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RESEARCH ARTICLE

# Biological, environmental and socioeconomic determinants of the human birth sex ratio in the Czech Republic

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**Abstract**

The Trivers–Willard Hypothesis (TWH) states that parents in good conditions bias the sex ratio towards sons and parents in poor conditions bias the sex ratio towards daughters. This study used data from a large nationwide population dataset ($N$=1,401,851) from the Czech Republic – a modern contemporary society. The study included air pollution and property prices in the TWH estimation, and had a more detailed focus on stillbirths than previous studies. Using official natality microdata from the Czech Statistical Office for years between 1992 and 2010 and data on levels of air pollution in the country over the same period, the study assessed whether the biological and socioeconomic status of mothers and environmental factors affected the sex of children. The results were largely insignificant and not robust across specifications. The presented epidemiological evidence suggests that stillbirths are randomly distributed in the Czech Republic and that the sex ratio is not affected by the socioeconomic status of mothers or by environmental characteristics.

**Keywords:** Trivers–Willard hypothesis; Sex ratio; Economic status

## Introduction

Trivers and Willard (1973) proposed a simple mechanism by which natural selection favours parents biasing the sex ratio of their offspring according to their ability to invest in them. The Trivers–Willard Hypothesis (TWH) states that there is a difference in investments in sons and in daughters depending on parental conditions and their position on the socioeconomic scale. Like many other studies (Almond & Edlund, 2007; Cameron & Dalerum, 2009; Schnettler 2013), this study operationalized parental conditions in terms of their socioeconomic status and wealth. In this way, it was possible to test if evolution would favour systematic deviations from the population sex ratio: higher sex ratio of the offspring of mothers living in good conditions (large family income, high parental education or good environment) and lower sex ratio of the offspring of mothers living in poor conditions (small family income, low parental education or harsh environment). In other words, the TWH expects women are considered a 'safe bet', since women almost always have some children, in contrast to men, who are only considered when enough resources are available to ensure that they will have children (the reproductive success of a male child tends to have a bigger variance, and it is more resource-sensitive).

There is a substantial amount of literature on the Trivers–Willard hypothesis (Veller *et al.*, 2016; Bereczkei & Dunbar, 1997; Valente, 2015; Kolk & Schnettler, 2016; Grech, 2018). An excellent example is a study by Almond and Edlund (2007), on which this study is built and expands on in multiple ways. Almond and Edlund used a general sample – US natality data from 1983–2001 (48 million births and 310,000 infant deaths) – and found results consistent with the TWH. It provided two main results: that married, better-educated and younger mothers bear more sons and that the infant deaths of males are greater if the mothers are young and unmarried.

Tests of the TWH are rare in modern contemporary societies. Moreover, tests of it on a general country population dataset are extremely uncommon since most research has been done on specific samples. To the authors' knowledge, this study is the first to consider the TWH in the Czech Republic, although Kaňková *et al.* (2007) found an increased sex ratio in the clients of expensive private reproductive medicine clinics in the Czech Republic. In addition, the research attempted to connect the TWH with the capitalization hypothesis. In other words, air pollution and property prices were tested among other determinants of the TWH (properties in a cleaner environment are more expensive as well, thus giving a better proxy of a household's socioeconomic status). Finally, the research focused on stillbirths in more detail than most previous papers.

The main research question was whether the biological and socioeconomic status of mothers and environmental characteristics such as air pollution affect the sex of children. To test the hypothesis, natality microdata were drawn from the Czech Statistical Office (CZSO) and data concerning levels of air pollution in the country were drawn from the Czech Hydrometeorological Institute (CHMI).

## The Trivers–Willard Hypothesis

Trivers and Willard (1973) showed that under certain well-defined conditions, natural selection favours systematic deviations from the natural sex ratio of 105–106 at conception and that these deviations tend to cancel out in the local breeding population. The hypothesis predicts that mothers living in wealthy conditions (relatively large parental investments) will have more sons, and that mothers in poor conditions (relatively small parental investments) will have more daughters. Because the reproductive success of a male child tends to be more variable and resource-sensitive, higher reproductive success is achieved if parents have a daughter in poor conditions and a son in wealthy conditions. The TWH says nothing about conscious motivations, as Hopcroft (2005, p. 1114) commented, and behavioural strategies that favour reproductive success have simply been selected and proliferated.

There are at least two biologic and/or economic reasons why parents should behave according to the TWH. The first is that parents should invest resources with the highest rate of return. In this case, the rate of return is their offspring's reproductive success. When the variance in the reproductive success is greater for males than for females, and when the male's reproductive success is more resource-sensitive, parents will invest more in males (or they will 'want' a male rather than a female), because then they will have a greater return on their investment (Clutton-Brock & Iason, 1986). Secondly, costs to the mother's future reproductive potential of producing a son versus a daughter vary with maternal conditions (Higashi & Yamamura, 1994). It is necessary to consider the effect of a given unit of investment, not only on the reproductive success of the offspring but also on the mother's future reproductive success (Clutton-Brock & Iason, 1986). For example, a poor mother cannot invest many other things except the time spent with a child. Moreover, because she comes from poor conditions, she probably has to go back to work earlier after pregnancy than a mother from good conditions. So, a female child can be, in some circumstances, a cheaper and more advantageous investment for a mother in poor conditions in terms of the offspring's reproductive success, the mother's reproductive success and the cost of children (Dubois & Rubio-Codina, 2012).

The model of Trivers and Willard depends on the following three assumptions:

1. The conditions of a child at the end of the parental investment will be correlated with the conditions of the parents during the parental investments. For example, more educated people will produce more educated children (Sewell & Shah, 1968; Oreopoulos *et al.*, 2006). Similarly, children of wealthy people will be wealthier.

