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Maternal age, birth order and other early-life factors: a family-level approach to exploring exceptional survival

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Abstract

The literature provides increasing empirical support for the idea that early-life experiences can greatly shape someone's future health and longevity. Besides shared early-life conditions, within-family variation in maternal age at time of childbirth and birth order have been found to be related to later-life survival. In this study, we examine whether there is a persisting effect of maternal age and birth order on survival to age 104 when both variables are considered and adjusted for season of birth and birth spacing. To address potential confounding by unmeasured family-level factors, we apply a case-sibling control analysis. Using data on 273 centenarians born in Quebec in the 1890–1900 period and their siblings, we show that children born to mothers over age 40 are less likely to reach age 104 while third- and fourth-born children are more likely to make this landmark. When examining the effect of maternal age in combination with the effect of birth order, we obtain higher estimates of both maternal age effects and birth order effects, indicating that the measured influence of one is suppressed when the other is not accounted for. We argue that being born early in the sibling row may provide a biological advantage related in part to the quality of the female reproductive system, but this effect may be counterbalanced by the precariousness of the family as a socio-economic unit at the earliest stages of its cycle. No mediation of these effects is seen when including birth spacing and season of birth. However, we find that birth order differences in longevity are most prominent among siblings born to older mothers and in families where the father was a farmer. We discuss other possible social and historical pathways through which maternal age, birth order and season of birth may operate to mould the offspring's longevity.

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1 Introduction

As the prospects for a long and healthy life have rapidly grown over the last decades, so has the scholarly and public interest in the reasons why some people may become centenarians while others may not. The importance of family in contributing to health and longevity is well-recognised. Many studies have shown that parents and siblings of centenarians have a survival advantage compared to other members of their birth cohort (Perls et al. 1998, 2002; Willcox et al. 2006; Jarry et al. 2012). Yet, of several siblings in a centenarian family, often only one will live to or beyond the age of 100 years. While it is known that centenarians' exceptional longevity is probably deeply rooted in genetic and environmental factors that are shared among family members, less established in the literature are the impacts of non-shared factors that vary within families and that are child-specific, such as parental age, birth order or season of birth. Much of the inequalities in longevity could thus be assigned to differences between siblings from the same family rather than to differences between families (Plomin 2004). The aim of this paper is to investigate whether variation in life duration within families rests on maternal age at the time of childbirth, birth order and other early-life child-specific characteristics.

1.1 Literature on parental age and birth order effects on mortality and longevity

There is a strong relationship between parental age and offspring mortality, although some studies did not find any evidence for this link (Hubbard etal. 2009; Robine et al. 2003; Westendorp and Kirkwood 2001). For those who did find an association, the most common finding is that an advanced parental age is associated with higher early- and old-age mortality (Bell 1918; Jalavisto 1959; Philippe 1980; Kemkes-Grottenthaler 2004). However, not all children may be as negatively affected by parental age. A retrospective analysis of records from the European aristocracy conducted by Gavrilov and colleagues revealed that daughters born to fathers aged 50 years or more were expected to die 4.4 years earlier compared to daughters from younger fathers aged 20–29 when longevity of the father was controlled for (Gavrilov et al. 1997). Smith et al. (2009) used a sample from the Utah Population Database of individuals born between 1850 and 1900 and discovered that for males, maternal age at birth above 35 was associated with an increase in the sons' adult mortality in comparison with a maternal age between 20 and 29. Myrskylä and Fenelon (2012) found that children born to mothers younger than age 25 or older than age 35 had worse outcomes regarding mortality and other health-related issues. However, only the relationship between a young maternal age and offspring mortality remains significant when controlling for maternal education and the age at which the child loses his mother, suggesting that detrimental effect of a delayed maternal age may not be driven by biology but rather by the loss of the mother early in life.

Needless to say, some of the parental age effects on offspring's longevity may be spurious and reflect the influence of birth order, both variables being correlated (Kalmijn and Kraaykamp 2005). The long-term effects of birth order have been addressed from a variety of perspectives in different fields. Psychology, medicine and economics offer many examples. Negative relationships between birth order and educational attainment, adult earnings, IQ, nutritional intake and certain health outcomes were reported (see Lehmann et al. 2012, Black et al. 2007 and Kantarevic and Mechoulan 2006 for reviews).. In the field of demography, studies examining the possible influence of birth order on adult and old-age mortality have been limited. Using a highly-gifted cohort, O'Leary et al. (1996) did not find any evidence that birth order was associated with adult all-cause, cardiovascular or cancer mortality. Using data from the Uppsala Birth Cohort Study, Modin (2002) found that birth order was linked to all-cause mortality for both men and women in adulthood, and for men only in middle to old age, controlling for other early-life and familial variables such as mother's age, marital status, social class and disease status at the time of birth, child's birth weight, gestational age at delivery and disease status in infancy. However, birth order was not directly related to mortality risks at older ages in this study. Instead, birth order was expressed indirectly via the attained social status. Finally, Smith et al. (2009), who found a detrimental effect of maternal age at childbirth above 35, did not, however, find a significant relation between birth order and adult mortality. To the best of our knowledge, there is only one empirical paper on centenarians that has simultaneously considered the later-life consequences of birth order and parental age at the time of childbirth using a fixed-effects framework. Among centenarians and their siblings, Gavrilov and Gavrilova (2012) showed that exceptional longevity was linked to first-born status, but that this relationship was driven by a young maternal age at the child's birth.

1.2 Theories and mechanisms of parental age and birth order effects

Researchers have pointed to various pathways through which parental age at childbirth and birth order may affect offspring longevity. From a biological and physiological point of view, there is a fairly clear consensus that an advanced maternal age increases the incidence of pregnancy-related medical complications as well as various genetic malformations in the offspring (Liu etal. 2011). One pathway involves the lower quality of female oocytes in older mothers resulting in an increased risk of birth defects (Pellestor et al. 2005). The mechanisms linking a delayed maternal age at reproduction and long-term morbidity and mortality in the offspring are less clear, but they probably involve an excess load of maternal defective mitochondria. Oocytes and ovaries of older mothers are more likely to contain damaged mitochondrial DNA which could be transmitted to the next generation, reducing the biological fitness, health and longevity of the offspring (Tarin et al. 1998). Other correlates of advanced maternal age include a decline in the efficiency of the uterus, an increase risk of placental dysfunction or increased variations in hormonal levels during pregnancy (Johnson et al. 2009; Nelson et al. 2012). Contrastingly, some studies found that a very young maternal age is also associated with birth defects and health problems that are thought to originate in the physiological immaturity and a poorer nutritional status of young mothers (Reefhuis and Honein 2004; Loane et al. 2009; Fraser et al. 1995).

