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Cognitive consequences of iodine deficiency in adolescence: evidence from salt iodization in Denmark*

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Abstract

Over the past three decades, many countries have introduced iodized salt policies to eradicate iodine deficiency. Iodine deficiency *in utero* is detrimental to cognitive ability, but little is known about the consequences of iodine deficiencies after birth. This paper examines the impact of iodine deficiency in adolescence on school performance. I exploit the introduction of iodized salt in Denmark during 1998–2001 as a natural experiment. Combining administrative records on high school grades over a 30-year period with geographic variation in initial iodine deficiency, I find that salt iodization increases the grade point average of students by 6–9 percent of a standard deviation.

Keywords: Health; human capital; iodine deficiency; iodized salt; nutrition

JEL classification: *I*15; *I*18; *J*24

1. Introduction

More than two billion individuals lack essential vitamins and minerals (WHO et al., 2007), and these micronutrient deficiencies are major causes of disease globally. Over the past three decades, the World Health Organization (WHO) has initiated global efforts to increase food fortification, which has reduced the incidence of micronutrient deficiencies (Allen et al., 2006). The adoption of iodized salt to eradicate iodine deficiency is a leading example of such food fortification. Iodine is a crucial mineral for metabolic functioning and brain development. While iodized salt has been used since the 1920s in the United States and Switzerland to prevent goiter, it became a global health policy after the 1980s, as researchers established that iodine

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deficiency during pregnancy is detrimental to brain development in children. In 1993, the WHO recommended worldwide adoption of iodized salt, and from 1990 to 2007 a large number of countries introduced salt iodization policies, thereby increasing worldwide access to iodized salt from 20 to 70 percent (WHO et al., 2007).

Today, iodine deficiency is recognized as the leading cause of preventable mental retardation (WHO et al., 2007) and recent studies in economics have shown that the introduction of iodized salt in the US and Switzerland increased the average IQ, educational attainment, and adult earnings of individuals exposed while *in utero* (Politi, 2010, 2015; Feyrer et al., 2017; Adhvaryu et al., 2020).

However, while salt iodization affects the entire population, little is known about the cognitive effects on individuals exposed after birth. A small experimental literature finds that iodine supplementation improves cognitive performance among school-age children (Zimmermann et al., 2006; Gordon et al., 2009), but it is unknown whether the benefits found in these small-scale controlled experiments also apply to real-world food fortification, and, in particular, to the recent wave of salt iodization policies implemented around the world.

In this paper, I study the contemporaneous effects of salt iodization on school performance. Specifically, I estimate the effect of the introduction of iodized salt in Denmark during the period 1998–2001 on the grade point average (GPA) of high school students.

The Danish fortification policy provides unique conditions to study the effect of the recent wave of salt iodization policies. First, the policy was implemented within a few years and legislation changed from an implicit ban on iodized salt to mandated iodization of salt. Because of a conservative view on food fortification and a belief that iodine deficiency was not a concern in Denmark, the Danish National Food Agency did not allow the sale of iodized salt until 1998. After several studies confirmed that iodine deficiency was a concern in Denmark, legislation changed to voluntary iodization of salt in 1998 and mandated iodization of salt after 2001. This sharp policy change resulted in a large and immediate improvement in the iodine status of the population, providing an ideal experiment to study the effect of salt iodization.

Secondly, before the introduction of iodized salt, the degree of iodine deficiency in Denmark varied substantially across areas due to differences in the concentration of iodine in drinking water. Drinking water accounted for 25 percent of the iodine intake in Denmark and the concentration of iodine in water varies more than 100-fold across areas (Pedersen et al., 1999). As salt iodization should only matter in deficient populations, I use this natural source of variation in pre-existing iodine deficiency as a measure of treatment intensity in a difference-in-differences design. Hence, I compare the impact of the introduction of iodized salt across individuals living in areas with high and low concentrations of iodine in drinking water.

Lastly, the availability of high-quality administrative data over three decades makes it possible to credibly estimate treatment effects. I measure school performance in adolescence using the final GPA of high school students. The data cover all students graduating from 1980 to 2011, providing 19 pre-reform years to verify the common trend assumption of the difference-in-differences method and 10 post-reform years to study the benefits of salt iodization. I combine the administrative records with information on the iodine concentration in local drinking water, based on data from groundwater samples collected by the Geological Survey of Denmark and Greenland (GEUS).[1,2]

My main finding is that salt iodization increases the final GPA of high school students by 0.06–0.09 standard deviations. The effect is immediate, with grades increasing from the first year of implementation, suggesting that salt iodization produces a contemporaneous improvement in cognitive performance among adolescents. To my knowledge, this is the first evidence that the benefits of salt iodization are not limited to the *in utero* period.

The estimated benefits of salt iodization are of the same order of magnitude as recent estimates of the effect of improved quality of school lunches on students' test scores in US public schools (Anderson et al., 2018). Compared with more standard school achievement policies, the effect of salt iodization amounts to one-half to one-fourth of the benefit of reducing class sizes (Krueger, 2003). However, because salt iodization is very cheap, it is 20,000 times more cost-effective than reducing class sizes.[3]

The results relate to a body of literature on the technology of skill formation (Cunha and Heckman, 2007). While the return to salt iodization in the pre-natal period is, on average, larger, my results show that the return to investments in adolescence are non-negligible (Heller et al., 2017). I show that the benefits of salt iodization accrue to the lower end of the skill

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[1] The GEUS is a research and advisory institution in the Danish Ministry of Energy, Utilities and Climate. Among other things, it collects and makes publicly available all water sample analyses used in the monitoring of drinking water quality. Additional information can be found at https://eng.geus.dk/about/.

[2] All drinking water in Denmark is derived from groundwater.

[3] According to estimates by the 2008 Copenhagen Consensus (Horton et al., 2008), the cost of salt iodization is US$0.05 per person per year. Estimates of the costs and benefits of reducing class sizes comes from Krueger (2003). He estimates the cost of reducing class sizes from 22 to 15 students to be US$3,385 per student per year (1998 US dollars; see table 5, row 1 in Krueger, 2003). The benefit from reducing class size is an increase in test scores of 0.2 standard deviations (Krueger, 2003).

distribution with twice the increase in the bottom quartile of grades as in the top quartile of grades. This contrasts with the predictions of dynamic complementarities (Cunha and Heckman, 2007), in which returns increase with initial skills, and suggests that policies designed to correct nutritional deficiencies can reduce inequality in school performance (Deaton, 2003).

Most studies of the benefits of salt iodization consider recent policies in poor countries (Field et al., 2009; Huang et al., 2020; Bengtsson et al., 2020) or historical policies in rich countries (Politi, 2010, 2015; Feyrer et al., 2017; Adhvaryu et al., 2020). I study a recent salt iodization policy in a wealthy country in Europe. Although iodine deficiency is not considered to be a public health concern in many European countries, Europe has the lowest rate of salt iodization of any WHO region (WHO, 2007), and 44 percent of school-age children in Europe do not consume adequate amounts of iodine (Andersson et al., 2012). Hence, my results suggest that even though severe iodine deficiency is rare in Europe, there are clear benefits to increasing access to iodized salt. To assess the post-natal benefits of salt iodization in more deficient countries, I estimate the relationship between initial iodine deficiency and the benefits of iodized salt and I use this to extrapolate beyond the range of deficiency observed in Denmark. I predict an average treatment effect of 0.1 standard deviations for students with a moderate deficiency and 0.6 standard deviations for students with a severe deficiency. Globally, 8.1 percent of school-age children are moderately iodine-deficient, while 5.2 percent are severely iodine-deficient (Andersson et al., 2012). Hence, the benefits of salt iodization are potentially much larger in other countries.

My results confirm that the benefits of iodine supplementation to children found in experimental studies also apply to real-world fortification policies (Zimmermann et al., 2006; Gordon et al., 2009). However, the biological mechanism behind this result is unclear. Iodine deficiency might affect school performance in adolescence in two ways: (i) by impairing normal metabolic functioning, causing fatigue and reduced brain activity; and (ii) by disturbing normal brain development during childhood and adolescence, causing permanent brain damage (Gordon et al., 2009). If salt iodization affects grades by preventing brain damage, the benefits should accumulate over time, resulting in larger treatment effects for students first exposed to iodized salt in early childhood versus late childhood. If salt iodization affects grades through the metabolism, only current iodine intake should matter and treatment effects should be identical for students first exposed to iodized salt in early or late childhood. Empirically, I find similar treatment effects for students first exposed to salt iodization at ages 6–18 (i.e., between 13 years and one year before finishing high school). This suggests that, in adolescence, iodine deficiency most likely affects school performance through its effect on the metabolism and not through brain damage. Because iodine deficiency affects the metabolism at all ages, this suggests that similar benefits might be found for adults. Considering that 29 percent of the world population and 30 percent of all school-age children remain mild to severely iodine-deficient (Andersson et al., 2012), my results suggest that there is still a large untapped economic potential in scaling-up salt iodization.

The rest of the paper is structured as follows. In Section 2, I provide more background on the biology of iodine deficiency and outline the Danish salt iodization policies. In Section 3, I describe the data. In Section 4, I explain the empirical method. In Section 5, I present the main results. In Section 6, I evaluate the robustness and external validity of the estimates. I conclude in Section 7.