2. The differences in the children's conditions at the end of the parental investment will tend to endure into adulthood. In the case of humans, parental investments are quite long and not pre-defined. In other words, parents can support their offspring for their whole life.
3. Resources have heterogeneous effects on male's/female's reproductive success. The reasoning for this assumption is as follows: women prefer men with greater resources (wealthier), so such men can attract a larger number of high-quality mates, and simultaneously men prefer younger and more attractive women for their mates (Buss, 1989, 2007; Kanazawa, 2003). As a result, women's reproductive success is largely orthogonal (not correlated) to their parent's socioeconomic status. Furthermore, women cannot produce many offspring due to their greater obligatory role in parental investment into each offspring (Kanazawa, 2003). Therefore, men with greater resources can afford more offspring, but for a woman, this does not hold. One of the problems with this assumption could be paternal investments. Trivers and Willard (1973) commented on this as follows:

> The application of the model to humans is complicated by the tendency for males to invest parental effort in their young (which reduces variance in male reproductive success), and by the importance of kin interactions among adults. Despite these complications, the model can be applied to humans differentiated on a socioeconomic scale, if the reproductive success of a male at the upper end of the scale exceeds his sister's, while that of a female at the lower end of the scale exceeds her brother's. (Trivers & Willard, 1973, p. 91).

Pérusse (1993) found that male reproductive success in Quebec in the years 1988–1989 did not increase with status (as measured by a composite of income, education and occupational prestige), but it did lead to greater sexual access. This finding, however, does not universally hold. Offspring numbers have been found to grow with income, wealth and educational level in men in most countries, whereas an inverse pattern, or no pattern at all, is true for women (Fieder & Huber 2007; Hopcroft, 2006, 2015; Nettle & Pollet, 2008; Goodman & Koupil, 2010; Lappegård & Rønsen, 2013; Morita *et al.*, 2017; Nisén *et al.*, 2018). For example Cameron and Dalerum (2009) investigated a group of the wealthiest people in the world (400 people from the Forbes billionaire list) and found that male billionaires had significantly more children, and a more variable number of children, than female billionaires. Nevertheless, Hopcroft (2005) argued that the differences in reproductive success do not need to hold today for the TWH to be valid:

> Given this situation in the evolutionary environment, by the logic of Trivers–Willard, there may exist evolved psychological and physiological mechanisms that promote high-status parents to invest more in sons and low-status parents to invest more in daughters, regardless of any contemporary sex differences in reproductive success. Given such evolved mechanisms, high-status parents are expected to invest more in sons, and low-status parents to invest more in daughters, even if males are not actually more reproductively successful in the contemporary environment. (Hopcroft, 2005, p. 1115).

This statement is also supported by the study of Freese and Powell (1999):

> Once such a tendency has evolved, its influence on parental investment should persist even in evolutionary environments in which the Trivers–Willard effect does not contribute to greater fertility (e.g., in contemporary American society and others in which social status and number of offspring are not positively related). (Freese & Powell, 1999, p. 1710).

Hill (1984), in their study of contemporary hunter–gatherer societies, stated that it is probable that a reliable relationship between reproductive success and male status existed among human ancestors. Moreover, Nielsen (1994) and Crawford (1998) claimed that modern developed societies have not existed long enough to reverse or substantively alter the cognitive mechanisms that have evolved over the last thousands or millions of years.

It can be expected that low-status parents will invest more in a female child than a male child, while high-status parents will invest more in a male child than a female child. The TWH can be further divided into two separate hypotheses. The first is that alteration of the sex ratio depending upon maternal conditions, both *in utero* and through infanticide after birth, is called Sex Ratio Biasing (SRB). The second is that allocation of more resources to offspring of one sex after birth (larger parental investments) depending upon the parents' conditions (family income, education, age or health) is called Resource Allocation Biasing (RAB) (Koziel & Ulijaszek, 2001). In the case of humans, this is not only the provision of nutrition to children while they are young, but also investment in education and the social and cultural development of children (Hopcroft, 2005).

Interestingly, a distinction between RAB and SRB predictions can be made. This article is not the first to emphasize the distinction and its implication for predictions based on the TWH. Anderson and Crawford (1993, p. 151) addressed the question with a simple model: 'Under what conditions do the parental behaviors that maximize numbers of grandchildren resemble the Trivers–Willard rules of thumb?' Using data from the !Kung of southern Africa, they found that optimal sex ratios are heavily influenced by the existing children of different ages and sexes in ways not predicted by the TWH. For this reason, some researchers only used the first child in their analysis (Kanazawa & Apari, 2009). For the RAB, Anderson and Crawford stated that optimum parental behaviour is sensitive to population dynamics, type of parental investment and, most importantly, relative ages of sons and daughters. Moreover, they concluded that it is doubtful whether the TWH rules (for the RAB) would maximize the number of descendants.

Another critique of the RAB is Keller *et al.* (2001); they argued that the TWH does not, in fact, predict the RAB in already existing offspring. According to the authors, the TWH should be limited to predicting those parental investments (e.g. the SRB, protection) that are related to fitness value. They used the following example:

> . . . consider two mothers in equally poor condition, one that has a son and one a daughter. Given the TWH assumptions, the mother with the daughter should have a fitness advantage over the mother with the son due to the different fitness values of the offspring; therefore selection favours a female-biased sex ratio for mothers in poor condition. However, the low-condition mother with the son should invest more in the son than the low-condition mother does in the daughter if the marginal benefit of investing additional resources is greater for sons. The bias for SRB, in this case, is in the opposite direction from the RAB bias. (Keller *et al.*, p. 357).

In conclusion, the RAB predictions are far more complex, and a simple prediction of the TWH about this matter can often be non-maximization strategy. This research focuses on the SRB only.

### *The Trivers–Willard Hypothesis – more research on humans*

There is an immense challenge in the testing of the TWH. It is probable that it may not be observed in societies that are resource-rich compared with ancestral environments. However, across time and area, the absolute level of resources varied considerably between ancestral groups, yet within each group, high-status males had higher reproductive success than low-status males. Keller *et al.* (2001) further commented on this issue:

> Because of this, a mechanism tracking absolute inputs (e.g. calories) would be disadvantageous compared to a mechanism that tracked relative inputs (e.g. status). Therefore, it is unlikely that the absolute level of resources has an effect on the putative TW mechanism. (Keller *et al.*, 2001, p. 347).