Similarly, increasing paternal age has been associated with a range of congenital syndromes, developmental disabilities, neuropsychiatric conditions and neurodevelopmental disorders in the offspring. The most replicated studies in this field showed a link between an advanced paternal age and increased risk for bipolar disorder, epilepsy, autistic behaviours and schizophrenia (Thacker 2004; Malaspina et al. 2005; Vestergaard et al. 2005; Frans et al. 2008; Dalman and Allebeck 2002). Most researchers attribute these associations to the accumulation of chromosomal aberrations and mutations during the maturation of germ cells (Liu et al. 2011; Gavrilov and Gavrilova 1997). Epigenetic alteration in the sperm of older men has also been proposed as an alternative explanation (Feinberg 2010). However, the negative association between paternal age at birth and longevity was put into question in a recent study: Eisenberg et al. (2012) investigated the effect of delayed paternal age of reproduction on the telomere length, which is an indicator of cumulative cellular ageing and thus of a reduced lifespan of the offspring. A telomere is a repeating DNA sequence found at the ends of the body's chromosomes that protects them from mutating (Blackburn and Gall 1978). Telomeres are known to shorten with age, thus leading to senescence (Eisenberg et al. 2012). Interestingly, the authors discovered that individuals born to older fathers inherited longer telomeres and thus a longer survival. Moreover, the authors noticed an additive effect of late reproduction by both fathers and grandfathers on the average length of the telomeres at birth, thus challenging earlier findings that an old paternal age is negatively associated with offspring longevity.

Even though the importance of many biological channels is supported by a large and growing literature, other mechanisms are also found to play a role. From a socioeconomic point of view, parents may not provide their children with the same amount of resources in childhood and over their lifetime and this may promote inequalities between them. In a natural fertility population, first-born children or children born to younger mothers may benefit from less resources overall than later-born children since these resources tend to increase over the family life cycle. Ejrnaes and Pörtner (2004) point out that the resource constraint could lead to older children leaving the family sooner and entering the labour market earlier, thereby increasing the available resources for the younger children. Furthermore, despite the fact that siblings have parents with the same baseline characteristics, they do not have the same exposure to family structures. Birdsall (1991) argues that parental constraint can be expressed as the amount of time a mother spends with her child. In this perspective, early-borns benefit from more individual care than later-borns since they spend more time in smaller families. Another way to conceptualise maternal age effect is to consider it as an indicator of how long a person has been exposed to a younger parent when growing up Kalmijn and Kraaykamp 2005). Birth order effects may also operate indirectly through variations in the attainment of adult characteristics such as education, socio-economic status or marital status. Modin (2002) found that birth order does not directly influence old-age mortality. Birth order effects on mortality risk in later life are rather expressed indirectly via attained social status. Likewise, Falbo et al. (2009), using structural equation modelling, report that the influence of birth order on health in later life can best be understood as reflective of other factors that may promote educational attainment, namely socio-economic status of origin and aptitudes.

1.3 The influence of seasonality of birth on longevity

Besides parental age at childbirth and birth order, the pattern of ageing may be influenced very early through other factors from the unshared environment. Seasonality influences on later-life mortality have been documented in a number of studies, most of which found that individuals born during winter exhibited increased longevity compared to those born during the remaining periods of the year (Huntington 1938; Doblhammer and Vaupel 2001; Gavrilov and Gavrilova 1999). The three studies devoted to centenarians, showed slightly divergent results. Gavrilov and Gavrilova (2011) observed that individuals of the 1880–1895 American cohorts who were born between September and November had about a 40% higher chance of living to age 100 as compared to their siblings who were born in March, supporting the idea of an early-life programming of human ageing and longevity. Using data on 925 age-validated semi-supercentenarians from Germany born between 1880 and 1900, Doblhammer et al. (2005) found that among the December-born, the relative risk of survival from birth to age 105+ was 16% higher than the average while among the June-born, it was 23% lower. Surprisingly, using the same set of data, Drefahl (2005) reported that among German semi-supercentenarians, those born in September had the lowest chances of surviving after age 105 whereas those born in February had the highest risk, although his conclusion seems to lean toward random variation. Old-age mortality differences according to season of birth also existed in preindustrial Quebec (Gagnon 2012). South of the Saint Lawrence River, winter-born female babies had the best survival prospects after age 60 whereas females born in autumn showed the lowest mortality after that age in the north.

Three main reasons motivated our choice to consider season of birth as an important variable. First, season of birth is often used in epidemiological studies as a proxy measure for intrauterine developmental conditions and for environmental influences occurring in early life. This is relevant particularly in historical populations in which both nutritional status and the burden of infectious diseases exhibited great seasonal variation. Season of birth can also be an indicator of temperature, sun exposure and vitamin D levels (Flouris et al. 2009; Ueda et al. 2013). Second, in contrast with birth order or parental age at conception, this indicator is cyclical and largely exogenous; younger or older siblings may or may not be born during the same season and the distribution of births along the seasonal cycle captures variations that are largely unrelated to family background and other socio-economic or environmental conditions (Doblhammer 2004). The third reason is related to the idea that, interacted with our main variables of interest, birth season provides means to delve deeper into the aetiology of the early-life conditions that favour longevity. As written above, children born early in the family life cycle benefited from fewer resources during growth than their younger siblings, who were presumably born at a time when the farm was well established. If early exposure to infectious diseases increases mortality via nutritional imbalances and perturbations to the immune system, it can be hypothesised that the effect of season of birth would be strongest for the former than for the latter. In other words, first-born children in the 'wrong' season could have suffered disproportionally higher death rates later in life. Contrastingly, since multiple pregnancies may lead to maternal depletion in a context of very high fertility such as that of historical French Canada, season of birth could have been instead more influential to children born from older mothers or, equivalently, late in the family life cycle. In such contexts, households carrying more children had increased disease loads, disproportionally affecting higher birth order children. As far as we can tell, there has been no research for such an interaction with regards to exceptional longevity.