2. Iodine deficiency and iodized salt in Denmark

The adverse effects of iodine deficiency originate from disturbances to the production of thyroid hormones in the thyroid gland. Thyroid hormones regulate the metabolism of most cells of the body and a lack or excess of these is associated with a wide range of physical and psychological illnesses. When iodine intake is low, the body initiates a number of compensatory biological processes. The most important is thyroid enlargement, also known as goiter, which enables the thyroid gland to produce more thyroid hormones from a given input of iodine. While this compensation is effective when individuals are mildly iodine-deficient, more severe cases result in insufficient thyroid hormone levels and a condition called hypothyroidism, which can affect cognitive performance through two separate mechanisms.

The first mechanism pertains to the effects of hypothyroidism on the metabolism. If thyroid hormone levels are too low, the metabolism slows down. The symptoms include lethargy, weight gain, and impaired brain activity (Samuels, 2014). This condition might cause impaired cognitive performance in the short run, but is reversible through increased iodine intake.

The second mechanism pertains to the effects of hypothyroidism on brain development. Thyroid hormones control a wide range of processes responsible for the development of the brain and organs. During the pre-natal period, when brain development is most rapid (Gilmore et al., 2018), maternal hypothyroidism can cause irreversible brain damage and long-term consequences for the cognitive ability of the child (Delange, 2001; Delange and Hetzel, 2004). While this second mechanism is especially important during the pre-natal period, brain development continues throughout childhood and adolescence. Therefore, iodine deficiency in adolescence might cause irreversible brain damage and long-run consequences for cognitive ability.

While these two mechanisms hold different predictions, they could both be at play when considering the effects of salt iodization on adolescents. In Section 5, I test and argue that the observed improvements in cognitive performance are consistent with the first mechanism going through the metabolism.

Excessive iodine consumption of up to 10 times the recommended intake is considered safe (Rasmussen et al., 1996). However, after long periods of iodine deficiency with overactivity and enlargement of the thyroid gland, the thyroid gland might be unable to return to normal activity (Laurberg et al., 2009). A subsequent increase in iodine intake, as with salt iodization, can lead to an excess production of thyroid hormones and a condition called hyperthyroidism, which is a known side effect of salt iodization. In contrast to hypothyroidism, hyperthyroidism is a state of overactive metabolism, causing nervousness, weight loss, and sweating. Together with goiter, hypothyroidism and hyperthyroidism are the most common of iodine-deficiency disorders.

2.1. Danish salt fortification

Salt iodization has been used to prevent high rates of goiter in the US and Switzerland since the 1920s. In Denmark, iodine deficiency was not considered a problem during most of the 20th century (Laurberg et al., 2009).[4] Several large studies of thousands of school-age children in Denmark found up to 15 percent goiter rates in some groups of the population, but no indication of clinically relevant goiter on a national level. Therefore, the Danish National Food Agency declined applications from salt producers to add iodine to salt.[5] In the 1980s and 1990s, evidence of iodine deficiency among older individuals and pregnant women started to accumulate, and in 1994 the Danish National Food Agency created a working group to determine whether an iodization program was needed. In 1996, the working group concluded that the population was mildly to moderately iodine-deficient and that an iodized salt program should be implemented. In June 1998, the National Food Agency introduced a voluntary salt iodization program in collaboration with salt producers. The program was expected to increase the average daily iodine intake by 50 μg,

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[4] This section is, to a large extent, based on a review article by Laurberg et al. (2009), which describes the historical context of the Danish fortification policy and the research of the DanThyr project – a research group set up to monitor the health effects of salt fortification in Denmark.

[5] Food producers have to apply for permission to sell fortified products.

from 50–100 μg per day (Rasmussen et al., 2002) to somewhere within the recommended range of 100–150 μg per day.

The voluntary program proved unsuccessful, with an average increase in iodine intake below 10 μg per day (Laurberg et al., 2009). Two years after implementation, only 50 percent of household salt and close to no salt in the food industry was iodized.[6] As a response, the National Food Agency decided to make the policy mandatory. This second reform was gradually implemented between July 2000 and April 2001, during which the remaining stocks of non-iodized salt could still be sold. According to estimates by Rasmussen et al. (2007), the two reforms combined met the goal of a 50 μg per day increase in average iodine intake. Both reforms were announced to the public and the issue received considerable media coverage in regional and national newspapers.

Even though the first and voluntary reform did not meet the target of a 50 μg per day increase in iodine intake, it might have caused a non-trivial reduction in thyroid hormone deficiency. Because the thyroid gland is partially able to compensate for iodine deficiency, the relationship between iodine intake and thyroid hormones is concave (Laurberg et al., 2010). Therefore, the small increase in iodine intake from the first reform might have been effective at alleviating the worst consequences of iodine deficiency, even though it did not eliminate iodine deficiency in Denmark.

The health effects of the Danish salt fortification policy have been studied extensively (for a review, see Laurberg et al., 2009). Using identification strategies similar to the one applied in this paper, medical researchers have confirmed that the increase in iodine intake following salt fortification led to a significant improvement in health, with a decrease in the incidence of thyroid enlargement from 17 percent before the reforms to 10 percent after (Vejbjerg et al., 2007). Medical researchers have also documented a temporary increase in the incidence of hyperthyroidism (Laurberg et al., 2009), consistent with a sudden increase in iodine intake after prolonged exposure to iodine deficiency. This suggests that the population was in fact iodine-deficient prior to the reforms, and that

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[6] The voluntary policy failed in part because food producers were legally required to report that their products contained iodized salt, but were not allowed to explain why, to mention that it was recommended by the National Food Agency or to use it in advertisements. In contrast, salt producers were allowed to state that iodine was added upon the recommendation of the National Food Agency, which might explain why they complied with the voluntary policy. At the time of the reforms, the vast majority of household salt in Denmark came from Dansk Salt A/S, which introduced iodized salt, but did not discontinue selling non-iodized salt. Therefore, access to iodized salt was most likely equally distributed throughout Denmark, while demand might have varied. While the voluntary policy in Denmark was not successful, voluntary salt iodization has been effective in many other countries, including in the US where salt producers were allowed to advertise their fortified products.

the salt iodization policies were effective at increasing iodine intake. In Section A.1 in the Online Appendix, I replicate these results using hyperthyroidism diagnoses at Danish hospitals. While hyperthyroidism is a temporary negative side effect of salt iodization, it is rare among the young and the observed increase in diagnoses is driven by the elderly.

3. Data

The empirical analysis is based on high-quality Danish administrative data on school achievement. High school grades have been recorded since 1977, while the records for lower/middle secondary school grades only go back to 2002.[7] For this reason, I focus on high school students and their individual GPAs as the main outcome of interest.

High school is voluntary in Denmark and students interested in upper secondary education can choose between four different programs that lead to the following final exams: (i) a standard Academic High School Examination (STX); (ii) a Higher Technical Examination (HTX) focusing on science and technology; (iii) a business-oriented Higher Commercial Examination (HHX); and (iv) a Higher Preparatory Examination Course (HF) meant for adults interested in further education. STX, HTX, and HHX are all three-year programs while HF is a two-year program.

Grades of HHX and HTX students are recorded from 1999 and are therefore not included in the analysis. As I consider the effect of iodine deficiency in adolescence and the HF program is intended for adults, HF students are also excluded. Hence, in the main analyses, I focus exclusively on STX students.

The STX program most closely resembles high school education in other countries and, over the data period, 60–70 percent of all high school students in Denmark were enrolled in the STX program. However, the main difference between the programs is the elective course catalog, and students can apply to all tertiary institutions, regardless of which high school program they graduate from. In the Online Appendix, I show that the main results are not sensitive to including HF students in the analysis.

Courses are categorized by A, B, and C levels according to difficulty and duration. A-level courses are the most comprehensive, and classes last from the first year of high school to graduation. C-level and B-level courses are predominantly one- and two-year courses, respectively. Grades take two forms: class participation grades and exam grades. Class participation

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[7] In Denmark, school attendance is compulsory until the end of year 9. Children attend primary school (*Folkeskole*) from kindergarten to year 9, which encompasses primary and lower/middle secondary education. High school refers to years 10–12.

grades are assigned by the teacher while exam grades are determined in agreement between the teacher and an external examiner. Teachers and examiners are instructed to give grades based on an absolute scale rather than grading on a curve.[8] Grades are based on the following scale: 0, 3, 5, 6, 7, 8, 9, 10, 11, and 13, where 0 is the lowest possible grade and 13 is the highest. Students need a GPA of 6 or more to graduate and the recorded GPAs of high school graduates therefore range from 6 to 13. The majority of exams take place just before graduation, and 60 percent of grades are determined during the last year of school. After graduation, the GPA determines which universities and tertiary courses students are eligible for acceptance into, and there is considerable incentive to perform well.[9]

Beyond educational outcomes, the data set includes a wide range of socio-economic characteristics of the students and their parents. The administrative data cover the universe of Danish citizens dating back to 1980. Parental characteristics include income, education, age, labor market participation, and marital status. To avoid using bad controls – controls that might be influenced by the reforms – I measure parental control variables eight years prior to graduation. Student characteristics include age, number of siblings, gender, school institution, and municipality of residence. I also use data from health registers, which contain information on the birth weight and birth length of all children born after 1973.