Koziel and Ulijaszek (2001) added that the TWH probably reveals itself in those populations where the extent of social stratification is sufficiently diverse.

Perhaps the best-known report on the TWH on humans is Dickemann's analysis of female infanticide in historically hypergynous societies (Dickemann, 1979). Her main result is that female infanticide was widespread among the upper classes in historically hypergynous societies because higher-class daughters had a smaller chance of 'marrying up' compared with higher-class sons. This fact can be interpreted as an indicator of an unwillingness to invest in the children of the murdered sex. However, other theoretical papers have suggested that infanticide would rarely be an adaptive strategy (Anderson & Crawford, 1993). Moreover, as Keller *et al.* (2001) pointed out, the sex bias produced by infanticide can be the opposite of that predicted by the TWH. An example is the study of Voland *et al.* (1991), who investigated high-status 18$^{th}$ and 19$^{th}$ century Germans in Krummhorn. They reported that high-status Germans were more likely to commit male infanticide in that time. This strategy helped them to keep their property undivided. Infanticide can sometimes be consistent with the TWH but it depends on the situation and the immediate goals of parents.

Chacon-Puignau and Jaffe (1996) and Zaldívar *et al.* (1991) tested the TWH in Venezuela using a large sample from the national birth registry (578,000 observations). They identified only a very small effect of women's marital status on the sex ratio. Zaldívar *et al.* reported no relationship between women's marital status and birth sex ratios or sex ratios at later ages. Using data from the Gabbra pastoralists of Kenya, Mace (1996) also reported no relationship between women's marital status and sex ratio at birth or among living children. On the other hand, Cronk (1989), investigating Mukogodo children (aged 0–4), found that this population was female-biased, and since the Mukogodo are at the bottom of a regional hierarchy, the results are consistent with the TWH. Jha *et al.* (2006) investigated the sex ratio of the population of India ($N$=133,738). Their main result in the context of this study was that better-educated women had a significantly higher adjusted sex ratio (683 girls to 1000 boys; 99% CI 610–756) than illiterate women (869 girls to 1000 boys; 99% CI 820–917). Finally, Luo *et al.* (2017) found that, in China, low-status family heads have more grandchildren through their daughters than their sons, whereas high-status family heads have more grandchildren through sons.

Overall, tests of the TWH in more developed societies have been inconclusive. Betzig and Weber (1995) used data on men in the US Executive Branch, including presidents, vice presidents and cabinet secretaries. They reported that parents in their sample produced more sons than daughters in the first cohort (Presidents Washington through Garfield); however, in the second cohort (Presidents Arthur through Reagan), they produced roughly equal numbers of sons and daughters. Essock-Vitale (1984) examined the number of children among the Forbes list of the 400 wealthiest Americans. She found that they had on average more children than the general US population and that wealthy Americans appeared equally likely to have sons as to have daughters. Cameron and Dalerum (2009) conducted a similar study on a sample of the 1000 wealthiest people in the world (they also used the Forbes billionaire list). However, they used just 399 observations (350 male billionaires and 49 female billionaires).

The goal of Schnettler's (2013) paper was to shed light on the matter of mixed results in the literature. He proposed two hypotheses – sample selection (mostly due to missing data) and lack of specification of the timing of wealth accumulation. He corrected both problems. Firstly, the analysis was based on a dataset of US billionaires with near-complete information on the sex of their offspring. Secondly, the subgroups of billionaires were distinguished according to the timing of their wealth accumulation. Although he found that the results on the hypothesis that billionaires have a higher share of male offspring than the general population were not consistent for all subgroups of billionaires, he also reported that heirs, but not self-made billionaires, had a higher share of male offspring than the US population. Contrary to this finding, the author also reported that heiresses had a much lower share of male offspring than the US average. These results imply that there are other mechanisms affecting the sex birth ratio as well; nevertheless, they were not uncovered in the paper.

There are also several papers that used a general population sample; Abernethy and Yip (1990) used linked birth–death records from the years 1976 to 1983 in the state of Tennessee. After stratification of the sample by socioeconomic indicators, they found the pattern for post-neonatal infant deaths to be supportive of the TWH. Norberg (2004) investigated maternal partnership status at the time of conception, and found that status could be taken as a determinant of the sex ratio. Almond and Edlund (2007) analysed the linked births and infant deaths of white mothers in the US from 1983 to 2001. The study provided two main results. Firstly, married, better-educated and younger mothers bore more sons and, secondly, male infant deaths occurred more frequently if the mother was unmarried and young. Finally, Guggenheim *et al.* (2007) provided a comprehensive analysis of nationally representative samples from 35 countries (survey data were collected by the Demographic and Health Surveys) and reported that the analyses did not support the TWH, but there was evidence of regional- and country-level differences.

### Mechanism of the Trivers–Willard Hypothesis

Most previous studied worked with a simple mechanism of the TWH: the effect of socioeconomic status on sex ratio at birth is based on the conditions of the mother. High-status mothers are more likely to be in good condition and are better able to carry a male fetus to term (Hopcroft, 2005). Almond and Edlund (2007) argued a similar mechanism, but nevertheless acknowledged that mortality *in utero* would be a more advantageous measure because the closer to conception, the lower the replacement cost of terminated offspring.

