Gender and age have also been shown to relate to risk preferences and are thus also useful controls in the second-stage model: e.g., men have a higher preference for risk taking than women and the preference for risk taking decreases with age (Dohmen et al., 2011; Donkers et al., 2001).

The third empirical specification uses an extended set of controls to assess if the digit ratio associations remain when accounting for possible hereditary or intergenerationally transmittable factors, or possible causal pathways. These additional controls are time-invariant (see Section 2) and assumed to be associated with the true digit ratio. The controls for race, left-handedness, and mother's level of education account for the presence of possible hereditary or intergenerationally transmittable factors that are associated with both risk preferences and the digit ratio (Kalichman et al., 2019; Alan et al., 2017). Further controls are added for several possible pathways (i.e., life outcomes) through which the digit ratio could be associated with risk preferences. For instance, education has been shown to be positively associated with both the digit ratio and risk preferences (Nye et al., 2017a, 2017b; Donkers et al., 2001). Therefore, it is possible that the digit ratio is related to risk preferences only indirectly, through a direct relationship with education. If so, we expect the digit ratio's association with risk preferences to diminish or disappear once education is controlled for. We include life outcomes that were identified in the literature to be related to the digit ratio, or prenatal testosterone, and to risk preferences: educational attainment, cognitive skills, self-reported health, body mass index (BMI), height, and smoking behavior (see Online Appendix 2 for references). Again, our estimates of the digit ratio's association with risk preferences are robust to these controls also or instead entering the perceived digit ratio equation (see Section 3.1 or Online Appendix 4).

While the associations of the additional covariates of the third

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[9] Our main findings remain when using random effects ordered probit models (see Online Appendix 6).

[10] Test results also suggested there was no need for making such corrections (Wooldridge, 2014; Vella, 1990), and Kimball et al. (2008), in an application of their method, report finding minimal differences between the unadjusted standard error estimates and those based on a bootstrap method.

[11] While the estimates of the covariates' second-stage coefficients, β_0 and $\boldsymbol{\beta}_2$, do not share this robustness, these are not of primary interest.

empirical specification with the digit ratios and risk preferences are of independent interest, we refrain from discussing these in the main text. The mechanisms governing these associations are complex and deserve more thorough investigations than we could provide here. Online Appendix 2 discusses the relevant literature in more detail. Finally, for the empirical estimations we demeaned the covariates by gender.

4. Empirical results

4.1. The digit ratio model

Both panels A and B in Table 4 confirm the sexually dimorphic nature of the digit ratio: for both the left and right hand, men are about 22 pp (percentage points) less likely than women to report that their index finger is longer than their ring finger.[12] This latter finding of about equal gender differences for both hands does not support the conclusion of Hönekopp and Watson (2010) that the digit ratio shows greater sex differences in the right hand.[13] Further, the estimated standard deviations (SD) of the random effects are in the range of 1.2–1.5 and, given the normalized standard deviation of the error term is equal to 1, suggest that a large proportion of the variation in the reported digit ratio is due to measurement error.

The digit ratio is not expected to change during adulthood. For men, the age effect is minor, but for women the probability of reporting that the index finger is longer than the ring finger goes up with age (Panel B). As argued in the literature, these findings could be related to the inability to fully extend the digits at advanced ages (Richards et al., 2017).

Furthermore, there is no empirical support for pooling across genders for both specifications (last rows of Panels A and B). Not reported in tables is that a specification with interactions between gender and the covariates included in the model of Panel B, also provides no empirical support for pooling across genders.[14]

4.2. Risk preferences and the digit ratio

The estimated expected digit ratios that enter the risk preferences model (Eqs. (7) or (8)) are computed based on the results of the digit ratio model estimated by gender (Table 4, last four columns).[15] This latter implementation prevents an assessment of the extent to which the gender difference in the digit ratio accounts for the gender difference in the preference for risk taking.[16]

Table 5 presents estimation results for various versions of the risk preferences model. In line with, e.g., Croson, Uri (2009) and Dohmen et al. (2011) we find that, on average, men have a higher preference for risk taking than women, and that older men or women have a lower preference for risk taking than younger ones (Table 5, Panels A and B).[17] Also, the strength of the association of gender with risk preferences is about the same as the one in Dohmen et al. (2011). Although the digit ratio associations are individually insignificant (column 1), they are jointly significant at the 1 % level for the specification of Panel A and at the 5 %-level for the specification of Panel B (H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r = 0$).