Because of a high school reform in 2008 and a large-scale municipality reform in 2007, the main analysis focuses on years prior to 2007.[10] Furthermore, because I measure parental controls eight years before graduation and parental controls are available from 1980, the main analysis period is 1988–2006.

The full sample consists of 544,023 STX students graduating during the years 1980–2011, while the main analysis sample consists of 308,718 STX students graduating during 1988–2006.

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[8] Grading on a curve would bias the observed treatment effects downward because school-wide increases in cognitive performance would not affect grades. Full relative grading would also imply that there are no year-to-year changes in average grades within schools. However, the standard deviation of average grades across years within the same school is 0.55. The overall standard deviation of grades is 1. Hence, relative grading is unlikely to bias the results.

[9] Grades in individual courses are only recorded from 1997. It is not possible to assess the importance of individual grades on the GPA because grades are given different weights in the calculation of the GPA and these weights are not recorded in the data. Nor is it possible to study grades by year of school as information on the timing of grades is only available from 2005.

[10] The high school reform introduced a new grading scale, different course structures, and additional requirements for cross-disciplinary activities. The municipality reform reduced the number of municipalities from 271 to 98.

4. Empirical method

I use an intensity-of-treatment difference-in-differences strategy to identify the causal effect of salt iodization on school performance in adolescence. This approach requires time-series variation in iodine intake and cross-sectional variation in treatment intensity. The time-series variation comes from the introduction of iodized salt in Denmark between 1998 and 2001. As a source of variation in treatment intensity, I exploit pre-existing differences in iodine deficiency. The assumption is that the benefits of salt iodization are larger for students who are more iodine-deficient.

I use the concentration of iodine in local drinking water as a measure of pre-existing iodine deficiency. All tap water in Denmark is derived from groundwater reserves, and the amount of iodine in groundwater is determined by time-invariant geological conditions (Voutchkova et al., 2015). Before the introduction of iodized salt, tap water accounted for 25 percent of the total iodine intake in Denmark (Rasmussen et al., 2000) and drinking water was one of the main drivers of regional differences in iodine deficiency (Rasmussen et al., 1996).[11] Geological conditions also affect the iodine concentration in milk, which accounts for another 25 percent of the total iodine intake (Rasmussen et al., 1996). In combination, these correlations produce a clear positive relationship between iodine in drinking water and iodine in urine – the most common measure of iodine intake (Pedersen et al., 1999).[12]

I measure the iodine concentration in drinking water using data from the GEUS on water works and groundwater analyses, which features 2,800 unique iodine samples from all parts of Denmark. The quality of groundwater in Denmark is generally high, and drinking water is only treated using simple aeration and sand filtration, which preserves most of the natural level of iodine (Voutchkova et al., 2015).[13] To relate these

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[11] Bottled water consumption is very low in Denmark (Voutchkova et al., 2015).

[12] Other studies have used geographical variation in goiter incidence rather than iodine in drinking water as a measure of iodine deficiency (see Politi, 2010, 2015; Feyrer et al., 2017). While goiter is a more direct measure of thyroid hormone deficiency, it is arguably a less exogenous one. Goiter is caused by low intake of milk and fish, and the use of goitrogens (goiter-inducers), such as alcohol and cigarettes. The consumption of each of these is correlated with socio-economic status. In contrast, the iodine concentration in drinking water is solely determined by geological conditions. Therefore, using iodine concentrations in drinking water rather than goiter rates provides a more exogenous source of variation in iodine deficiency. Nonetheless, because drinking water is an important determinant of iodine intake, the two measures are highly correlated (see Feyrer et al., 2017). Because iodine deficiency was not considered a problem in Denmark throughout most of the 20th century, iodine deficiency disorders, including goiter, are not well recorded during the pre-reform period. Therefore, it is not possible to provide robustness checks using goiter rates as an alternative to iodine concentrations in drinking water.

[13] There are no restrictions on iodine concentrations in drinking water in Denmark (Voutchkova et al., 2015).

measurements to the iodine intake of high school students, I match water works to the five nearest iodine samples and then collapse the data at the municipality level.[14,15] See Online Appendix A.2 for a description of the approach. Municipalities are responsible for water supply and represent the smallest geographical unit available in the data. Furthermore, as shown in Figure A.3 in the Online Appendix, the within-municipality variation in iodine concentrations in groundwater is limited.[16]

Figure 1 displays the derived iodine concentrations in drinking water across municipalities in Denmark. The geographical pattern closely resembles previous studies using direct drinking water samples.[17] The iodine concentration ranges from 1 to 67 μg per liter. Hence, with an average tap water consumption of 1.7 liter per day, drinking water accounts for 1–76 percent of the recommended iodine intake of 150 μg per day.[18] The lowest concentrations are found in Mid-West Denmark and the highest concentrations are found in North-West Denmark and East Denmark. Hence, while inhabitants in Mid-West Denmark get almost no iodine from drinking water, inhabitants in North-West Denmark and parts of East Denmark get up to 76 percent of the recommended iodine intake from drinking water.

I define two treatment intensity variables based on the drinking water data: (i) a discrete treatment variable equal to one for students living in municipalities with below median iodine concentrations in drinking water; (ii) a continuous treatment variable specified as: $Treat = -log(IodineConcentration)$, following previous studies (Feyrer et al., 2017). The continuous specification captures the likely concave relationship

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[14] I match iodine samples to water works to account for the location of water works within municipalities.

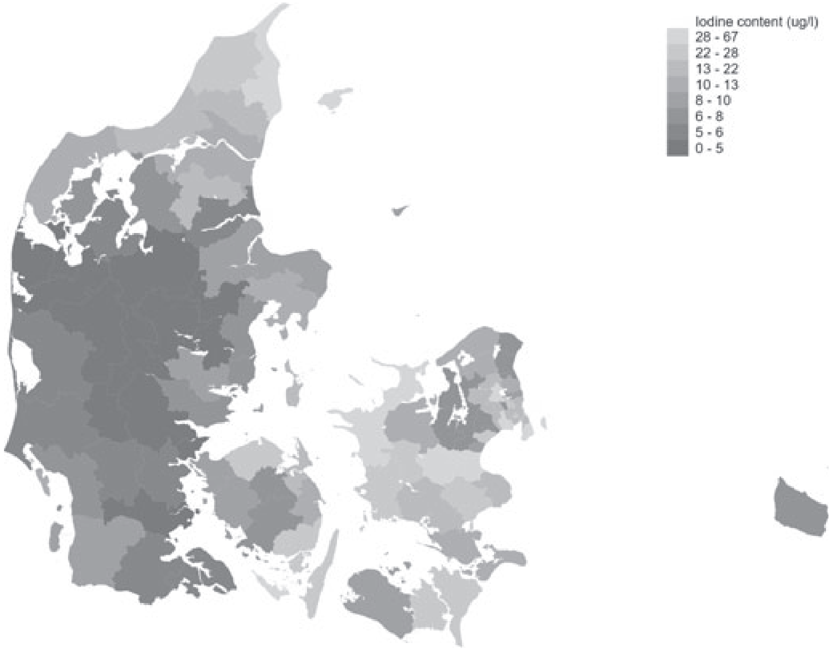
[15] In 2007, a big municipal reform reduced the number of municipalities in Denmark from 271 to 98. To avoid this data break, I use post-2007 municipality borders throughout the analysis. I could use pre-2007 municipalities in the main analysis using the years 1988–2006. However, iodine concentrations in drinking water are based on noisy data and pre-2007 municipalities are rather small geographical units. Therefore, using pre-2007 municipalities rather than post-2007 municipalities yields similar results, but increases the variance. In addition, many pre-2007 municipalities shared the same water works and the actual variation in iodine concentrations within post-2007 municipalities is therefore limited (see Figure A.3).

[16] I discuss the implications of measurement error in iodine concentrations in Online Appendix A.4.

[17] See, for instance, Voutchkova et al. (2015, Figure 3, Panel A) or Pedersen et al. (1999, Figure 1).

[18] This number comes from Pedersen et al. (1999), who regress iodine in urine – a common measure of iodine intake – on the iodine concentration in drinking water and find a well-fitted linear relationship of $IodineUrine = 43.2 + 1.7 * IodineWater$, where $IodineWater$ is measured in μg per liter and $IodineUrine$ is measured as μg per day. This is consistent with an average tap water consumption of 1.7 liter per day, which is reasonable as bottled water consumption is very low in Denmark (Voutchkova et al., 2015).

Figure 1. Iodine concentration in drinking water in Danish municipalities



Notes: The figure shows the iodine concentration (μg per liter) in drinking water for each municipality in Denmark. Recommended iodine intake is 150 μg per day. The values are based on data from groundwater analyses by the GEUS.

between initial iodine intake and cognitive performance. Because the thyroid gland is able to partially compensate for insufficient iodine intake, mild iodine deficiency might not matter for cognitive performance, while moderate to severe iodine deficiency might have drastic consequences. In Online Appendix A.3, I show that the continuous specification provides a good fit of the observed relationship between iodine concentrations in drinking water and the municipality-level change in high school GPA.