2 Objective and research questions

This study aims to examine how the association between inequalities in longevity among siblings may originate from social or biological events experienced at a very early age. Despite all the possible mechanisms, considerable debate exists as to whether the influences of parental age and birth order are genuine or whether they are the result of their common associations with confounders. Various possible factors, observed or unobserved, affecting both longevity and parental age have been identified in the literature. Family poverty, socio-economic status (SES) or maternal education can alter the association as parents of lower SES may be more likely to have more children and earlier. It thus seems important to keep in mind that individuals who have their first children at an early age may be quite different in many respect from other parents. Furthermore, individuals and families vary greatly in their vulnerability to survival. This heterogeneity is often hidden or unmeasured and can be shared by members of a same group (Vaupel 1988). It is well known for instance that parental longevity tends to be correlated with offspring's longevity as the proclivity to live long is in part determined by the health of the mother or the familial underlying genetic and biological vulnerability to death.

To address potential confounding by unmeasured family-level factors, we performed within-family analyses using a sample of 273 centenarians who died after the age of 104 years and their siblings. The main question this paper addresses is whether child-specific characteristics established early in life matter in the long run. More specifically, we ask whether there are persisting effects of maternal age at the time of childbirth and of birth order on longevity when both variables are considered and when shared early-life factors are adjusted for. Motivated by the significance of early-childhood environment for later-life mortality, we also explore the relationship between maternal age, birth order and longevity controlling for birth spacing and season of birth as both of them belong to the non-shared environment of siblings. Finally, we shall also investigate the interactions between maternal age and season of birth and between birth order and the socio-economic status of the family.

3 Material and methods

3.1 Study population

The dataset that we built for this study contains information on French-Canadian families with at least one child who lived to or beyond the age of 104 years at the end of the 20th and beginning of the 21st century. The identification of the centenarians was the starting point in establishing the database. In the first step, we obtained from the Statistical Institute of Quebec a list of all individuals who died at age 100 and above in Quebec during the period 1970–2004, giving for each case the name of the centenarian, the name of his or her parents and spouse, the dates of birth and death and the place of birth. To ensure the reliability of ages at death, a systematic and complete validation of these ages was done through vital statistics dating back to the end of the 19th century. As only French-Canadian Catholics[1] were kept in the sample, the declared age at death of each centenarian was validated by finding their baptism certificate through the parish registers and by linking it to their burial certificate.[2] The second step was to select the centenarians to be included in this study. Because the family reconstitution requires time-consuming and resource-intensive work that can only be completed over a long period of time, the strategy we employed in this research project was to select centenarians aged 104 years and over who died in Quebec between 1994 and 2004 (birth cohort 1890–1900). The choice of a 104 cutoff, rather than the more commonly used 105 cutoff, was motivated by the effort to include a sufficient number of oldest olds. Throughout this paper, we use the terms 'exceptional survival', 'exceptional longevity' and 'centenarians' to refer to individuals aged 104 and over.

After a meticulous authentication process in which centenarians were thoroughly validated, we reconstituted the family of each and everyone of them, including the timing of births of the entire sibship. The family reconstitution was achieved by linking the 273 centenarians aged 104+ to their family members through the nominative rolls of the Canadian censuses which are available for the years 1891,

[1] The reasons why we confine this study to French-Canadians born and deceased in Quebec are discussed in Desjardins and Bourbeau (2010).

[2] A complete description of the validation process can be found in Beaudry-Godin (2010).

1901 and 1911.[3] In order to reduce the risks of missing a birth record or of mistaking an identity we manually scrutinised the relevant parish registers, year after year, starting from the date of marriage of the parents. In addition to helping us find and validate each birth in the family, this procedure allowed us to trace nearly all children who died at a young age and who were not present in the censuses. We selected only families with at least two children and families in which all children were born to their biological mother. Thus, all subjects came from biologically intact families and individuals who were allegedly adopted and half-siblings were excluded from the analyses. In one particular family, we found two centenarians born inside the 1890–1900 time window. Both of them were included in the analyses. Overall, our working database includes 273 centenarians and 2,477 siblings gathered in 272 families. Centenarians were born between 1890–1900 while their siblings were born in a wider time window (1870–1918) but their mean birth year was the same as that of their long-lived siblings, namely 1895. The oldest recorded sibling was born in 1870 while the youngest was born in 1918, but the year of birth of most of them (75%) was between 1880 and 1910. The mean age at death of centenarians' siblings conditional upon survival to age 20 was 72.2 years. Surviving to age 104 was an exceptional achievement as centenarians outlived their adult siblings by more than 30 years.

Once the database was completed, we searched for the date of death of each sibling through the Quebec Consolidated Deaths Index from the *Genealogical Society of Quebec*. This database allows users to find the dates of death and of birth, maiden names and other information on persons who died in Quebec between 1926 and 1996. For deaths occurring beyond 1996 and until 2010, we used a list of registered deaths of people aged 85 and above provided by the *Institut de la Statistique du Québec*. Record linkage was made on the basis of information contained in both the censuses and the death registers using the subjects' name, date and place of birth, as well as the name of the parents. In the event of any reported difference in day, month, or year of birth, the individual was identified on the basis of agreement between other variables, notably the name of the parents or of the spouse, the place of last residence or the place of death. After the dataset was completed, all individual information was made anonymous and centenarians and their siblings were identified only by a unique ID number.

3.2 Outcome of interest

The dependent variable is the likelihood to achieve age 104. We obtained data on the age at death for 87.8 per cent of the members of the sample. Difficulties in matching a person with a frequent name, missing or false dates or an emigration history account for the remaining 12.2 per cents of individuals who could not be

[3] Available online through www.ancestry.ca and www.automatedgenealogy.com.

linked. The validation of the age at death of the centenarians is crucial for this paper, but not knowing the exact age of death of siblings of centenarians is not too problematic as long as we are able to rule out the possibility of them becoming centenarians themselves. One potential bias with the missing information on ages at death is that people for whom we do not find a death certificate or any information on their age at death may have lived until age 104 or may even still be alive. The latter possibility is quite unlikely, since we have found the date of death of all individuals born between 1912 and 1918 (n = 77), and none of them appeared to have reached the 104 landmark. For those born prior to 1912 and for whom we did not find a death certificate, we assume that it is quite unlikely, albeit possible, that they are still alive today. Thus, even if not all the dates of death were found, a bias by exclusion from the registry of siblings who might have achieved age 104 is highly unlikely. Another potential bias is that we may not have found all births. However, because the age difference between two children of consecutive birth order is in general smaller than 3 (90% of cases) and the median is 1.7, we believe that the information we used to construct our birth order indicator is reasonably clean of measurement errors caused by missing children.