For men and women combined, and allowing for a gender difference in risk preferences, the estimated associations of the digit ratio with the preference for risk taking are about − 0.1 for each hand separately (second and third columns of Panels A and B). Because only the digit ratio of the left hand or of the right hand is included in the risk preferences model and the two hands' ratios are strongly correlated (see Table 4), these associations also capture part of the association of the excluded hand's digit ratio. Nevertheless, Table 5 shows that there is a significant association with the digit ratio for each hand separately and that these associations are of about equal size.

Equal digit ratio associations for the left and right hand are not rejected (H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r$) and the results in the fourth column are for a model that imposes this equality (column "M & W, $\widetilde{\beta}_l = \widetilde{\beta}_r$"; Eq. (8)). For each hand, a one-standard deviation change in the true digit ratio is associated with about a 0.05 points reduction in the preference for risk taking (on a 0–10 scale). Accordingly, a one-standard deviation change in *both* hands' digit ratios is associated with a roughly 0.1 points reduction, twice the association of a single hand (see Eq. (8)).[18] This latter association is about the same as the association with a single hand estimated in the models that use only one hand in the risk preferences model, as seen in the second and third columns. This reflects a very high positive correlation between the hands' digit ratios (see also the about 0.83 correlation coefficient of the random effects of the digit ratio model, Table 4).

Furthermore, the null hypothesis of identical associations with the digit ratio for men and women is not rejected (Table 5, H_0: $\widetilde{\beta}_l^M = \widetilde{\beta}_l^W$, $\widetilde{\beta}_r^M = \widetilde{\beta}_r^W$). Nevertheless, the last two columns of the table present the results by gender and show the associations are about the same as those based on the combined sample of men and women, albeit less precisely estimated (see Table A.4 for all results by gender). Finally, allowing for measurement error in the reported digit ratio to be related to age hardly affects the estimated associations of the digit ratio with risk preferences (Panel A vs. Panel B).

4.3. Extended empirical specification of the risk preference model

Hereditary or intergenerationally transmittable factors that are associated with both risk preferences and the digit ratio can explain part of the estimated association of the digit ratio with the preference for risk taking. To examine this, we controlled for characteristics typically known at birth or in early life, namely race, left-handedness, and mother's level of education. Furthermore, the digit ratio's association with risk preferences can be mediated through later life outcomes related to human capital formation (level of education, numeracy, vocabulary, and verbal skills), or related to health (BMI, having arthritis, height, self-assessed health, and smoking behavior). We refer to Section 3.2 and Online Appendix 2 for further discussion.

When controlling for these characteristics, the associations of the digit ratio with risk preferences are marginally strengthened (Table 6). Furthermore, as is also the case for the empirical specifications of Table 5, the test results in Table 6 suggest equal digit ratio associations with risk preferences for the left and right hand (H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r$) and identical associations for men and women (H_0: $\widetilde{\beta}_l^M = \widetilde{\beta}_l^W, \widetilde{\beta}_r^M = \widetilde{\beta}_r^W$). The last three columns of Table 6 show results by gender and for White, non-Hispanic, respondents separately. While the digit ratio association

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[12] Table A.2 shows the associations for the extended empirical specification (see Section 3.2).

[13] A LR-test is used for testing the null-hypothesis 'Pooling men & women'. The pooled model includes a gender specific intercept (i.e., the model in the first two columns vs. the models in last four columns of Table 4).

[14] There are gender differences in the variance-covariance matrix. Computing the estimated expected digit ratio based on the pooled estimates (Table 4, first two columns) has, however, no discernible impact on the estimated associations of the digit ratios with the preference for risk taking in Tables 5 and 6. See also Online Appendix 5.

[15] To preserve robustness of our model to whether controls affect the true digit ratio or its measurement error (Section 3.1), the risk preferences model includes interactions between the covariates and gender. Summary statistics of the estimated expected digit ratios are in Table A.3.

[16] See Online Appendix 5 for such an assessment based on the results in the first two columns of Panel A (Table 4).

[17] For all specifications, the coefficient corresponding to age-squared was not significantly different from zero at the 5 % level.

[18] For Panel A it is 2 x − 0.055 = −0.11 and for Panel B it is 2 x − 0.052 = −0.104.

Table 4
Associations of gender and age with the probability of the index finger being longer than the ring finger (a high digit ratio).