I scale the continuous treatment variable such that the difference between the 95th and 5th percentiles is equal to one. Therefore, the coefficients reflect the effect of going from the 95th to the 5th percentile of iodine concentrations in drinking water – from a mildly iodine-deficient municipality to a moderately iodine-deficient municipality.[19]

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[19] Students living in areas in the 95th percentile have a predicted urinary iodine excretion, based on Pedersen et al. (1999), of 64 μg per liter compared to 33 μg per liter for students living in areas in the 5th percentile. Severe, moderate, and mild iodine deficiencies are defined as iodine concentrations in urine below 20 μg per liter, between 20 and 50 μg per liter, and between 50 and 100 μg per liter (Andersson et al., 2012).

I estimate the effect of salt iodization using a standard difference-in-differences model. As high school students in Denmark graduate in late June and the two salt iodization reforms were implemented in June 1998 and between July 2000 and April 2001, the reforms were implemented too late in the year to affect the GPA of students who graduated in 1998 and 2000/2001. Therefore, the first students to benefit from the voluntary program in 1998 and the mandatory program in 2000–2001 graduated in 1999 and 2001/2002, respectively. The estimation model is

$$GPA_{it} = \pi_t + \omega_m + \beta_1 P1_t \times Treat_m + \beta_2 P2_t \times Treat_m + X_{it}\delta + \epsilon_{it}, \qquad (1)$$

where GPA_{it} is the individual GPA of high school students graduating in year t, π_t are year dummies, ω_m are municipality fixed effects, $P1_t$ and $P2_t$ are dummies for post-reform years 1999–2001 and from 2002, respectively, $Treat_m$ is either the discrete or continuous treatment variable, X_{it} is a vector of controls, and ϵ_{it} is an error term. I include the following control variables: parental income percentile, years of schooling, and age (I include separate controls for fathers and mothers); student age, birth year, gender, number of siblings, and birth order. All control variables are discretized and included in the regressions with dummies for each value to avoid assumptions on functional form.[20] Standard errors are clustered at the level of treatment (municipality) to allow for autocorrelation in errors (Bertrand et al., 2004).[21]

The β_1 coefficient reflects the treatment effect of the 1998 reform, while the β_2 coefficient reflects the combined treatment effect of the 1998 and 2000–2001 reforms. The identifying assumption is that outcomes in the treatment and control groups would have followed similar trends had it not been for the introduction of iodized salt. This common trend assumption is not directly testable, but I can assess its validity by studying differences in pre-trends. If the GPA of students in iodine-rich and iodine-poor municipalities follow similar trends prior to salt iodization, it is reasonable to assume that they would have continued to do so in the absence of the reforms. Therefore, I also estimate regressions of the form,

$$GPA_{it} = \pi_t + \omega_m + \sum_{t \neq 1998} \beta_t I(year = t) \times Treat_m + X_{it}\delta + \epsilon_{it}, \qquad (2)$$

where the β_t coefficients reflect the difference in the average GPA of students across iodine-poor and iodine-rich municipalities over time.

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[20] To include students with an unknown or dead parent, I add dummies for missing values.

[21] The significance of the results does not depend on the choice of cluster-robust standard errors. Table A.7 in the Online Appendix shows results with standard errors clustered by high school, two-way clustering by high school and municipality, and by provinces (i.e., 11 large geographical areas).

Even with identical pre-trends, the common trend assumption is violated if, for reasons unrelated to salt iodization, the difference in grades between students in iodine-rich and iodine-poor municipalities changes when the reforms are introduced. There are two types of shocks that can cause such a bias: shocks to determinants of grades; and endogenous selection into high school across years. I discuss these concerns in Section 6 and argue that they do not pose a threat to the identification strategy.

A related issue concerns the impact of salt iodization on parents and the response of parental investments to the policy. If salt iodization has a positive effect on parental resources, this might improve the school performance of their children, regardless of whether the students themselves benefit from salt iodization. Moreover, for a given level of parental resources, an increase in the children's school performance might affect parental investments. If public investments (e.g., salt iodization) and parental investments are complements, parents will respond by increasing investments in children, thus magnifying the treatment effect. However, if the two types of investments are substitutes, parental investments will decrease and attenuate any treatment effect on children. Empirically, I cannot distinguish between the direct effect of salt iodization on children and the effects going through parents and parental investments. The estimated treatment effects thus represent a mix of both.

4.1. Summary statistics

Table 1 presents summary statistics of high school students who graduated during the pre-reform period 1988–1998. I split the data into treatment and control groups using the discrete treatment variable (below median iodine concentration in drinking water). Overall, the characteristics of the students are remarkably well balanced across the two groups.

The average age of high school graduates in the treatment and control groups is 19.39 and 19.36, respectively. More girls than boys graduate from the STX program, with only 40 percent boys in the treatment group and 42 percent in the control group. Students in the treatment and control groups have, on average, 1.34 and 1.22 siblings, respectively. High school offers two tracks: science and humanities. Science students follow courses in mathematics, physics, and chemistry, while humanities students take classes in Latin, French, German, and Spanish. This choice variable is balanced across groups with 62 percent of the students enrolled in the science track. The GPAs of graduates – the outcome variable in the empirical analysis – range from 6 to 13, with an average of approximately 8.32 and a standard deviation close to one. Parental characteristics are also similar in the two groups. Parents in the treatment and control groups are, on average, 48 years old and have around 13 years of schooling. However, parents in the

Table 1. Summary statistics of STX graduates from 1988 to 1998

	Treatment (1)	Control (2)	Difference (3)	Difference, within region (4)
Student characteristics				
Age	19.39	19.36	0.031	−0.035
	(0.65)	(0.74)	(0.029)	(0.023)
Male	0.40	0.42	−0.014*	0.004
	(0.49)	(0.49)	(0.007)	(0.006)
Number of siblings	1.34	1.22	0.117***	0.020
	(0.86)	(0.85)	(0.033)	(0.029)
Science track[a]	0.62	0.62	−0.003	0.006
	(0.48)	(0.48)	(0.009)	(0.008)
GPA	8.33	8.32	0.008	0.016
	(0.94)	(0.96)	(0.019)	(0.016)
Parental characteristics				
Number of parents	1.98	1.97	0.004	0.002
	(0.15)	(0.16)	(0.003)	(0.002)
Parental age	48.1	48.2	−0.055	−0.020
	(4.6)	(4.6)	(0.102)	(0.091)
Parental years of schooling	13.3	13.4	−0.190	0.068
	(2.6)	(2.5)	(0.136)	(0.112)
Parental wealth[b]	467,399	488,279	−20,880	43,739
	(6,704,080)	(4,089,203)	(76,219)	(60,304)
Parental income[b]	514,211	537,700	−23,489	11,564
	(600,511)	(532,949)	(20,738)	(17,241)
Geographical concentration[c]				
Densely populated area	0.20	0.33	−0.132	−0.031
	(0.40)	(0.47)	(0.146)	(0.115)
Intermediate density area	0.38	0.40	−0.011	0.017
	(0.49)	(0.49)	(0.126)	(0.151)
Thinly populated area	0.42	0.28	0.143	0.014
	(0.49)	(0.45)	(0.112)	(0.125)
Number of observations	91,172	90,852	182,024	182,024

Notes: Columns 1 and 2 display the mean characteristics of students in the treatment and control groups in the pre-reform years 1988–1998. Standard deviations are reported in parentheses. Column 3 presents the difference between the treatment and control groups, based on a regression of the specific characteristic on the discrete treatment variable. Standard errors clustered by municipality are reported in parentheses. Column 4 repeats this exercise, but controlling for a "West Denmark" dummy in the regression, such that coefficients reflect within-region differences between the treatment and the control groups. (a) High school students choose between a science or humanities track. This variable is only recorded for the years 1988–2004. (b) Wealth and income variables have been converted to 2011 levels using nominal GDP. (c) The geographical categories follow from Eurostat's DEGURBA (degree of urbanization) classification. $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

treatment group have less wealth and lower income than parents in the control group.

As shown in Figure 1, the majority of treatment municipalities are placed in West Denmark. On average, West Denmark is similar to East Denmark, but with more rural areas and a larger share of the work force employed in industry and agriculture. The bottom rows of Table 1 show how municipality-specific population densities vary across the treatment and control group. The treatment group is more likely to live in rural areas than the control group. 42 percent of the students in the treatment group live in thinly populated areas, compared to 27 percent of the students in the control group.[22] As in most developed countries, regional differences in socio-economic outcomes in Denmark are largely due to rural/urban divides. Hence, even though the students' characteristics are well balanced, there could be a worry that the treatment and control groups are exposed to different shocks, which might pose a threat to the analysis. In Section 6, I add different kinds of region-by-year fixed effects to the regressions to show that the main results are robust to using only within-rural/urban area or within-West/East Denmark variation in treatment.