3.3 Covariates

3.3.1 Maternal age and birth order

The main independent variables are the age of the mother at childbirth and birth order. Maternal age at birth was divided into six age categories: less than 20 years, 20–24, 25–29, 30–34 (considered to be the reference category), 35–39 and 40+ years. As paternal age correlates with maternal age (r = 0.79, $p < 0.001$), we did not include both measures in the fixed-effects models. We focused on maternal age because in additional analyses we found that after adjustment for maternal age, paternal age was not associated with longevity (results not shown). Thus, longevity appears to be more strongly associated with maternal age than paternal age. The distribution of maternal age, birth order and other early-life variables is given in Table 1. Among the centenarians (cases), the mean maternal age is 29.9 years whereas it is 31.2 years for the siblings (controls) (p = 0.0041). The oldest recorded age at maternity is 53 whereas the youngest is 14. Only 2.6 per cent of children were born to mothers aged less than 20 years while about 12 per cent of the mothers were older than 40 years at the birth of their child. This sample satisfies the definition of a natural fertility population as the average number of children per women was 11.

Three different measures of birth order were used. We initially looked at birth order as a count variable or an absolute measure. We then used a relative measure of birth order, which is defined as the ratio $(r-1)/(n-1)$ where r is the absolute birth order and n refers to the number of children in the household, meaning that the first-born will always have the value zero and the last-born the value one. The relative birth order measure can be interpreted as the share of older siblings a child

Table 1:
Descriptive statistics, centenarians (cases) and siblings (controls).

Variables	Cases, no. (%)	Controls, no. (%)	Total, no. (%)
Maternal age			
<20	8 (2.9)	62 (2.5)	70 (2.6)
20–24	53 (19.4)	410 (16.6)	463 (16.8)
25–29	83 (30.4)	569 (23.0)	652 (23.7)
30–34	60 (22.0)	598 (24.1)	658 (23.9)
35–39	48 (17.6)	510 (20.6)	558 (20.3)
≥40	21 (7.7)	314 (12.7)	335 (12.2)
missing	0 (0)	14 (0.6)	14 (0.5)
Mean ± SD	29.9 (6.4)	31.2 (6.8)	31.1 (6.7)
Median	29.0	31.0	31.0
Range	17–53	14–52	14–53
Birth order			
1–2	63 (23.0)	480 (19,4)	543 (19.7)
3–4	83 (30.4)	448 (18.1)	531 (19.3)
5–7	62 (22.7)	658 (26.6)	720 (26.2)
≥8	65 (23.8)	891 (36.0)	956 (34.8)
Mean ± SD	5.1 (3.1)	6.6 (3.8)	6.2 (3.8)
Median	4.0	6.0	6.0
Range	1–14	1–19	1–19
Birth interval			
<1.3	49 (18.0)	559 (22.6)	608 (22.1)
1.3–2.3	138 (50.5)	1238 (50.0)	1376 (50.0)
2.3–3.5	40 (14.6)	321 (13.0)	361 (13.1)
≥3.5	26 (9.5)	107 (4.3)	133 (4.8)
Last Born	20 (7.3)	252 (10.2)	272 (9.9)
Season of birth			
Winter	75 (27.5)	586 (23.7)	661 (24.0)
Spring	72 (26.4)	637 (25.7)	709 (25.8)
Summer	58 (21.2)	655 (26.4)	713 (25.9)
Fall	68 (24.9)	587 (23.7)	655 (23.8)
Missing	0 (0)	12 (0.5)	12 (0.4)
Family social status			
Family head farmer	121 (44.3)	1036 (41.8)	1593 (57.9)
Family head not a farmer	152 (55.7)	1441 (58.2)	1157 (42.1)
Gender			
Men	44 (16.1)	1210 (48.8)	1254 (45.6)
Women	229 (83.9)	1243 (50.2)	1472 (53.5)
Unknown	0 (0)	24 (1.0)	24 (0.9)
N	273	2477	2750

Note: The category 'Unknown gender' includes infant deaths of unknown sex and the <1.3 birth spacing category includes twins.

has Tenikue and Verheyden 2010). Finally, because the effect of birth order is likely to be non-linear, we defined the birth order position using the following categories: (1) first and second-borns; (2) third and fourth-borns; (3) fifth, sixth and seventh-borns; and (4) eighth child and beyond. Twinning (n = 24) did not change anything in our results since no centenarians was a twin. In the final models, we utilised the categorical specification of birth order. Because maternal age and birth order were strongly correlated, we checked the models for collinearity using the variance inflation factor.[4]

3.3.2 Season of birth, birth spacing and socio-economic variables

Next to maternal age and birth order, we also included the following covariates; season of birth, birth spacing and socio-economic status of the family. Seasons were defined using the solstices and equinoxes. To investigate possible confounding between maternal age and season of birth, we fitted additional models that included an interaction between both variables. In these analyses, maternal age was categorised into two age groups: maternal age below 35 and maternal age 35 and over.

The biodemographic measure of birth spacing was introduced in the models to capture a number of biological and social effects originating in the perinatal and postnatal periods. Many studies have reported an association between a short preceding or following birth interval and a poor nutritional status, low birth weight and increased risk of mortality in the offspring.[5] A negative effect for closely spaced children may be due to sibling competition for parental resources such as nutrition. It has also been argued that birth spacing with the previous child might mediate the effect of birth order (Zajonc 1976). The variable was operationalised as the age difference between the main individual and his or her next-youngest sibling. The idea here is that if the next child is born in a very short interval, the mother will tend to give less attention to the elder sibling in order to provide care to the newborn, thus leading to greater competition for parental time and resources.

We also tested in the models the inclusion of a year of birth variable as one might suspect that what appears as a maternal age or a birth order effect could in fact be the result of a cohort effect. Because of improvements in life expectancy over time, later-born children may have a better chance of achieving exceptional old age than earlier-born children. Omitting such cohort effect could lead to an underestimation of the effects of maternal age within families. When testing this variable in a linear fashion, we found that the effect of year of birth was positive, suggesting a very small

[4] Pearson correlation indicated that maternal age at birth was correlated with birth order (r = 0.79, $p < 0.0001$), reflecting the fact that older born siblings are born to older parents. However, the correlation is not perfect because there is variation in the spacing of births between siblings within families as well as between families.