M = Men W = Women	M & W Left hand	M & W Right hand	M Left hand	M Right hand	W Left hand	W Right hand
Index >ring (proportion)	0.359	0.325	0.284	0.248	0.430	0.397
Number of observations	9976		4294		5682	
Number of individuals	5898		2496		3402	
Panel A: Controlling for gender.	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)
Male (vs female)	-0.222***	-0.219***				
	(0.012)	(0.012)				
SD random effect	1.212***	1.233***	1.267***	1.252***	1.371***	1.490***
	(0.035)	(0.035)	(0.055)	(0.055)	(0.105)	(0.112)
Correlation random effects	0.833***		0.819***	0.845***		
	(0.011)		(0.017)		(0.015)	
Correlation error terms	0.737***		0.779***	0.704***		
	(0.014)		(0.020)		(0.020)	
H_0: Pooling men & women†	0.087					
Panel B: Controlling for gender and age	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)
Male (vs female)	-0.218***	-0.217***				
	(0.012)	(0.012)				
Age/10‡	0.022***	0.008*	0.002	-0.008	0.046***	0.027***
	(0.004)	(0.004)	(0.005)	(0.005)	(0.006)	(0.006)
SD random effect	1.211***	1.236***	1.269***	1.252***	1.161***	1.218***
	(0.035)	(0.035)	(0.055)	(0.055)	(0.045)	(0.046)
Correlation random effects	0.834***		0.820***	0.843***		
	(0.011)		(0.016)		(0.015)	
Correlation error terms	0.735***		0.778***	0.707***		
	(0.014)		(0.020)		(0.020)	
H_0: No age associations†	0.000***		0.076		0.000***	
H_0: Pooling men & women$^{a)}$	0.000***					

Notes. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.005$. Based on the estimation results of the digit ratio model (Eqs. (5)–(6)). Weighted average marginal effects are computed and the standard errors are clustered at the individual level. Index (ring) = index (ring) finger length. † Entries shown are p-values. ‡ Based on a quadratic age profile. These profiles show no strong curvature and have no turning points within the sample's age range (20–89).

Table 5
Estimated associations of the digit ratio (DR) with the preference for risk taking.

	M & W	M & W	M & W	M & W, $\widetilde{\beta}_l = \widetilde{\beta}_r$	Men, $\widetilde{\beta}_l = \widetilde{\beta}_r$	Women, $\widetilde{\beta}_l = \widetilde{\beta}_r$
Panel A: Controlling for gender.	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)
Male (vs female)	0.558***	0.558***	0.557***	0.557***		
	(0.054)	(0.054)	(0.054)	(0.054)		
DR-L	-0.073	-0.106***				
	(0.084)	(0.034)				
DR-R	-0.036		-0.102***			
	(0.083)		(0.034)			
DR-L + DR-R				-0.055***	-0.051*	-0.058*
				(0.017)	(0.025)	(0.024)
H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r = 0^{\dagger}$	0.007**	0.002***	0.003***	0.002***	0.046*	0.015*
H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r^{\dagger}$	0.819					
H_0: $\widetilde{\beta}_l^M = \widetilde{\beta}_l^W, \widetilde{\beta}_r^M = \widetilde{\beta}_r^W{}^{\dagger}$	0.068	0.451	0.744	0.842		
R^2	0.017	0.017	0.017	0.017	0.001	0.002
N	9976	9976	9976	9976	4294	5682
Panel B: Controlling for gender and age.	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)
Male (vs female)	0.550***	0.550***	0.550***	0.550***		
	(0.055)	(0.055)	(0.055)	(0.055)		
Age/10‡	-0.056***	-0.056***	-0.056***	-0.056***	-0.037	-0.074***
	(0.019)	(0.019)	(0.019)	(0.019)	(0.029)	(0.025)
DR-L	-0.052	-0.099***				
	(0.084)	(0.034)				
DR-R	-0.051		-0.098***			
	(0.084)		(0.034)			
DR-L + DR-R				-0.052***	-0.054*	-0.050*
				(0.017)	(0.025)	(0.024)
H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r = 0^{\dagger}$	0.012*	0.004***	0.004***	0.003***	0.035*	0.035*
H_0: $\widetilde{\beta}_l = \widetilde{\beta}_r^{\dagger}$	0.996					
H_0: $\widetilde{\beta}_l^M = \widetilde{\beta}_l^W, \widetilde{\beta}_r^M = \widetilde{\beta}_r^W{}^{\dagger}$	0.073	0.640	0.541	0.926		
R^2	0.020	0.020	0.020	0.020	0.003	0.005
N	9976	9976	9976	9976	4294	5682

Notes. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.005$. Based on the estimation results of Eqs. (7) and (8). DR = digit ratio, L = Left hand, R = Right hand, M = Men, W = Women, N = number of observations. Weighted average marginal effects are computed and the standard errors are clustered at the individual level. † Entries shown are *p*-values. ‡ Based on a quadratic age profile. These profiles show no significant curvature at the 5 % level.