In Column 4 of Table 1, I re-estimate differences in characteristics, controlling for whether the student lives in West or East Denmark. The coefficients are either insignificant or have the opposite sign to the raw differences in Column 3. The differences in population density also largely disappear. Hence, even though treatment assignment is not random, it is not systematically related to characteristics of the students.

5. Results

Figure 2 displays the average GPA of high school graduates in the treatment and control groups for each year during the period 1980–2006, without the addition of control variables or municipality fixed effects. The average GPA is slightly higher in the treatment group than in the control group throughout the pre-reform period. If the students were randomly assigned to the treatment and control groups, we would expect the opposite – that iodine deficiency is associated with lower grades. However, the difference-in-differences method does not require random assignment but only that the common trend assumption is satisfied. Grades in the treatment and control groups evolve in parallel throughout the entire 19-year pre-reform period, although the gap between two groups narrows slightly over time. Overall, Figure 2 suggests that the common trend assumption is valid and that grades

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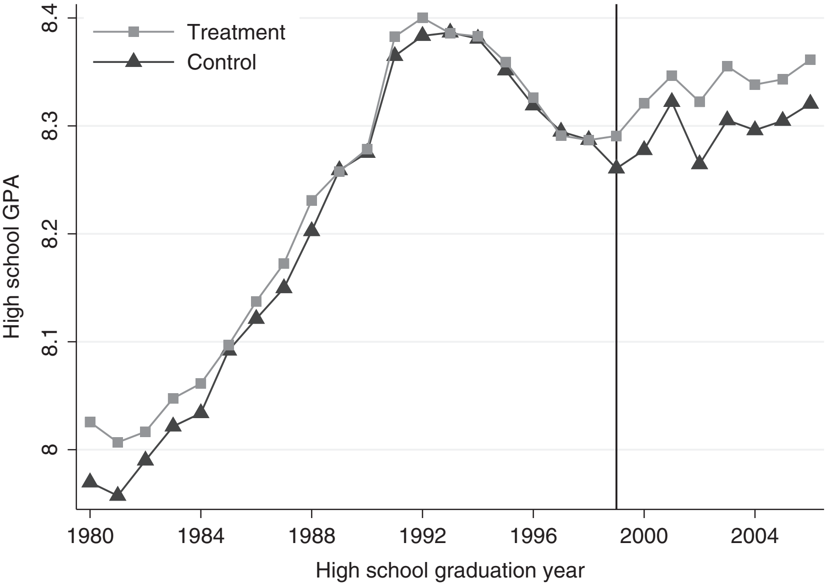
[22] The geographical groups are based on Eurostat's DEGURBA (degree of urbanisation) classification http://ec.europa.eu/eurostat/ramon/miscellaneous/index.cfm?TargetUrl=DSP_DEGURBA.

Figure 2. Trends in GPAs before and after salt iodization



Notes: The figure plots the average GPA among high school graduates in the treatment and control groups for each year during the period 1980–2006. The vertical line at year 1999 marks the introduction of iodized salt.

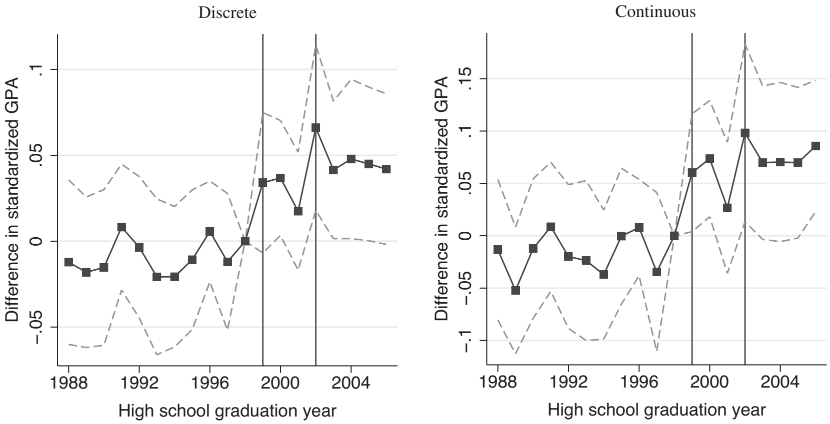
in the two groups would have continued to mimic each other had it not been for the introduction of iodized salt.

Turning to the effects of salt iodization, it is clear from Figure 2 that grades in the treatment group increase relative to the control group from 1999 and onward. This is consistent with the timing of the first salt iodization reform and the hypothesis that iodine deficiency impairs cognitive performance in adolescence.

Figure 3 plots the difference in the average standardized GPA across iodine-poor and iodine-rich areas over time, using specification (2). As in Figure 2, the difference in GPA is stable across years, using both the discrete and continuous measures of treatment. More interestingly, Figure 3 exhibits two upward shifts in grades in 1999 and 2002, consistent with the voluntary program in 1998 and the mandatory program in 2000–2001. This suggests that the iodized salt policies produced an immediate improvement in school performance among adolescents.

Table 2 reports the difference-in-differences estimates. When considering the combined effect of the two reforms, shown in the row “Second reform”, I find that salt iodization increases the GPA of high school students in iodine-poor areas by 5.7 percent and 9.4 percent of a standard deviation, for the discrete and continuous measures of treatment, respectively.

Figure 3. Difference in GPAs across iodine-poor and iodine-rich areas over time



Notes: The figure plots the difference in the average standardized GPA between iodine-poor and iodine-rich areas for each year during the period 1988–2006, relative to the base year 1998. The dotted grey lines represent 95 percent confidence intervals using standard errors clustered by municipality. The left panel shows results for the discrete treatment variable, and the right panel shows results for the continuous treatment variable. Baseline controls are used: for parents, income percentile, years of schooling, and age; for students, age, birth year, gender, number of siblings, birth order, and municipality fixed effects. The vertical lines at 1999 and 2002 mark the introduction of voluntary and mandatory salt iodization. All control variables are included as dummies.

Recall that the discrete treatment variable identifies the difference in the effect of salt iodization between students living in areas with iodine concentrations in drinking water below and above the 50th percentile, while the coefficient on the continuous treatment variable reflects the difference when going from the 95th to the 5th percentile. The two coefficients are, therefore, not directly comparable.[23]

Table 2 also reports the effect of the first salt iodization reform ("First reform"), compared with the effect of both reforms ("Second reform"). Two-thirds of the increase in grades is caused by the first and voluntary reform. Hence, even though the first reform only increased iodine intake by 10 μg per day (Laurberg et al., 2009), compared to 40 μg per day in the second reform, the first reform had a larger impact on school performance than the second reform. This suggests that the relationship between iodine intake and cognitive performance is very concave. To test this, I estimate the benefits of salt iodization across the distribution of initial iodine intake.

I re-estimate treatment effects with four treatment groups based on the distribution of iodine in drinking water: 1st–10th percentile, 10th–25th percentile, 25th–50th percentile, and 50th–75th percentile. I use

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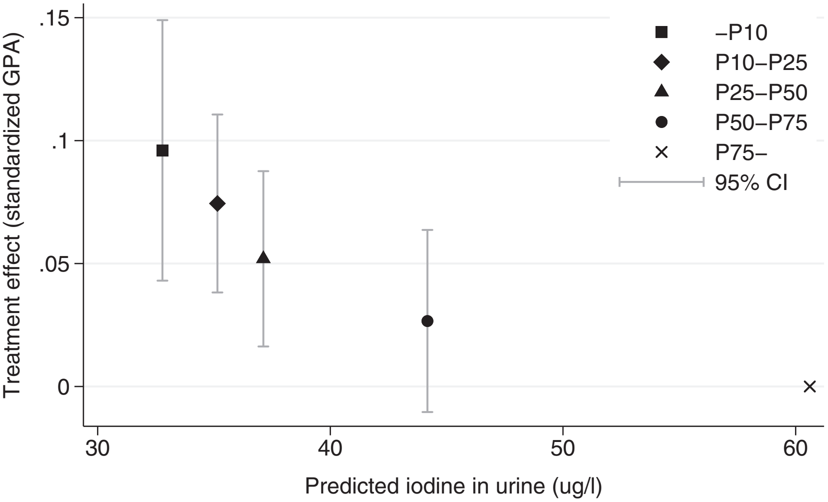
[23] If I compare the predicted treatment effect for students in municipalities with iodine concentrations below versus above the median for both treatment variables, they provide very similar results (see Online Appendix A.3).

Table 2. Effect of salt iodization on the GPAs of high school students

	Discrete	Continuous
First reform	0.039^{***}	0.070^{***}
	(0.012)	(0.017)
Second reform	0.057^{***}	0.094^{***}
	(0.013)	(0.020)
Observations	308,718	308,718
p-value (first reform = second reform)	0.133	0.217
R^2	0.120	0.120

Notes: The estimates reflect the differential change in the standardized GPA of high school students in iodine-poor versus iodine-rich areas from 1988–1998 to 1999–2001 ("First reform") and 2002–2006 ("Second reform"). Column 1 shows the results for the discrete treatment variable, and Column 2 shows the results for the continuous treatment variable. Baseline controls are used: for parents, income percentile, years of schooling, and age; for students, age, birth year, gender, number of siblings, birth order, and municipality fixed effects. All control variables are included as dummies. Standard errors clustered by municipality are reported in parentheses. $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

Figure 4. Heterogeneity by degree of iodine deficiency



Notes: The figure plots the change in the average standardized GPA from 1988–1998 (pre-reform) to 2002–2006 (post-reform) of high school students living in municipalities belonging to different parts of the distribution of iodine concentrations in urine, relative to students in municipalities above the 75th percentile. Iodine in urine is predicted using drinking water iodine concentrations and estimates from Pedersen et al. (1999). Standard errors are clustered by municipality. Baseline controls are used: for parents, income percentile, years of schooling, and age; for students, age, birth year, gender, number of siblings, birth order, and municipality fixed effects. All control variables are included as dummies.

municipalities with iodine concentrations in drinking water above the 75th percentile as a control group.