Another branch of research has focused on maternal diet. Apparently, a diet high in saturated fats but low in carbohydrates results in higher levels of circulating glucose, which can lead to the birth of significantly more male than female offspring (in laboratory mice) (Folmer *et al.*, 2003). Mathews *et al.* (2008) investigated the effect in a human population; they used data on 740 British women who were unaware of their fetus's sex. They reported that: 'Fifty-six per cent of women in the highest third of preconceptional energy intake bore boys, compared with 45% in the lowest third. Intakes during pregnancy were not associated with sex, suggesting that the foetus does not manipulate maternal diet,' (Mathews *et al.*, 2008, p. 1661). In contrast, Gibson and Mace (2003) reported a strong association between the sex of the most recent birth and maternal nutritional status in Kenya in 2000. Based on this evidence it seems likely that the nutritional status of the mother (as an important part of the costs of reproduction) plays a significant role in adjusting sex ratios.

### Air pollution and property prices

First, a simple yet informative model is used to explain why this paper used air pollution and property prices to test the validity of the TWH. Let's assume two identical communities which differ only in air pollution level. In the case of zero moving costs and identical property prices, everybody would want to live in the community with the lower level of air pollution. However, as people move out from the more polluted community, the property prices go down in the more polluted community. Because of the moving people, the property price in the less-polluted community increases. This mechanism continues up to the point where the two communities reach equilibrium – the difference between the property prices in the two communities is greater than the marginal willingness to pay for a reduction in air pollution of the people in the more polluted community. In this situation, the pollution is capitalized in property prices.

Polinsky and Shavell (1975) summarized the debate over the relationship between air pollution and property values. Smith and Huang (1995) conducted a more recent meta-analysis. They reported that the range of these estimated marginal values (measured as a change in asset prices) lies between US$0 and US$98.52 (in 1982–1984 dollars) for a unit reduction in total suspended particulates (in micrograms per cubic metre). Furthermore, the mean marginal willingness to pay for the reduction in air pollution is about five times larger than the median (US$109.90 vs US$22.40), so the outliers play an important role in any summary statistics for these estimates. Moreover, suburban properties (with lower air pollution and in an overall cleaner environment) are much more expensive than properties in the city centre (Harrison & Rubinfeld, 1978).

The second mechanism explaining why air pollution can affect the sex ratio is motivated by the fact that male fetuses are more vulnerable and thus more prone to miscarriages (Catalano, 2003; Peterka *et al.*, 2004; Helle *et al.*, 2008). Worse quality of air can cause miscarriages, and since boys are more likely to be a miscarriage, they should be affected more frequently. In other words, more girls should be observed in more polluted areas.

## Methods

### *Czech Statistical Office (CZSO) dataset*

The study utilized official microdata on newborns and stillbirths and their parents from the CZSO dataset for the following available years: 1992, 1994, 1996–2004, 2006, 2008 and 2010 (i.e. all births in a given year in the Czech Republic). The whole country population dataset contains 1,401,851 observations with the below-described variables.

The data on the prices of flats and houses also came from the CZSO. Annual data on these prices for all Czech districts in the period of 2001 to 2011 were also used. The prices in a district where the child was born were matched to the dataset of births (at a Local Administrative Unit (LAU1) level based on the EU Classification of Territorial Units for Statistics). There are 77 LAU1 districts in the Czech Republic. The variables are described in Table 1.

### *Czech Hydrometeorological Institute (CHMI) data*

Daily data were taken from the CHMI on level of air pollution from 216 district stations in the Czech Republic ranging from 1993 to 2012. The variable was measured at a LAU1 district where the child was born. For the purposes of the study, such a detailed dataset was not needed because the prices of properties do not react on a daily basis, but rather on a long-term average level. Because of this, the data on pollution were transformed to monthly averages.

The dataset contained many missing observations. Ideally, the dataset should contain 216 (the number of stations) times 240 (the number of months in the 20-year period), which is 51,840 measurements. However, it only contained 28,513 measurements, so approximately 45% were missing, which is a clear limitation of this variable. However, as the variable might enrich the existing knowledge in the field, it was still considered in the empirical analysis. The air pollution variable was 'Air pollution (PM10)'. Particulate matter concentrations refer to fine suspended particulates less than 10 microns in diameter (PM10) that are capable of penetrating deep into the respiratory tract and causing significant health damage (World Development Indicators, World Bank, 1993 to 2012).

### *The Index of Property Prices*

The correlation between the prices of flats and houses was 0.93, which is quite large. These data are ideal for a dimension reduction, which means that a new variable could be created – the Index of Property Prices – representing the flat and house price variables using principal component analysis (PCA). Bartlett's test $\chi^2$ with one degree of freedom has a critical value of 6.63 (based on a 99% level of confidence, i.e. $\alpha$=0.01). The resulting statistic is around one and a half million, which is much higher than the critical one. The *p*-value is practically zero, so the null hypothesis is rejected. Based on the test, the dimension reduction is justified. In the PCA, the number of variables is equal to the sum of eigenvalues. Table 2 demonstrates that the first component can explain almost 97% of the variance in the original two variables. Applying Kaiser's rule, only the first component is included. This decision is further supported by the evidence in Table 3, which presents the

**Table 1.** Descriptions of study variables

| Variable | Description |
|---|---|
| Birth date | Full date of birth (day, month and year) |
| Male child | Dummy variable; male=1, female=0 |
| Vitality | Dummy variable; child born alive=1; not alive=0 |
| Multiple birth | A multiple birth occurs when more than one fetus is carried to term in a single pregnancy. The variable has a value of 1 for single births; 2 for twins; 3 for triplets, and so on. |
| Multiple birth – dummy variable | Dummy variable: 1 if woman had multiple births, and 0 otherwise |
| Weight | Birth weight (g) |
| Gestation age | Length of pregnancy, from last normal menstrual period to birth (weeks) |
| Czech citizen | Dummy variable: 1 if mother has Czech citizenship, and 0 otherwise |
| Number of previous children | Number of children the mother had before the current child. |
| Child's order | Variable reflecting the child's order calculated as a number of previous children plus one. |
| Single | Dummy variable: 1 if mother is single, 0 otherwise |
| Divorced | Dummy variable: 1 if mother is divorced, 0 otherwise |
| Married | Dummy variable: 1 if mother is married, 0 otherwise |
| Widowed | Dummy variable: 1 if mother is widowed, 0 otherwise |
| Education of father | 1=basic education; 2=lower secondary education; 3=higher secondary education; 4=tertiary education |
| Education of mother | As above |
| Mother's age | Age of the mother (years) |
| Flat prices | Average price per square metre of a flat at the time of a child's birth in the district in which they were born (LAU1). |
| House prices | Average price per square metre of a house at the time of a child's birth in the district in which they were born (LAU1). |
| Air pollution (PM10) | Particulates less than 10 microns in diameter (PM10) that are capable of penetrating deep into the respiratory tract and causing significant health damage. The variable is measured in the district the child was born (LAU1). |
| LAU1 district | Dummy variable reflecting district at the LAU1 level based on the EU Classification of Territorial Units for Statistics, where the child was born |
| Year | Dummy variable reflecting the year the child was born |