[5] See Dewey and Cohen (2007) for an extensive review addressing the effect of birth interval on child nutritional status.

improvement of survival over time (OR = 1.04, p = 0.32). However, the coefficients were not significant and their inclusion in the models had only minor impact on the estimates. Because maternal age, birth spacing and year of birth are highly correlated, we did not include the birth year variable in fixed-effects models where both maternal age and birth spacing were considered, resulting in estimates slightly smaller, but still significant.

All models include the sibling's gender as a control variable. Finally, to examine whether or not birth order effects were more or less pronounced in different socio-economic status levels, we conducted separate analyses for families with different social status. Social class during childhood was classified according to the occupation of the head of the household as recorded in the 1901 and 1911 Canadian censuses. The most informative socio-economic classification in terms of longevity for the cohorts under study resulted from the distinction between farmers and non-farmers (Gagnon et al. 2011).

3.4 Modelling strategies

In an attempt to answer our questions and to take full advantage of our data, it was convenient to use a methodology that considered the issue of unobserved heterogeneity. Therefore, we used logit fixed-effects models (also known as conditional logistic models) to compare siblings who were born at different ages of their parents (Rosenzweig 1986; Paulhus et al. 1999; Gavrilov and Gavrilova 2011). The advantage of a within-family design is that centenarians are compared with their own siblings rather than unrelated controls, thus neutralising the influence of measured and unmeasured factors that make siblings similar to one another. Accordingly, the effect of the shared environment, including urban/rural status, father's occupation and father's literacy, are not estimated. Furthermore, because all siblings come from the same mother, any confounding influences that are shared among them, like maternal health, family frailty or genetic heritage remain constant. Hence, fixed-effects regression modelling permits to isolate the effect of a number of characteristics on which siblings do not have common values. While shared family characteristics cannot be explicitly measured, we can be reasonably confident that their influence is accounted for.

The fixed-effects model used to estimate the relationship between child-specific characteristics and longevity outcome can be written as follows:

$$y_{ij} = X_{ij}\beta + \alpha_i + \mu_{ij} \tag{1}$$

where y_{ij} is our binary variable of interest for sibling j in family i which is equal to 1 if the individual has achieved age 104 and 0 otherwise, X_{ij} denotes a vector of within-family covariates that are different among siblings and that, we hypothesise, will affect longevity, namely maternal age at birth, birth order, season of birth and birth interval. The error term is broken into two components: α_i, a family fixed effect and μ_{ij}, an individual-specific error for sibling j in family i. The α residual is constant for siblings in a given family.

In the logistic framework, the probability can be expressed as follows:

$$Pr(y_{ij} = 1 \mid X_{ij}) = F(X_{ij}\beta + \alpha_i) \quad (2)$$

where F is the cumulative logistic function given by:

$$F(z) = \frac{\exp(z)}{1 + \exp(z)}. \quad (3)$$

Our family fixed-effects models are estimated with a conditional logit model, which is based on a conditional likelihood maximisation approach initiated by Chamberlain (1980).

To confirm that early-life variables are pervasive across the life course, all of the main analyses were performed on three data sets (Gavrilov and Gavrilova 2012): (1) The full sample which refers to all siblings in a family regardless of their age at death, (2) a selected subsample of siblings who survived past the age of 20 years and, (3) a selected subsample of siblings who were known to have reached at least 50 years of age. If our results are fully driven by infant and child mortality selection one would expect to find no influence of maternal age or birth order beyond age 20 or 50.

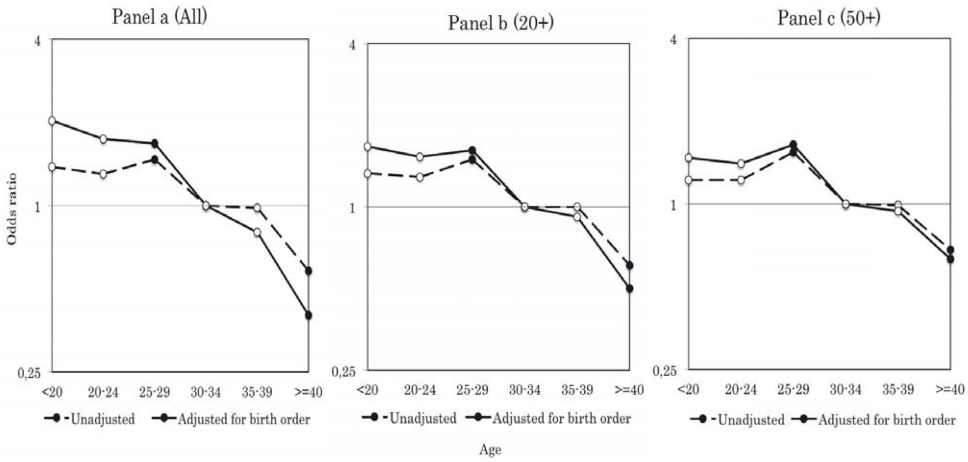
4 Results

4.1 Maternal age and longevity

The odds of living to age 104 given maternal age at birth from the conditional logistic regression model are shown in Figure 1. Odds ratios are reported separately for the full sample (Figure 1a) and for the restricted samples of individuals who survived to age 20 and 50 (respectively in Figure 1b and 1c). Looking at the unadjusted analyses (dotted line), it can be seen that children born to mothers aged between 25 and 29 were approximately 1.5 times more likely to survive to age 104 compared to their brothers and sisters born to mothers aged between 30 and 34, the reference group. The odds of reaching age 104 for children born to 40-year-old mothers were roughly twice as small as this reference group. Consistent with the existing literature on health and longevity, old maternal age at the time of birth seems to reduce the chance of living to an exceptional old age. The results are quite similar for those who survived to age 20 or 50. When including the birth order variable, the effect sizes are increased for all maternal age categories (solid-line), especially in the very young maternal age category in the full sample.[6] This suggests that the negative effect of an

[6] The use of the continuous measure when controlling for birth order did not substantially alter the findings.

Figure 1:
Fixed-effects logistic regression examining the effect of maternal age on the odds of reaching age 104



Notes: Significant estimations ($p < 0.05$) are shown with filled dots. Birth order was treated as a categorical variable.

early birth order may suppress the true positive effect of a very young maternal age (Kalmijn and Kraaykamp 2005).[7]

4.2 Birth order and longevity

A number of approaches were taken to model the effect of birth order. In the first regression analysis reported in Table 2, in which birth order was treated as a continuous variable and no covariates were included, we found a negative association: as the order of birth increases, the odds of achieving age 104 decrease (OR = 0.95, p = 0.013). When maternal age was adjusted for, the birth order variable lost its significance (OR = 0.96, p = 0.59). Treating birth order as a relative measure did not appreciably change the results: an increased relative birth order was associated with a decrease in the odds of achieving age 104. None of these measures of birth order yielded significant coefficients for the subsample of individuals who reached age 50.