Table 6
Associations of the digit ratio (DR) with the preference for risk taking: the importance of controlling for possible hereditary or intergenerationally transmittable factors and pathways through education and health outcomes.

	M & W	M & W	M & W	M & W, $\tilde{\beta}_l = \tilde{\beta}_r$	M, $\tilde{\beta}_l = \tilde{\beta}_r$	W, $\tilde{\beta}_l = \tilde{\beta}_r$	M & W, White, non-Hispanic, $\tilde{\beta}_l = \tilde{\beta}_r$
	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)	Coef. (Std.Err.)
Male	0.556***	0.556***	0.558***	0.557***			0. 607***
(vs female)	(0.066)	(0.066)	(0.066)	(0.066)			(0.071)
DR-L	-0.109	-0.112***					
	(0.086)	(0.035)					
DR-R	-0.004		-0.102***				
	(0.084)		(0.035)				
DR-L + DR-R				-0.056***	-0.057*	-0.055*	-0.047*
				(0.018)	(0.026)	(0.025)	(0.020)
H$_0$: $\tilde{\beta}_l = \tilde{\beta}_r = 0^\dagger$	0.006**	0.001***	0.003***	0.002***	0.026*	0.024*	0.004***
H$_0$: $\tilde{\beta}_l = \tilde{\beta}_r{}^\dagger$	0.528						0.551
H$_0$: $\tilde{\beta}_l^M = \tilde{\beta}_l^W, \quad \tilde{\beta}_r^M = \tilde{\beta}_r^W{}^\dagger$	0.100	0.647	0.597	0.962			0.260
R^2	0.056	0.056	0.056	0.056	0.027	0.051	0.060
N	9247	9247	9247	9247	4031	5216	6672

Notes. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.005$. Based on the estimation results of Eqs. (7) and (8). DR = digit ratio, L = Left hand, R = Right hand, M = Men, W = Women, N = number of observations. Weighted average marginal effects are computed and the standard errors are clustered at the individual level. The estimated expected DRs are based on the estimates of the digit ratio model (Eqs. (5)–(6)) with the extended empirical specification: See Section 3.2 (or Tables A.2 and A.5 for the full set of results and list of covariates). † Entries shown are *p*-values.

remains, these estimates have lower precision.

5. Discussion

Our analysis provides empirical support for the hypothesized negative association between the digit ratio and the general preference for risk taking. The estimated difference in the preference for risk taking of a one-standard deviation larger true digit ratio is about − 0.1 (on a 0–10 scale). This difference equals about 18 % of the estimated gender difference in the preference for risk taking, suggesting a meaningful biological basis for risk preferences.[19] While we refrain from making causal inferences, the estimated negative association between the digit ratio and the preference for risk taking remains after having controlled for characteristics related to possible intergenerationally transmittable factors and mediating pathways.

Lack of replicability of the estimated association between the digit ratio and risk preferences is a major concern in this strand of literature and hinders the use of the digit ratio as a biomarker, arguably for prenatal exposure to testosterone, and to gain insights into the possible biological roots of life outcomes. To improve on previous studies, which mostly relied on lab-experimental evidence with small samples (Neyse et al., 2020) or on non-representative samples, we chose a rather different research setup. Like Neyse et al. (2021) we have used a large population survey of about 6000 adults from the Understanding America Study. Individuals' risk preferences were elicited with a question about general risk preferences, with answer categories on a Likert scale. The digit ratios were elicited by asking respondents to compare the lengths of their ring and index fingers for each hand. These survey questions can easily be included in large population surveys, which can facilitate replication studies. Compared to previous studies, our approach comes at the costs of not having information on the full distribution of the digit ratio, and of having additional measurement error because of the self-reported nature of the measurements.