Figure 4 plots the estimated treatment effects against iodine concentrations in urine, which I predict using estimates from Pedersen et al.

(1999).[24] Severe, moderate, and mild iodine deficiencies are defined as iodine concentrations in urine below 20 μg per liter, between 20 and 50 μg per liter, and between 50 and 100 μg per liter (Andersson et al., 2012). Clearly, the relationship between treatment effects and initial iodine intake is non-linear. The control group – municipalities above the 75th percentile – is mildly iodine-deficient with a predicted iodine concentration in urine of 60 μg per liter. The iodine concentration in urine in municipalities in the 50th–75th percentile is 16 μg per liter lower than in the control group and the treatment effect for these students is 0.027 standard deviations and not statistically significant. The iodine concentration in urine in municipalities below the 10th percentile is 27 μg per liter lower than in the control group and the treatment effect for these students is 0.096 standard deviations and highly statistically significant. This pattern is consistent with a very concave relationship between iodine intake and cognitive performance, where the benefits of salt iodization are concentrated among individuals with moderate to severe iodine deficiency.

In Online Appendix A.5, I estimate the effect of *in utero* exposure to salt iodization in Denmark and provide suggestive evidence that cohorts born after the first iodization policy obtained higher mathematics grades in lower/middle secondary school. Furthermore, Online Appendix A.1 shows that among the elderly the first salt iodization reform caused an increase in hyperthyroidism cases, which is a known negative side effect of increasing iodine intake. Both of these analyses support my main results and show that even though the first and voluntary salt iodization reform was unsuccessful at eliminating iodine deficiency, it was successful at alleviating the worst consequences thereof.

In the rest of the paper, I focus on estimates using the continuous treatment variable, which uses the available variation in drinking water iodine more efficiently than the discrete treatment variable, and the functional form of the continuous treatment variable accurately fits the observed relationship between the benefits of salt iodization and drinking water iodine (see Figure A.4 in the Online Appendix). The results for the discrete treatment variable are qualitatively similar and provided in Online Appendix A.7.

5.1. Heterogeneous treatment effects

Iodine deficiency disorders are much more prevalent among women than men (Pedersen et al., 2002; Vanderpump, 2011) and a number of studies find larger effects of *in utero* exposure to iodine deficiency among women

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[24] Pedersen et al. (1999) estimate the relationship between iodine in urine and iodine in water: $IodineUrine = 43.2 + 1.7 * IodineWater$, where $IodineWater$ is measured in μg per liter and $IodineUrine$ is measured as μg per day. To convert the predicted iodine in urine to μg per liter, I assume an average adult daily urine output of 1.5 liters.

(Field et al., 2009; Politi, 2010; Adhvaryu et al., 2020). The medical reasons for this gender difference is not well understood. Nonetheless, in line with previous studies, Table A.2 in the Online Appendix shows that the total effect of the salt iodization reforms is larger for girls than boys. The difference across genders is, however, not statistically significant.

Figure 5 shows the effect of salt iodization on different parts of the distribution of grades, estimated using quantile regression. I use the jittering method (Machado and Santos Silva, 2005), which allows for discrete outcome variables, because the recorded GPA of students is rounded to one decimal point and the magnitude of treatment effects is close to one decimal point.[25] The jittering method is computationally demanding. Therefore, I do not include control variables and I pool years in groups of three.

The lines in Figure 5 represent the difference in the first, second, third, and fourth quartile of grades across iodine-poor and iodine-rich areas for each year during 1988–2006. The coefficients for the four quartiles are all fairly stable during the pre-reform period and then increase in 2000 (1999–2001), when salt iodization is introduced.

There are large differences in the effect of salt iodization across grade quartiles, with larger improvements in the bottom of the distribution of grades. Figure 5 reports the difference-in-differences estimates for each quartile. The effect on the first quartile of grades is twice as large as on the fourth quartile of grades and the difference between the two estimates is statistically significant at a 10 percent confidence level.[26] Hence, students in the bottom of the grade distribution benefit most from salt iodization. This is at odds with the predictions of James Heckman's work on skill formation in different periods of childhood (Cunha and Heckman, 2007), which posits that returns to investments in adolescence increase with initial skills. My findings suggest that human capital policies, in particular nutritional policies, in adolescence might reduce initial disadvantage and reduce inequality in economic outcomes.

Although the improvements in grades are largest in the bottom of the distribution of grades, the share of high school students who graduate does not change in response to the reforms (see Figure A.9 in the Online Appendix).[27]

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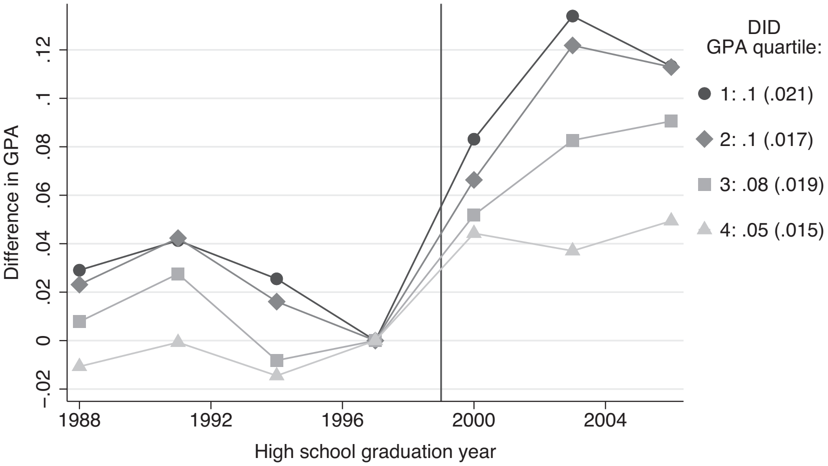
[25] Figure 5 reports the marginal effects at the average on the smoothed outcome variable (Z in Machado and Santos Silva, 2005).

[26] This is based on standard errors bootstrapped using 500 repetitions and clustered sampling by municipality. However, to make this computationally feasible I use only one repetition in the jittering method. In other words, I estimate standard quantile regressions by adding noise to the discrete outcome variable, but I do not take the average estimate over many different draws of the noise.

[27] One likely explanation is that students who do not graduate from high school because of low grades represent a small share of total dropouts. Because grades of non-graduates are not

Figure 5. Effect of salt iodization on different quartiles of GPAs



Notes: The figure shows the difference in the first, second, third, and fourth quartiles of GPA across iodine-poor and iodine-rich areas during the period 1988–2006 using the continuous treatment variable. The coefficients are estimated with quantile regression using the Jittering method with 1,000 repetitions (Machado and Santos Silva, 2005). Years are pooled in groups of three (e.g., the coefficient in 1991 is based on the years 1990, 1991, and 1992). Estimates are relative to the baseline level in 1997. Difference-in-differences estimates are reported to the right. These reflect the effect of salt iodization on each GPA quartile. No control variables are included in the regressions. Misspecification-robust standard errors are reported in parentheses. Cluster-robust standard errors have not been developed for the jittering method. If I instead estimate the coefficients using just one repetition and standard quantile regression with standard errors clustered by municipality, the estimates and standard errors are: 0.11 (0.025), 0.09 (0.023), 0.08 (0.024), and 0.05 (0.030) from the first to fourth quartile of grades, respectively.

5.2. Mechanisms

Having established that salt iodization improves cognitive performance in adolescence, I now turn to the question of why this is. There are two mechanisms through which iodine deficiency can affect cognition: through the effect of iodine deficiency on metabolic functioning and brain activity; and through brain damage induced by disturbances to normal brain development. I make two separate empirical predictions based on the mechanisms.

Metabolic functioning. If the adverse consequences of iodine deficiency arise through an effect on the metabolism, then the treatment effect from salt iodization should be independent of the age at which the students are first treated, as, within this mechanism, only current iodine intake matters for cognitive performance.

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recorded in the data, these individuals cannot be separately identified. Overall, around 90 percent of students who start high school end up graduating.

Brain development. If the effects of iodine deficiency work through disturbances to normal brain development, each year a person lives with iodine deficiency during childhood has an independent negative long-run impact on cognitive ability in high school. Therefore, the treatment effect from salt iodization should be higher for students first treated earlier in life, who are protected from more years of brain damage. Specifically, if we assume that the incremental damage of one year of iodine deficiency during childhood does not depend on age, cumulative treatment effects decrease linearly with the age at which students are first treated.[28,29,30]

I test the predictions of the two competing mechanisms by running the baseline regressions for the extended period 1988–2011. Because high school students are, on average, 19 years old when they graduate, students who finished high school in 2011 were 6 years old when the first reform was implemented in 1998. Hence, at the time of their final exams, students who graduated in 2011 had been treated since age 6, whereas students who graduated in 1999 had been treated since age 18. I can, therefore, compare the effect of salt iodization on children first treated at ages 6–18 by estimating separate treatment effects for students who graduated during 1999–2011.