7 However, I would like to address a warrant as this category may not have enough observations for a sound statistical analysis.

A better indication of the nature of the relationship between birth order and longevity, however, was achieved using the categorical measure. In Table 2, all birth order odds ratios are relative to the first-born and second-born children, the omitted category. In unadjusted analyses, we found that the odds to achieve exceptional longevity were approximately 1.5 times higher for the third and fourth-born children compared to first and second-borns, even for those who reached age 50, suggesting that birth order has a long-lasting effect on mortality (see Table 2, Model 1). When maternal age at childbirth is taken into account as a continuous variable, the estimates are further strengthened, as third and fourth-born children have roughly 1.75 times the odds to become centenarians than first and second-borns, this being true even when the analysis is performed on individuals who survived to age 20 or 50 (see Table 2, Model 2).[8] Here again, when examining the effect of birth order in combination with maternal age at childbirth, we find a stronger effect of birth order, suggesting that both variables tend to act as each other's suppressor.[9]

Does the birth order effect hold across all social classes? To address this question, we interacted birth order with the socio-economic status of the family. We contrasted two groups according to those owning a piece of land, i.e. farmers, versus those having no access to land at all. When the sample is split between farmers and non-farmers, the birth order effect is no longer significant in families where the father is not a farmer (see Table 3). Note that the mean family size is 11 in both family types, suggesting that the birth order penalty for the children brought up on the farm is not an artefact of a larger family size in agricultural areas. Note also that the estimates in the non-farmers' group, although not significant, yielded findings consistent with the direction of effect. Additional analyses should be done using a better indicator of socio-economic status. Perhaps the number of acres owned by the household head, as proxy for the socio-economic standing, presuming that a higher number of acres owned implied a higher socio-economic status, could be a more adequate measure (Gagnon and Bohnert 2012; Baskerville 2001). One would think that the birth order effect may vanish in families with more valuable landholdings.

4.3 Birth spacing, seasonality and longevity

To investigate whether these birth order and maternal-age effects were mediated by differences in birth spacing and season of birth, we included these variables in the

8 When maternal age was entered in the models as a control variable, the results were consistent whether the variable was treated as a categorical or continuous measure. The addition of a quadratic term for maternal age to test for possibility of a nonlinear relationship was not significant.

9 Many other specifications of birth order were tested but the results are not shown in this paper. For example, since many other studies have shown that the first-born children or last-borns often have an advantage compared to other siblings, we tried a dummy specification for first- and last-born children. Using this birth order measure, we were able to see that being first-born does not confer any advantage, nor does being the last-born.

Table 2:
Fixed-effects logistic regression examining the effect of birth order on the odds of reaching age 104

Measures of birth order (BO)	Full sample (from birth)		Restr. sample (50+)	
	Model 1	Model 2	Model 1	Model 2
Absolute BO	0.95**	0.96	0.95***	0.95
Relative BO	0.63**	0.97	0.59**	0.90
BO Categories				
1–2	1.00	1.00	1.00	1.00
3–4	1.48**	1.82***	1.52**	1.75***
5–7	0.96	1.29	0.98	1.23
≥8	0.91	1.45	0.94	1.41
Maternal age		0.78**		0.82*
Observations	2750	2736	1992	1978

[a]Model 1: adjusted for gender and year of birth.

[b]Model 2: adjusted for gender, year of birth and maternal age (with a linear effect).

***Estimate statistically significant at the 0.5% level.

**Estimate statistically significant at the 1% level.

*Estimate statistically significant at the 5% level.

Table 3:
Fixed-effects logistic regression examining the effect of birth order on the odds of reaching age 104, by family social status

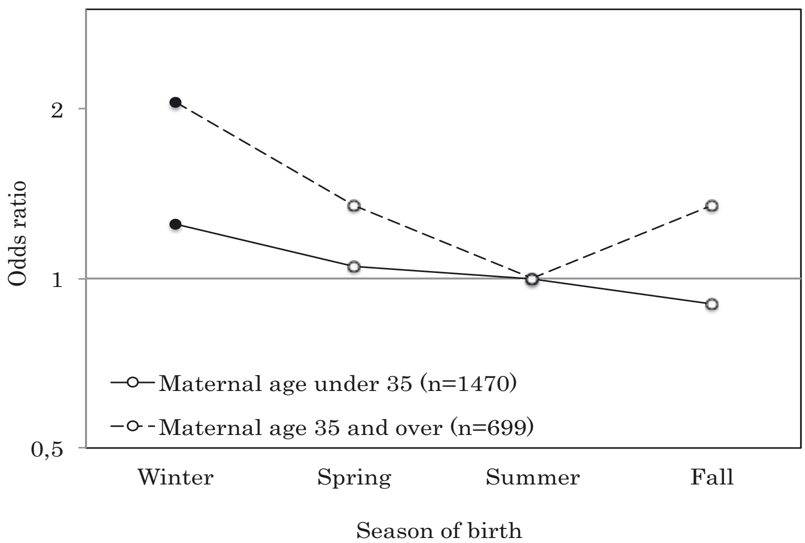
Variables	Full sample (from birth)			Restricted sample (50+)		
	Farmer	Non-farmer	Full sample	Farmer	Non-farmer	Full sample
Birth order						
1–2	1.00	1.00	1.00	1.00	1.00	1.00
3–4	2.06***	1.38	1.82***	1.83**	1.55	1.75***
5–7	1.55	1.08	1.29	1.33	1.04	1.23
≥8	2.40	1.10	1.45	1.90	1.06	1.41
Maternal age	0.70**	0.88	0.78**	0.73*	0.94	0.82*
Observations	1585	1151	2736	1156	822	1978

Note: All analyses adjusted for gender, year of birth and maternal age.
***Estimate statistically significant on a 0.5% level.
**Estimate statistically significant on a 1% level.
*Estimate statistically significant on a 5% level.

final model. Table 4 shows that birth order estimates are robust to the addition of these controls as neither the magnitude nor the statistical significance are altered (Model 2 and 3). The same is true when taking maternal age as the main focus variable (results not shown).