**Table 2.** Eigenvalues and total variance explained: the Index of Property Prices

| | Initial eigenvalue | | |
|---|---|---|---|
| Component | Total | % of variance | Cumulative % |
| 1 | 1.938 | 96.877 | 96.877 |
| 2 | 0.062 | 3.123 | 100.000 |

Source: authors' calculations based on property prices from CZSO data.

**Table 3.** Component matrix and communalities

| Component loading | 1 | 2 | Communalities |
|---|---|---|---|
| Flat prices | 0.984 | −0.177 | 0.969 |
| House prices | 0.984 | −0.177 | 0.969 |

Source: authors' calculations based on property prices from CZSO data.

component loadings. The component loadings and their least squares, as well as the communalities, also suggest that the one resulting variable represents the original variables very well.

### *Analysis*

The Trivers–Willard sex ratio hypothesis was tested in two ways. First, the CZSO microdata sample was used to assess whether high-status people are more likely to have male offspring. Sex ratio was analysed by mother's age, citizenship, marital status and education of the mother and father. Inspired by Almond and Edlund (2007), the same perspective was adopted whereby the sex of a child is mostly endogenous to the characteristics of the mother. Marital status, education and citizenship are also good proxies for socioeconomic status in the Czech Republic: there is general mortality advantage for married people (Murphy *et al.*, 2007) and depressive symptoms have been found to be positively associated with being unmarried (Bobak *et al.*, 2006); low level of education strongly correlates with low income and well-being, mortality and stress-related illnesses, and is a good measure of deprivation (Bobak *et al.*, 1999, 2005; Chase 1998; Hayo & Seifert, 2003); female immigrants have poorer self-rated health in the Czech Republic (Pikhart *et al.*, 2010).

Although there could be mechanisms affecting the sex ratio at conception, the authors do not possess data to test this possibility. Therefore, the study focused on how mortality *in utero* shapes the sex ratio at birth. Data on early fetal deaths were not available, whereas data on stillbirths were available, so these were used to study the extent to which mortality in the late fetal period (more than 28 weeks) may be considered a proximate mechanism for the Trivers–Willard effect. The authors hypothesize that there will be greater mortality among males born to mothers in poor conditions, which would lead to a positive association between maternal conditions and male sex among live births.

The regression specification was as follows:

$$male_i = \alpha_0 + \alpha_1 X_i + \alpha_2 H_i + \alpha_3 C_i + \gamma_t + N_t + \in_i \quad (1)$$

where male$_i$ is a dummy variable taking the value 1 if child $i$ is male; $\alpha_0$ is the intercept; $\boldsymbol{X}_i$ is a matrix of the socioeconomic (citizenship, marital status and education) and biological (age) characteristics of the mother, which capture her conditions; $H_i$ is a matrix of variables capturing the father´s education; $C_i$ is a matrix of control variables (pollution, property prices); $\gamma_t$ is a vector of dummy variables for particular years (when the child was born), which accounts for the annual differences in the sex ratio and captures trend changes; $N_i$ is a vector of dummy variables capturing the districts where the child was born (at LAU1 level) and $\epsilon i$ is an error term. Under the TWH, $\alpha_1$ can be expected to be positive characteristics such as education. Also, married mothers can be expected to be more likely to have a son (under the assumption that married mothers are in a better conditions than unmarried mothers). As there might be differences with respect to the survival of the child, equation (1) was solved for three samples: 1) all births; 2) all live births; and 3) stillbirths. Under the TWH, children born to mothers in good conditions would be less likely to be stillbirths.

As an additional robustness check, the study aimed to include variables concerning infant's health status at birth (measured by gestation time and birth weight) because boys are heavier on average than girls, but also suffer from a different mortality risk at a given birth weight.

Empirically, the relationships among variables were first described with the help of a correlation matrix, and then the logistic regression was estimated because the dependent variable only have values of 0 and 1 (Wooldridge, 2002).

## Results

### Descriptive statistics

Table 4 presents the descriptive statistics of study sample. In terms of the mother's characteristics, most had Czech citizenship, their average age at the time of birth was almost 27, and most of them had had their first or second child (more precisely, 85.4%). More than 75% were married, and more than a half had higher secondary education or even tertiary (university) education.

The children's characteristics revealed that approximately 51.4% were boys, which is close to the natural ratio of 105 boys to 100 girls (51.2%). Most of the babies were alive at the time of birth, and the proportion of multiple births was 3%. The gestation time was close to 40 weeks with a standard deviation of 2.2, and the birth weight was 3308 g on average. The Index of Property Prices had zero mean and standard deviation of one, which is caused by the design of the PCA.

Unfortunately, information on fathers' education was filled in on a voluntary basis and thus there were many missing values in the dataset. Table 4 shows that about 20.1% of fathers reported that they had no education (compared with 0.4% of mothers), which of course does not reflect the educational structure of the Czech economy. This issue was caused by the fact that the coding of the CZSO´s dataset for father´s education did not make any distinction between missing data and the 'no education' category. There were two options on how to face this potential source of bias. First, all values with 'no education' could have been treated as missing and the regressions estimated. This could have resulted in losing about 20% of the original sample. Second, all values could have been treated as the 'no education' category and compared with the estimates based on the reduced sample to see if there were any differences in the findings.