If the common trend assumption holds throughout the period, this straightforward empirical approach is able to identify all cumulative effects of correcting iodine deficiency at ages 6–18 on grades in high school. This encompasses the age interval considered by Gordon et al. (2009) and Zimmermann et al. (2006), who use randomized experiments to study short-run effects of iodine supplementation on cognitive performance.

Figure 6 plots the treatment effects for students first treated at ages 6–18 (graduated during 1999–2011). To test the two mechanisms, I fit a linear prediction line through these points and estimate the relationship between

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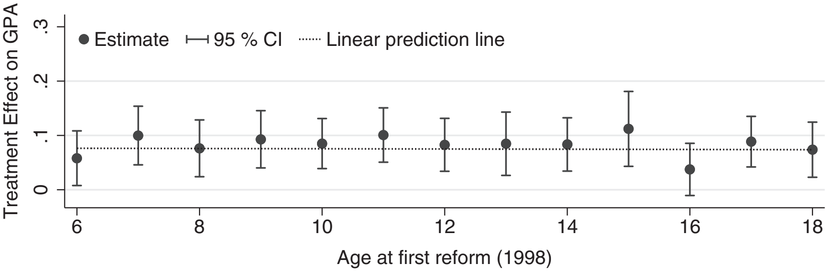
[28] Importantly, a different and indirect long-run effect could arise from dynamic complementarities and learning effects – improved learning in lower/middle school might lead to higher grades in high school.

[29] If salt iodization does have long-run benefits on cognitive ability, the reforms could crowd-out investments from parents and schools. In the extreme, this could lead to constant net effects on grades in high school, even if the benefits of salt iodization, in isolation, are larger for students exposed earlier in life.

[30] This prediction relies on the assumption that the treatment effect from one year of exposure to salt iodization is the same for all ages during childhood. There are several reasons why this might not be the case. (i) For a given degree of deficiency, iodine deficiency is likely to be more detrimental for brain development in early childhood than in late childhood, as brain development is more rapid early in life (Gilmore et al., 2018). However, this means that treatment effects should decrease with exponential decay rather than linearly with the age at which the students are first treated. (ii) The degree of iodine deficiency is not necessarily constant by age. If children aged 6–17 are not iodine-deficient, this could explain why I do not observe long-run benefits of exposure to salt iodization in these ages.

Figure 6. Treatment effects by age at introduction of iodized salt



Notes: The figure plots estimates of the effect of salt iodization on the standardized high school GPA of students first affected by iodized salt at the ages 6–18, using the continuous treatment variable. Each point is a separate difference-in-differences estimate for students who graduated in the post-reform years 1999–2011. Students who graduated in 1999–2011 were, on average, 18–6 years old when the first salt iodization reform was implemented in 1998. Hence, the coefficient for age 6 (age 18) in the figure is the difference-in-differences estimate for students who graduated in 2011 (1999). Standard errors are clustered by municipality. Baseline controls are used: for parents, income percentile, years of schooling, and age; for students, age, birth year, gender, number of siblings, birth order, and municipality fixed effects.

Table 3. Slope of prediction line and tests of the mechanisms

Intercept	Slope	Test 1 (slope = 0)	Test 2 (intercept = slope)
0.0737	0.0002	0.9039	0.0004
(0.0190)	(0.0018)		

Notes: The table reports the slope and intercept of the prediction line in Figure 6. The intercept is the estimated treatment effect for students first treated at age 18, and the slope represents the effect of reducing the age of first treatment by one year. Columns 3 and 4 report, respectively, the *p*-value of a *t*-test for whether the slope is different from zero, and the *p*-value of an *F*-test for whether the intercept is equal to the slope. Standard errors are clustered by municipality.

treatment effects and age of first exposure to salt iodization. Table 3 reports the intercept and slope of this prediction line. The intercept measures the baseline effect on individuals first treated at age 18. The slope represents the additional long-run effect of having been exposed to salt iodization at an earlier age. The first mechanism implies that treatment effects are constant across ages and that the slope of the prediction line is zero. The second mechanism implies that treatment effects accumulate and increase linearly from ages 18–6, with a slope equal to the intercept.[31] As shown in Figure 6 and Table 3, the treatment effects on high school GPA are not larger for students first exposed to iodized salt at an earlier point in life. The slope of the prediction line is not significantly different from zero and I can clearly reject that the slope of the prediction line is equal to the intercept.

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[31] Under the assumption that the incremental damage of one year of iodine deficiency during childhood does not depend on age, the effect of preventing one additional year of brain damage during childhood, the slope, is the same as the treatment effect on students exposed one year before graduation, the intercept.

These results suggest that while the *in utero* consequences of iodine deficiency work through disturbances to normal brain development, the consequences of iodine deficiency in childhood and adolescence documented in this and related papers (Zimmermann et al., 2006; Gordon et al., 2009) are caused by an entirely different biological mechanism. One likely candidate is the effect of iodine deficiency on the metabolism, with short-run consequences for brain activity, memory, and concentration.

6. Robustness

The two main threats to the identification strategy are contemporaneous shocks to determinants of grades and endogenous selection into high school across years. As a first step, I address these concerns by including an extra set of control variables in the regressions. Table A.4 in the Online Appendix shows that including labor market controls for parents or controls for health of the students at birth, measured using birth weight and birth length dummies, does not affect the results. This suggest that changes in the composition of parental characteristics or initial endowments of the students are unlikely to drive the results.

Table A.5 reports estimates from family fixed effects regressions, in which treatment effects are identified using only variation between siblings. This accounts for any time-invariant family characteristics, but increases the variance of the estimates. The family fixed effects estimates are smaller, but not statistically significantly different from the baseline estimates.

The treatment group is concentrated in a few areas. Therefore, the results might be sensitive to regional shocks coinciding with the introduction of iodized salt. To address this concern, I include region-by-year fixed effects in the regressions. In doing so, the effect of the reforms is identified using only within-region variation in treatment, which eliminates the influence of any region-specific shocks. I use three different geographical control variables; the degree of urbanization (DEGURBA) classification from Eurostat, an extended DEGURBA classification created by Statistics Denmark, and a dummy indicating whether the student lives in West or East Denmark.[32] I use the West Denmark split because the majority of treatment group municipalities are placed in West Denmark (see Figure 1).

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[32] The DEGURBA classification by Eurostat splits municipalities into three categories: (1) densely populated areas; (2) intermediate density areas; and (3) thinly populated areas (http://ec.europa.eu/eurostat/ramon/miscellaneous/index.cfm?TargetUrl=DSP_DEGURBA). The extended DEGURBA classification by Statistics Denmark, splits intermediate density areas and thinly populated areas in Eurostat's classification into five groups based on the number of inhabitants – a total of six degrees of urbanization. West Denmark is defined as Jutland and Funen.

Table 4 presents the regression estimates. As reported in the summary statistics in Table 1, students in the treatment group are more likely to live in rural areas than students in the control group. To quantify how much of the variance in treatment assignment is actually explained by these differences, the last row of Table 4 reports the R^2 from a regression of the continuous treatment variable on the geographical control variables.

The degree of urbanization classifications explain between 8 and 15 percent of the variation in the continuous treatment variable. Even though this means that a large part of the variance in treatment assignment comes from comparisons across rural and urban areas, the results are not sensitive to excluding this source of variation and using only within-rural/urban area variation to identify the treatment effect. Regardless of the urbanization classification used, the estimates are close to the baseline results, albeit slightly smaller. The smaller coefficients might reflect that including the geographical controls worsens the attenuation bias from measurement error in the treatment variables.[33,34] This is particularly likely in Column 4 of Table 4, which reports the estimates using only within-West/East Denmark variation in treatment. The West Denmark dummy explains 25 percent of the variation in the continuous treatment variable. The estimated coefficients are smaller than the baseline estimates but they remain economically and statistically significant. The total effect of the two reforms is 6.4 percent of a standard deviation.

In Online Appendix A.4, I derive a ballpark estimate of the degree of measurement error in the treatment variables, which suggests that the baseline estimates are significantly downward-biased and that the true treatment effects are around 1.6 times larger. Furthermore, I derive theoretical predictions of the increase in the attenuation bias caused by the inclusion of region-by-year fixed effects and show that the change in coefficients in Table 4 is consistent with these predictions.

6.1. Sample selection

High school is voluntary in Denmark and about 30 percent of a cohort choose to enroll in the STX program after finishing lower/middle secondary school.[35] Because the data only contain information on the GPA of STX

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[33] The treatment variables are measured with substantial error. Even in the unlikely case that the groundwater samples perfectly predict actual iodine intake from drinking water, there are many other determinants of iodine deficiency.