The estimates of the covariates are also worthy of mention. Our findings suggest that birth interval is not significantly associated with exceptional longevity in siblings aged 20 and over; however, when all siblings are included, a longer birth interval with the next child, of more than 3.5 years, is associated with higher odds of reaching age 104 compared to an interval of 1.3–2.3 year long (Table 4; full sample, Model 2) whereas a short birth interval, of less than 16 months, is associated with lower chances of living to an exceptional old age. This suggests that birth spacing is mainly an important predictor of infant and child mortality.[10]

Figure 2:
Interaction effect between maternal age and season of birth (restricted sample of individuals who reached age 20)



Notes: Significant estimations ($p < 0.05$) are shown with filled dots.

Focusing on Model 3 of Table 4 we see that children born in winter have almost 1.5 times the odds to reach age 104 compared to their siblings born in summer.[11]

[10] Additional analyses of the relationship between birth spacing and infant mortality are available upon request.

[11] Since marriage was a seasonal event, sensitivity analyses excluding first-borns were performed (results not shown). The estimates are very similar, albeit slightly higher.

Table 4:
Fixed-effects logistic regression examining the effect of birth order and other early-life variables on the odds of reaching age 104

	Full sample			Restricted sample (50+)		
	Model 1	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
Birth order						
1–2	1.00	1.00	1.00	1.00	1.00	1.00
3–4	1.82***	1.78***	1.75***	1.75***	1.70***	1.68***
5–7	1.29	1.21	1.18	1.23	1.13	1.08
≥8	1.45	1.43	1.41	1.41	1.35	1.27
Maternal age	0.78**	0.84*	0.85*	0.82*	0.88*	0.89*
Birth spacing (yrs)						
<1.3		0.72**	0.78*		0.80	0.88
1.3–2.3		1.00	1.00		1.00	1.00
2.3–3.5		1.11	1.09		1.03	1.03
≥3.5		1.47*	1.43*		1.33	1.25
Birth season						
Winter			1.47**			1.55**
Spring			1.29			1.25
Summer			1.00			1.00
Fall			1.30			1.23
Observations	2736	2736	2736	1978	1978	1978

Model 1: adjusted for gender and maternal age.

Model 2: adjusted for gender, maternal age and birth spacing.

Model 3: adjusted for gender, maternal age and birth spacing and season of birth.

***Estimate statistically significant on a 0.5% level.

**Estimate statistically significant on a 1% level.

*Estimate statistically significant on a 5% level.

The pattern of season-of-birth does not change appreciably when looking at the subsample of people living to age 50 and older, meaning that seasonality of birth has a long-lasting effect on old-age mortality. Additional analyses shown in the Appendix support theses observations as babies born in January, February and March are significantly more likely to achieve exceptional longevity than babies born in July (Table A.1). Furthermore, in order to determine whether there is an interaction between the season of birth and maternal age, analyses of seasonality were performed separately for different maternal-age groups. Being born in summer appears to have adverse effects on longevity for children regardless of the maternal age, but this effect is stronger for children born of older mothers. Among children born from mothers aged 35+, children born in winter have twice the odds of achieving age 104 compared to children born during the summer months (OR = 2.08, p = 0.013). These results suggest that children born of older mothers may be more vulnerable to environmental injury experienced during foetal or early-life developments, which are partly proxied in this study by the season of birth.

5 Discussion

The aim of this study was to build upon and extend existing research on longevity by investigating how early-life characteristics that vary within families can influence the proclivity to achieve exceptional old age. For long-lived families that settled their household in Quebec in the late 19th and early 20th century, achieving exceptional longevity was associated with both maternal age at childbirth and birth order. Children born to mothers aged 40+ were less likely to live to age 104 while maternal ages 25–29 were associated with an increased chance for survival to that exceptional old age. Adjusted for birth order, maternal age estimates were strengthened (with the parameters referring to very young maternal age even closer to significance), indicating that the effect of this variable was suppressed in models that did not include the other.

It appears from abundant biological and medical literature (see introduction) that, on balance, being born from young parents improves health and thus should increase the chance of reaching an old age. However, besides maternal age, which is an important determinant of longevity within families, the birth order effect is genuine and some underlying social and cultural causes may account for it. Based on research from the social sciences and economic fields, the intuition behind our findings is that being born early in the sibling row may provide a biological advantage, but being too soon may also bring along detrimental socio-economic disadvantages, thereby cancelling out the beneficial influence of the mother's young age.[12] While the demographic, economic and medical literature has usually highlighted the positive advantage of being first-born in a range of outcomes, including old-age survival, we instead found larger survival benefits for the third or fourth-born.

Position in the sibling row may engender various forms of inequalities in access to resources, which translates into differential mortality risks later in life. One possible explanation for the above result lies in the rules of heritage and transmission of property among French Canadian farmers. The cultural norm embodied in these intergenerational transfers was to establish as many sons as possible on a piece of land Bouchard 1996; Gagnon et al. 2006). However, because of increasing population size and density, this was not always possible. The decision on the succession was not imposed from above, but rather resulted from a bilateral negotiation between two parties with conflicting interests: the children who wished access to property of

[12] This suppression effect was also found in other studies analysing jointly the effect of parental age and birth order, namely in Kalmijn and Kraaykamp (2005), where mother's age had a positive effect on educational attainment, whereas birth order position had a negative one.

the familial holding as early as possible and the parents who did not want to give it away too quickly (Gervais 1996). Primogeniture was not the decisive factor and the choice of successor was determined by the age of the father (Bouchard 1994). At the father's retirement, older children were more likely to have already left home and settled elsewhere, perhaps in the city, where they would have lost the protective effect of living on a farm (Gagnon et al. 2011). Supporting this hypothesis is the variation in birth order effects depending on the land status of the family: in families living on a farm, the oldest children exhibited lower chances of achieving exceptional old age compared to siblings from third and fourth ranks, whereas in households with no access to land, there were less mortality differences by birth order, and these differences were not significant.

The above explanation may hold for male centenarians, but is less plausible for females, who represent the vast majority of cases in this study. An alternative argument is that children born early in the sibling row were comparatively more likely to grow up in a resource-poor environment during their early and critical stages of development. According to the foetal-origins hypothesis, environmental conditions occurring in the pre- or perinatal periods can profoundly influence human biology, long-term health and longevity (Barker 1998). Early-life nutrition is among the best-documented examples of such conditions. One important element of this hypothesis is the concept of a critical window during which a deficiency of nutrients can produce a latent immune vulnerability that persists well beyond childhood. First born children came to life on a familial estate that was often not completely cleared. These children may have suffered from a poor nutritional intake during critical or sensitive periods of development, with implications for chronic disease and mortality in later life. Intense workload on the farm during the first years of settlement could also have diverted maternal energy away from the growing foetus (Gagnon 2012).