Since each hand's digit ratio was elicited twice, our statistical model based on Kimball et al. (2008) made it possible to account for measurement error. Our digit ratio question was apparently difficult to answer for many respondents, as shown by the changes in answers over time. Further research on survey methodology to improve accuracy is warranted. Technological innovations that use the camera on respondents' devices to measure the lengths of their digits may further facilitate the elicitation of the digit ratio in large surveys (Huang et al., 2014).

An important advantage of our statistical model is that it reduces the multiple ordinal measurements of the digit ratio to a one-dimensional measure, which facilitates the interpretation of empirical results. In particular, our statistical model provides estimates of the associations with the true digit ratio, which makes our estimates comparable with those from studies that use a continuous measure of the digit ratio.[20] This model is suitable for estimating a linear relationship between the digit ratio and risk preferences, in line with most previous studies. Further research may be needed to address the possibility of a nonlinear relationship, such as that found in studies that related the digit ratio to altruism, wages, and academic achievement (Brañas-Garza et al., 2013; Galizzi and Nieboer, 2015; Nye et al., 2012, 2017a, 2017b). For risk preferences, however, there is currently no empirical support for a nonlinear relationship (Neyse et al., 2021; Parslow et al., 2019).

Our empirical findings provide insight into the mixed findings on the digit ratio's association with general risk preferences (Bönte et al., 2016; Brañas-Garza et al., 2018; Neyse et al., 2021; Stenstrom et al., 2011). We provide empirical support for a negative association of the digit ratio with the general preference for risk taking. The estimated effect size is small, which suggests the need for large samples to detect a digit ratio's association with risk preferences (Apicella et al., 2015; Van Leeuwen et al., 2020). In addition, our findings suggest similar associations of the digit ratio with risk preferences for both hands and for both genders. Imposing such equalities increases the precision of the estimates. Finally, for men and women combined, the precision of the estimated associations of the digit ratio with risk preferences suggests that these associations are plausibly replicable (Benjamin et al., 2018). The associations by gender are estimated to be about the same as those for both genders combined, but with lower precision because of smaller sample sizes. Investigating whether our findings hold for other populations or extending the analysis with a lab-experimental measure of financial risk preferences or domain-specific risk preferences would be valuable research avenues.

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[19] A comparison of a digit ratio association of − 0.1 with a gender association of 0.56 (Table 5).

[20] Unfortunately, based on the information provided in previous studies, or because no significant associations were found, we could only compare the directions of the associations.

Finally, our findings show empirical support for a biological basis for risk preferences, adding to support provided in studies that have used twin or genetic data (Benjamin et al., 2012; Cesarini et al., 2009; Cronqvist et al., 2015; Linnér et al., 2019). While the literature argues that a possible interpretation of the digit ratio's negative association with risk-taking preference is that the digit ratio is a retrospective biomarker of prenatal exposure to testosterone (e.g., Coates et al., 2010; Manning, 2011), these assumed relationships are part of ongoing debate and research (Hönekopp et al., 2007; Voracek, 2014; Van Leeuwen et al., 2020; Warrington et al., 2018; Neyse et al., 2021). In addition, little is known about why individuals differ in their levels of prenatal testosterone. Findings of Rizwan et al. (2007) suggest an effect of maternal smoking on the fetus' digit ratio for boys (not for girls), which points toward the importance of in utero conditions for later life outcomes (Barker, 1995). The findings of Loehlin et al. (2006) suggest that differences in the digit ratio are due to genetic differences rather than environmental factors. Heritability of the digit ratio has been shown (Paul et al., 2006), as well as its genetic roots (Kalichman et al., 2019; Voracek and Stefan, 2009; Warrington et al., 2018). Next to further research on the link between genetic endowments and the digit ratio (Warrington et al., 2018), further research on the endocrinology of the digit ratio and on the possible factors affecting the digit ratio in utero, can shed light on the causal mechanisms underlying the digit ratio's association with risk preferences and, possibly through it, health and economic outcomes.

Disclosure statement

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Ethical review

This study has been approved by both the University of California's Institutional Review Board and the Ethics Committee of the Faculty of Law, Economics and Governance at Utrecht University. Informed consent was obtained from all participants and/or their legal guardians, and all methods were carried out in accordance with the relevant guidelines and regulations.

CRediT authorship contribution statement

Brian Finley, Adriaan Kalwij and Arie Kapteyn: contributed to all aspects of this study.

Data Availability

All data are available through the Understanding America Study's website (https://uasdata.usc.edu).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ehb.2022.101178.

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