### Correlation matrix

As the first step in the empirical approach, a correlation matrix of all variables was created (Table 5). Most of the variables did not appear to be correlated with the variable of interest (male child born), except the variables quantifying gestation time and birth weight, which significantly relate to the child´s sex.

### Logistic regression estimates

Table 6 shows the regression estimates for the whole sample, and it includes three estimated models considering the impact of the different independent/control variables. Table 7 shows separate estimates for just live births and stillbirths (all models were estimated with the robust standard errors).

Also, the level of collinearity among the estimated regressions was inspected with the help of correlation matrices and the Variance Inflation Factors (VIF) test, and a high level of collinearity was found between factors reflecting a child's health (gestation time and birth weight) and the mother's education. Every time these characteristics were included in the regressions, all parameters became statistically significant. Thus, models including both mother's conditions and child's birth characteristics were biased from multicollinearity and could not be used for evaluation of the TWH. The present estimates therefore relied only on parents' characteristics and did not suffer from multicollinearity (Wooldridge, 2002). The regressions also included dummies for

**Table 4.** Descriptive statistics of study sample[a]

| Variable | % | Min/Max |
|---|---|---|
| Male child | 51.4 | |
| Child alive | 99.7 | |
| Mother Czech citizen | 98.2 | |
| Mother's marital status | | |
| Single | 19.2 | |
| Married | 75.5 | |
| Divorced | 5.1 | |
| Widowed | 0.3 | |
| Mother's education | | |
| No education | 0.4 | |
| Basic education | 12.3 | |
| Lower secondary education | 35.8 | |
| Higher secondary education | 39.3 | |
| Tertiary education | 12.2 | |
| Father's education | | |
| No education or missing data | 20.1 | |
| Basic education | 4.5 | |
| Lower secondary education | 31.7 | |
| Higher secondary education | 24.9 | |
| Tertiary education | 12.8 | |
| | **Mean (SD)** | **Min/Max** |
| Mother's age | 26.7 (5.1) | 12/61 |
| Number of previous children | 1.7 (0.9) | 1/17 |
| Multiple births | 1.0 (0.2) | 1/4 |
| Gestation time (weeks) | 39.3 (2.2) | 0/46 |
| Birth weight (g) | 3308.2 (561.6) | 0/6890 |
| Flat prices (per $m^2$) | 14,368.2 (10,622.5) | 1914/51,649 (*N*=712,746) |
| House prices (per $m^2$) | 2302.4 (1793.9) | 648/7979 (*N*=715,107) |
| Index of Property Prices | 0.0 (1.0) | 0.0/3.4 (*N*=708,524) |
| Air pollution (PM10) | 35.8 (19.9) | 3.7/205.1 (*N*=935,014) |

[a]*N*=1,401,851, unless indicated otherwise.
The Index of Property Prices was extracted from the principal component analysis and represents two variables: flat price per $m^2$ and the house price per $m^2$ (all in CZK).
Source: authors' calculations based on the natality dataset from the CZSO; the property prices were also from the CZSO, and the air pollution dataset was from the CHMI.

LAU1 districts and year dummies. Finally, the models were estimated with the two operationalizations of father's education. No differences in the estimates were observed in the two cases, once the observations with father's no education/missing category were excluded, as well as when they

**Table 5.** Correlation matrix showing bivariate zero-order correlations

| | Malechild | Mother's age | Mother's nationality | Number of previous children | Mother's marital status | Mother's education | Father's education | Air pollution | Flat prices | House prices | Index Property Prices | Gestation time | Birth weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Male child | 1.0000 | | | | | | | | | | | | |
| Mother's age | 0.0005 | 1.0000 | | | | | | | | | | | |
| Mother's nationality | −0.0003 | −0.0064* | 1.0000 | | | | | | | | | | |
| Number of previous children | −0.0012 | 0.4321* | −0.0012 | 1.0000 | | | | | | | | | |
| Mother's marital status | 0.0003 | 0.2713* | 0.0131* | 0.2230* | 1.0000 | | | | | | | | |
| Mother's education | 0.0015 | 0.2880* | 0.0370* | −0.1605* | 0.1623* | 1.0000 | | | | | | | |
| Father's education | −0.0002 | 0.2392* | 0.0181* | −0.1089* | 0.0361* | 0.5672* | 1.0000 | | | | | | |
| Air pollution (PM10) | −0.0002 | −0.0228* | 0.0044* | −0.0040* | 0.0067* | 0.0055* | 0.0179* | 1.0000 | | | | | |
| Flat prices | 0.0004 | 0.2184* | −0.1023* | −0.0594* | −0.0174* | 0.1469* | 0.1865* | −0.0190* | 1.0000 | | | | |
| House prices | 0.0002 | 0.1980* | −0.1114* | −0.0615* | −0.0177* | 0.1329* | 0.1932* | 0.0146* | 0.9375* | 1.0000 | | | |
| Index of Property Prices | 0.0003 | 0.2117* | −0.1091* | −0.0617* | −0.0181* | 0.1420* | 0.1931* | −0.0020 | 0.9843* | 0.9843* | 1.0000 | | |
| Gestation time | −0.0191* | −0.0558* | 0.0210* | −0.0516* | 0.0280* | 0.0647* | 0.0548* | 0.0036* | −0.0496* | −0.0454* | −0.0486* | 1.0000 | |
| Birth weight | 0.1227* | 0.0406* | 0.0166* | 0.0063* | 0.0764* | 0.1150* | 0.1158* | 0.0016 | 0.0060* | 0.0046* | 0.0053* | 0.5811* | 1.0000 |

*Correlation significant at the 0.05 level (two-tailed).
Source: authors' calculations based on the natality dataset from the CZSO; property prices were also from the CZSO and the air pollution dataset was from the CHMI.