The foetal-origin hypothesis is also relevant for our findings regarding the season of birth, which indicate that winter babies are more likely to reach age 104 than summer babies, especially when comparing those who lived to the age of 50 and those who were born from older mothers. In late 19th and early 20th-century Quebec, the seasons dictated the availability of food and thus the intake of specific nutrients from pregnant mothers and their growing foetus (Gagnon 2012). Women who gave birth after the harvest season had access to a greater variety of food and a more nutritious diet during the last trimester of their pregnancy, i.e. precisely at a time when the foetus underwent rapid growth (Vaiserman and Voitenko 2003; Doblhammer 2004). In addition, food shortages that sometimes came at the end of a long winter could have affected the development of foetuses that were to be born during the spring or the summer. The seasonal pattern of mortality was also shaped by exposure to infectious diseases. The disease load was higher during summer, corresponding to the period of warmer temperatures and to the peak incidence of waterborne diseases. Maternal infections occurring during that period could impair foetal growth and engender permanent increase in inflammation levels, thereby entailing a higher risk of mortality at older ages (Crimmins and Finch 2006).

Closely spaced children could also have been exposed to the risk of poor nutrition or infectious diseases. Mothers who had their next child too early were less likely to meet the needs of their young children close in age. Likewise, the older child of a closely spaced pair could compete with the next foetus/child for nutrients. Consequently, an early weaning of the oldest child could affect health through a greater risk of postpartum nutritional deficiency and infectious diseases (Haaga 1989). However, while birth spacing is often found to have an effect on child mortality, it does not seem to be associated with exceptional survival when we exclude from the sample siblings who did not reach age 50 and compare the survival of those who did. In this paper, we presented results based on the length of the following birth interval as a measure of interbirth spacing, but we did conduct additional analyses using the length of the preceding birth interval, which stands out in the literature as one of the most important factors affecting infant mortality (results not shown) (Preston 1985). No evidence of a relationship between a short preceding birth interval and lower odds of achieving age 104 was found either.

There are limitations in the present study that should be acknowledged. First, we were not able to adequately assess the interaction between maternal age and birth order; this task would have required a much larger dataset. Another potential limit is that despite the efforts to achieve full coverage of ages at death for siblings, we may have missed some cases in the control group that went on to live to age 104 in the last few years. Moreover, since the birth order effect could rest on the differential allocation of parental resources between siblings, our measure of birth spacing may not be the most appropriate one. The relation between birth order and survival may be affected by various factors related to the sibship constellation and the sibling rivalry that cannot be captured by our measures. Further research in this area should focus on investigating interactions since the effect of birth order may well be mediated or moderated by the number of older/younger siblings in the household and by the gender composition of the sibship. Finally, because the sample was highly selected based on the age of the centenarians, the year of birth and the region of birth, our study may not yield findings that are applicable to other populations of oldest-old. One should bear in mind that this research focuses on the determinants of surviving to age 104 within families, not on overall longevity.

Nonetheless, our findings point to life-prolonging effects of early-life conditions and child-specific characteristics. The patterns of interactions between all those previous variables could be key to understanding the link between early-life exposure and old-age mortality. Perhaps there are subtle interactions between the timing of birth within the family and the moment of birth during the year. For instance, both a summer birth and a birth early in the sibling row may have independent and negative effects on longevity through at least one common pattern: nutritional deprivation in utero and during the first months of life. One may think that the risk of mortality is aggravated for children born in summer to a young mother (among the first birth orders), as both of these circumstances may signal nutritional deprivations acting multiplicatively. However, we did not find the summer birth effect to be amplified by first-born status. Quite intriguingly, we found instead a stronger birth season effect for babies born to older mothers. Perhaps older women had more young children in the house which could have lead to higher rates of infection early in life for the higher-order birth ranks. Studying the 1714 measles epidemic in Quebec, Mazan (2011) showed that older siblings increased the risk of measles death among younger siblings as secondary cases, presumably through the introduction of the virus into the household from multiple contacts with the outside. Susceptibility to infectious diseases among more contemporary Quebec dwellers could have been increased if, due to birth season, infants were more likely to suffer from low nutritional intake in the pre- and postnatal periods. The season may in that case trigger disease in the already vulnerable children. Alternatively, as stated in the introduction, maternal depletion was more frequent in older mothers which, combined with a summer birth, could have compromised further the intrauterine development, with heightened later-life consequences.

In sum, both biology and the social and cultural context of early life could explain why siblings, who tend to have a similar lifespan, do not quite have the same chances of achieving exceptional old age. The challenge remains to disentangle those different pathways connecting maternal age, birth order and season of birth, among other early-life variables, to longevity.

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Appendix

Table A.1:
Fixed-effects logistic regression examining the effect of season and month of birth on the odds of reaching age 104

	Full sample No. (%)	Restricted sample (50+) No. (%)	Full sample	Restricted sample
Season of birth				
Winter	661 (2.9)	477 (24.0)	1.46**	1.53**
Spring	709 (19.4)	525 (26.3)	1.28	1.22
Summer	713 (30.4)	513 (25.7)	**1.00**	**1.00**
Fall	655 (22.0)	467 (23.4)	1.27	1.22
Missing	12 (0.4)	12 (0.6)		
Month of birth				
January	202 (7.4)	133 (6.7)	1.43	1.70*
February	188 (6.8)	143 (7.2)	2.30***	2.15**
March	271 (9.8)	201 (10.1)	1.82**	1.71*
April	236 (8.6)	174 (8.7)	1.68	1.60
May	226 (8.2)	169 (8.5)	1.32	1.22
June	247 (9.0)	182 (9.1)	1.61	1.54
July	257 (9.3)	170 (8.5)	**1.00**	**1.00**
August	228 (8.3)	172 (8.6)	1.58	1.47
September	228 (8.3)	171 (8.6)	1.33	1.11
October	223 (8.1)	160 (8.0)	1.62	1.43
November	218 (7.9)	169 (8.5)	1.73*	1.54
December	214 (7.8)	138 (6.9)	1.35	1.32
Missing	12 (0.4)	12 (0.6)		
Observations	2750	1994	2738	1982

[1] Analyses are adjusted for gender.

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