**Table 6.** Logistic regression estimates for the whole sample to test the Trivers–Willard hypothesis (that high-status mothers bear more sons)[a]

| Variable | Model 1 | Model 2 | Model 3 |
|---|---|---|---|
| Mother's age 18–21 years | 0.0220 | 0.0562 | −0.102 |
| | (0.0793) | (0.107) | (0.313) |
| Mother's age 22–29 years | 0.0206 | −0.00402 | −0.0977 |
| | (0.0442) | (0.0508) | (0.0892) |
| Mother's age 30+ years | 0.0785 | 0.0936 | 0.119 |
| | (0.0539) | (0.0627) | (0.0930) |
| Mother's nationality: Czech | −0.00587 | −0.00854 | −0.0339 |
| | (0.0129) | (0.0150) | (0.0241) |
| Child's birth order | −0.00304 | −0.00434* | −0.00104 |
| | (0.00193) | (0.00221) | (0.00355) |
| Mother married | 0.00294 | −0.00544 | −0.0149 |
| | (0.00483) | (0.0103) | (0.0112) |
| Mother divorced | 0.00242 | −0.00725 | −0.0128 |
| | (0.00877) | (0.0207) | (0.0223) |
| Mother widowed | 0.0156 | 0.113 | 0.0411 |
| | (0.0318) | (0.0996) | (0.105) |
| Mother's education: basic | −0.0151 | −0.0791 | −0.0668 |
| | (0.0275) | (0.0630) | (0.0718) |
| Mother's education: lower secondary education | −0.0200 | −0.0871 | −0.0679 |
| | (0.0272) | (0.0626) | (0.0708) |
| Mother's education: higher secondary education | −0.0164 | −0.0773 | −0.0671 |
| | (0.0271) | (0.0626) | (0.0707) |
| Mother's education: tertiary education | −0.00269 | −0.0637 | −0.0493 |
| | (0.0273) | (0.0627) | (0.0709) |
| Father's education: lower secondary education | | −0.00501 | 0.000398 |
| | | (0.00925) | (0.0155) |
| Father's education: higher secondary education | | −0.0119 | −0.00483 |
| | | (0.00974) | (0.0161) |
| Father's education: tertiary education | | −0.0107 | −0.00665 |
| | | (0.0109) | (0.0176) |
| Air pollution (PM10) | | | 0.0000123 |
| | | | (0.000194) |
| Index of Property Prices | | | −0.00150 |
| | | | (0.0137) |
| Constant | 0.0775* | 0.157* | 0.177* |
| | (0.0305) | (0.0659) | (0.0808) |

(*Continued*)

**Table 6.** (*Continued*)

| Variable | Model 1 | Model 2 | Model 3 |
|---|---|---|---|
| Year dummies | Yes | Yes | Yes |
| LAU1 districts dummies | Yes | Yes | Yes |
| Observations | 1,401,851 | 1,120,096 | 446,411 |
| Pseudo $R^2$ | 0.000 | 0.000 | 0.000 |
| AIC | 1,942,343.5 | 1,551,967.8 | 618,597.9 |
| BIC | 1,943,583.2 | 1,553,220.4 | 619,577.7 |
| Log likelihood | −971,069.8 | −775,878.9 | −309,209.9 |
| Wald $\chi^2$ | 95.90 | 88.28 | 59.29 |

[a]Sex of child: boy=1.
Robust SE logistic regression. Standard errors in parentheses: *$p<0.05$.
Reference categories for dummy variables: mother's age: <18; mother's nationality: non-Czech; mother's marital status: single; mother's education: no education; father's education: basic.
Source: authors' calculations based on the natality dataset from the CZSO; property prices were also from the CZSO and the air pollution dataset was from the CHMI.

**Table 7.** Logistic regression estimates for the whole sample to test the Trivers–Willard hypothesis (that high-status mothers bear more sons)[a]: pattern reinforced by post-neonatal mortality

| | Model 4 | Model 5 |
|---|---|---|
| Variable | Live births only | Stillbirths only |
| Mother's age 18–21 years | | 0.415 |
| | | (0.770) |
| Mother's age 22–29 years | | 0.435 |
| | | (0.767) |
| Mother's age 30+ years | | 0.578 |
| | | (0.771) |
| Mother's nationality: Czech | −0.00252 | 0.201 |
| | (0.0152) | (0.484) |
| Child's birth order | −0.00438* | −0.0149 |
| | (0.00222) | (0.0347) |
| Mother married | −0.00501 | −0.226 |
| | (0.0103) | (0.262) |
| Mother divorced | −0.00587 | −0.960† |
| | (0.0207) | (0.537) |
| Mother widowed | 0.114 | |
| | (0.0996) | |
| Mother's education: basic | −0.0813 | 0.145 |
| | (0.0631) | (0.983) |
| Mother's education: lower secondary education | −0.0895 | 0.125 |
| | (0.0628) | (0.977) |

**Table 7.** (*Continued*)

| Variable | Model 4 Live births only | Model 5 Stillbirths only |
|---|---|---|
| Mother's education: higher secondary education | −0.0800 | 0.248 |
| | (0.0627) | (0.976) |
| Mother's education: tertiary education | −0.0663 | 0.216 |
| | (0.0628) | (0.982) |
| Father's education: lower secondary education | −0.00479 | −0.151 |
| | (0.00926) | (0.157) |
| Father's education: higher secondary education | −0.0113 | −0.318† |
| | (0.00976) | (0.172) |
| Father's education: tertiary education | −0.0102 | −0.333 |
| | (0.0109) | (0.207) |
| Constant | 0.153* | 0.0904 |
| | (0.0661) | (1.262) |
| Year dummies | Yes | Yes |
| LAU1 district dummies | Yes | Yes |
| Observations | 1,117,154 | 2942 |
| Pseudo $R^2$ | 0.000 | 0.027 |
| AIC | 1,547,891.7 | 4167.7 |
| BIC | 1,549,108.2 | 4790.4 |
| Log likelihood | −773,843.9 | −1979.9 |
| Wald $\chi^2$ | 85.69 | 106.4 |

[a]Sex of child: boy=1.
Robust SE logistic regression. Standard errors in parentheses: †$p<0.10$; *$p<0.05$.
Reference categories for dummy variables: mother's age: <18; mother's nationality: non-Czech; mother's marital status: single; mother's education: no education; father's education: basic.
Note that mother's age dummies were excluded during the estimation procedure in Model 4. However, when a control model was estimated where mother's age was included as a continuous variable, the results were not different from the presented estimates.
Source: authors' calculations based on the natality dataset from the CZSO; the property prices also from the CZSO and the air pollution dataset was from the CHMI.

were left in the analysis. However, as it is not known which observations are missing and which really describe the fathers with no education, the results have been reported without this education category, even though it decreases the sample size.

### *Evaluation of the Trivers–Willard hypothesis for the whole sample*

Table 6 reports three regressions showing different model specifications depending on a set of independent variables. Model 1 includes only mother's characteristics, Model 2 adds father's education and Model 3 adds pollution and property prices. The obtained estimates do not prove a statistically significant impact of parents' characteristics and environmental determinants on the likelihood of a male being born. The only variable that was found to be statistically significant was that measuring a child's birth order in Model 2, which might indicate that the more children a mother has, the less likely it is that the next one will be a boy. Nevertheless, the significance of this variable was not proven in the remaining models. The presented estimates do not empirically support the Trivers–Willard hypothesis.

### *Evaluation of the Trivers–Willard hypothesis for live births and stillbirths only*

If stillbirths operate in a manner consistent with the TWH, the coefficients in the sample 'live births' can be expected to be reinforced to the side consistent with the TWH. However, Table 7 does not confirm this hypothesis. Besides the child's birth order, there is only one new significant variable in Model 5 – father's higher secondary education. This finding indicates that, compared with fathers with basic education, the likelihood of a stillborn boy is lower for fathers who obtained higher level of secondary education. This nevertheless suggests that stillbirths are primarily random, or at least not affected by the variables this study possessed. In other words, high-status women have the same likelihood of experiencing a male stillbirth as low-status women. Interestingly, no empirical support was found for the often-observed pattern of 'competing forces' (biological and socioeconomical) as noted by Royer (2004). The effect of maternal age on an infant's health comprises a tension between biological and socioeconomic conditions. Younger mothers tend to be healthier than older mothers, but their socioeconomic status tends to be worse.

## Discussion

The study findings suggest that the Trivers–Willard mechanism is not active in the Czech Republic. Three possible explanations for these results are identified. First is the biological and socioeconomic status of the father. Probably one of the most severe problems in this dataset is the lack of information on the biological and socioeconomic characteristics of fathers. Information was only available for mothers, and by using only that, the assumption is simply that the biological and socioeconomic conditions of parents (on aggregate) are correlated. If this assumption does not hold (as is probably the case), then the data used were not adequate to test or reject the TWH properly.

Secondly, there was insufficient variability of wealth: absolute wealth is unlikely to be a driver of the Trivers–Willard mechanism. That said, relative differences do matter. However, imagine a situation where the relative differences are too small and the Trivers–Willard mechanism cannot operate. In other words, to assess the size of the relative differences in the Czech Republic, a proxy can be used – for example, the Gini coefficient. The Czech Republic, with a value of 24.9, was the fourth most egalitarian country among 31 European countries in the year 2012 (Eurostat, 2012). In previous years, the situation was similar.

Lastly, the evolutionarily novel environment might be responsible. This hypothesis is related to the previous one. It is highly possible that various forces of the cultural evolution of human co-operation (Richerson & Boyd, 2006; Houdek & Novakova, 2016; Houdek *et al.*, 2016) mask the TWH or the TWH is not culturally compatible with some aspects of modern society. Guggenheim *et al.* (2007) provided a comprehensive analysis of nationally representative samples from 35 countries and found only regional and country-level evidence. Further research is needed to answer the question of why the TWH mechanisms are active in some countries and inactive in others.

In conclusion, this study investigated the effect of the biological and socioeconomic status of mothers and environmental characteristics (air pollution and property prices) on the sex of children born in the Czech Republic. No evidence for the Trivers–Willard hypothesis was found. Three causes of the insignificant results were identified, but none was testable with the current dataset. There are many potential topics for future research. An obvious one is to extend the dataset presented in this article – especially for fathers' biological and socioeconomic characteristics. Secondly, it should be determined why the TWH is active in some areas of the world but inactive in others. Thirdly, TWH research should be connected to (income) inequality research.

The TWH poses several interesting questions (Jayachandran & Kuziemko, 2011; Baker & Milligan, 2013; Bharadwaj & Lakdawala, 2013; Barcellos *et al.*, 2014). For example, if the TWH mechanisms work, then there is reason to believe that the effect will be stronger in more unequal countries (Deaton & Paxson, 1997; Deaton, 2003). If this is the case, then the TWH can contribute to social mobility, since parents in poor conditions will be more likely to have a girl, and parents in good conditions will be more likely to have a boy, and the probability that those two will marry will increase. In contrast, one may pose the question as to whether the TWH contributes to the selection of abortions. Moreover, when focused on the after-birth TWH, where more resources are allocated to a boy by parents in good conditions, while parents in poor conditions should invest more in a girl, other relevant questions can be raised, such as: Are mothers in good conditions with a girl expected to return to the workforce earlier than those with a boy (or vice versa)? Or, is the TWH mechanism at least partly responsible for the education gap between men and women? Lastly, are fathers with a boy more interested in their paternal investments or in having the mother breastfeed longer? Generally, the most interesting question in the context of the TWH is whether parents ever maximize their number of offspring, and if yes, under what conditions they do so.

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**Ethical Approval.** The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

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