[34] Region-by-year fixed effects worsen the attenuation bias because they reduces the true variation in the treatment variables without reducing the variation of the measurement error. See Online Appendix A.4 for a thorough discussion.

[35] In Denmark, school attendance is compulsory until the end of year 9. Children attend primary school (*Folkeskole*) from kindergarten to year 9, which encompasses primary and lower/middle secondary education. High school refers to years 10–12.

Table 4. Robustness to geographical control variables

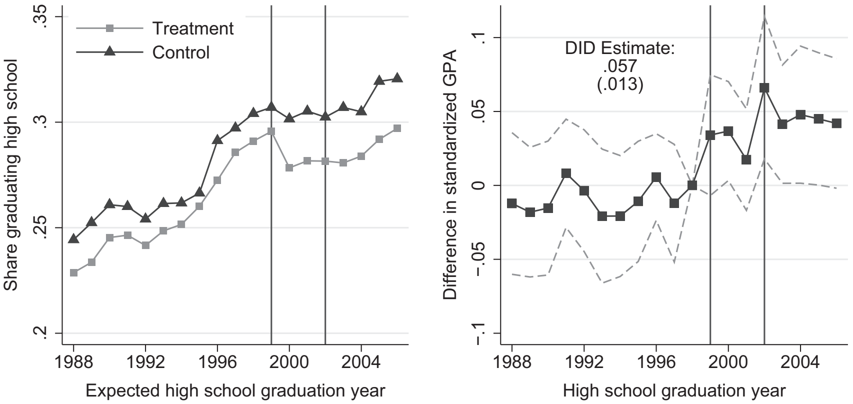
	(1)	(2)	(3)	(4)
First reform	0.070***	0.070***	0.069***	0.049***
	(0.017)	(0.017)	(0.018)	(0.019)
Second reform	0.094***	0.085***	0.085***	0.064***
	(0.020)	(0.021)	(0.021)	(0.024)
Baseline	X	X	X	X
DEGURBA 1		X		
DEGURBA 2			X	
West Denmark				X
Observations	308,718	308,718	308,718	308,718
R^2	0.120	0.120	0.120	0.120
p-value, diff. first reform		0.909	0.966	0.092
p-value, diff. second reform		0.201	0.325	0.037
R^2 of treat		0.063	0.105	0.283

Notes: The estimates reflect the differential change in standardized GPA of high school students in iodine-poor versus iodine-rich areas from 1988–1998 to 1999–2001 ("First reform") and 2002–2006 ("Second reform", using the continuous treatment variable. Baseline controls: for parents, income percentile, years of schooling, and age; for students: age, birth year, gender, number of siblings, birth order, and municipality fixed effects. DEGURBA 1: dummies for the three categories in Eurostat's DEGURBA classification interacted with graduation year dummies. DEGURBA 2: dummies for the five categories in Statistics Denmark's extended DEGURBA classification interacted with graduation year dummies. West Denmark: dummy for living in Jutland or Funen (West Denmark) interacted with graduation year dummies. Standard errors clustered by municipality are reported in parentheses. $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

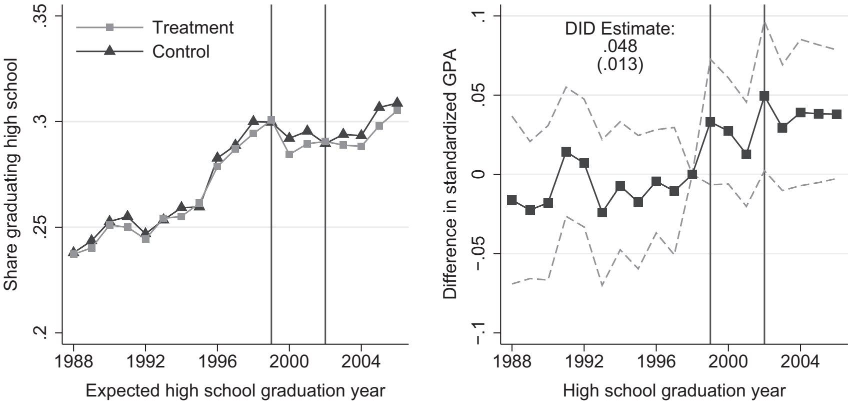
graduates, differential selection into high school across years might affect the results. Figure 7(a) plots the share of lower/middle secondary school graduates who finish an STX high school education in treatment and control group municipalities, defined using the discrete treatment variable. I plot the graduation rates by the predicted graduation year to show when we can expect selection into high school to affect average grades. The predicted graduation year is set to three years after lower/middle secondary school graduation, at which point 90 percent of high school students graduate.

Throughout the data period, children in treatment group municipalities are less likely to obtain an STX high school education than children in control group municipalities. The gap narrows over time and then broadens in 2000, with a larger drop in graduation rates in treatment group municipalities. If marginal high school students would have achieved grades below those of the average graduate, the widening of the gap in graduation rates in 2000 might produce a mechanical increase in grades in the treatment group relative to the control group. However, because the effect on grades in the main results, shown in Figure 7(b), starts in 1999, the results cannot be explained by a change in graduation rates in 2000.

Figure 7. Sample selection



(a) Sample selection, raw (b) Effect on GPA, raw



(c) Sample selection, matched (d) Effect on GPA, matched

Notes: (a) reports the share of lower/middle secondary school graduates in treatment and control group municipalities who graduate from an STX high school education. I plot this for each expected high school graduation year (three years after leaving lower/middle secondary school) during the period 1988–2006. (b) shows baseline estimates of the difference in average standardized GPA between the treatment and control groups for each year during 1988–2006, using the discrete treatment variable. The dotted grey lines represent 95 percent confidence intervals, using standard errors clustered by municipality. Baseline controls are used: for parents, income percentile, years of schooling, and age; for students, age, birth year, gender, number of siblings, birth order, and municipality fixed effects. The vertical lines at 1999 and 2002 mark the introduction of voluntary and mandatory salt iodization. (c) and (d) replicate (a) and (b), but on a matched sample. The matching is based on inverse probability weighting. The propensity score P is estimated with Probit, using high school enrollment rates for each municipality and for each year as explanatory variables. I take the propensity score as given in the estimation of standard errors. The weights are $1/P$ for the treatment group and $1/(1-P)$ for the control group.

In Figure A.10 in the Online Appendix, I show that the widening gap in graduation rates in 2000 is caused by a reduction in the number of schools offering the business-oriented HHX high school program in control group municipalities.[36] With fewer schools offering HHX programs, more individuals chose to enroll in the STX program, making the 2000 drop in STX high school graduation rates smaller in control group municipalities. If I drop municipalities that experienced a school closure during this period, the difference in graduation rate levels and trends disappear, while the original results on grades remain (see Figure A.10).

Furthermore, in Figure A.11, I predict the GPA of students based on the full set of control variables and show that there is no change in this summary measure of observable characteristics of students around the introduction of iodized salt. In addition, Table A.6 shows that the main results are robust to including municipality-level pre-reform shares of lower/middle secondary school graduates enrolling in the STX, HHX, HTX, and HF high school programs interacted with year. This accounts for the potential concern that effects are driven by areas with a tradition of preferring one type of high school program over another. In summary, the results are unlikely to be driven by changes in the composition of students graduating from high school around the time of the reforms.

To show more formally that sample selection is not an issue, I match treatment and control municipalities based on STX high school graduation rates. If the results are caused by sample selection, the effect on grades would be zero if graduation rates were identical in the two groups. By matching on graduation rates, I can test this scenario and evaluate whether sample selection drives the results.

I use inverse probability weighting (Mansournia and Altman, 2016) to conduct the matching. I estimate the propensity score by Probit and use STX high school enrolment rates in each municipality and for each expected graduation year during 1988–2006 as explanatory variables.[37] The results are shown in Figures 7(c) and (d).

The matching is accurate. As shown in Figure 7(c), there is no visible gap in graduation rates between treatment and control group municipalities in the matched sample. More importantly, there is no widening gap from 2000 and onward. Nonetheless, the effect on grades, shown in Figure 7(d), persists. The estimated treatment effect is close to the baseline effect for the

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[36] HHX is the second-largest high school program and around 10 percent of a lower/middle secondary school cohort enroll in the HHX program after graduation. The reduction in the number of high schools offering HHX programs in control group municipalities around 2000 is most likely because of relatively small cohorts in those years.

[37] I match on enrolment in high school rather than completion because the probability of dropping out of high school can be endogenous to treatment.

discrete treatment variable reported in Figure 7(b). This shows that sample selection cannot explain the results of the empirical analysis.

6.2. External validity

This paper estimates the causal effect of salt iodization on cognitive performance among Danish high school students. A natural question is whether this sample is representative of the general population in Denmark, and how the results for Denmark relate to salt iodization policies in other parts of the world.

Because upper secondary education is voluntary in Denmark and most high school graduates go on to complete a tertiary education, high school students represent a positively selected sample of higher-achieving individuals. Because high-achieving students benefit less from salt iodization than low-achieving students (see Figure 5), I expect larger estimates for the general population of adolescents. Hence, given that the estimates for high school students are internally valid, they most likely represent lower bounds on the population-wide benefits of salt iodization in Denmark.

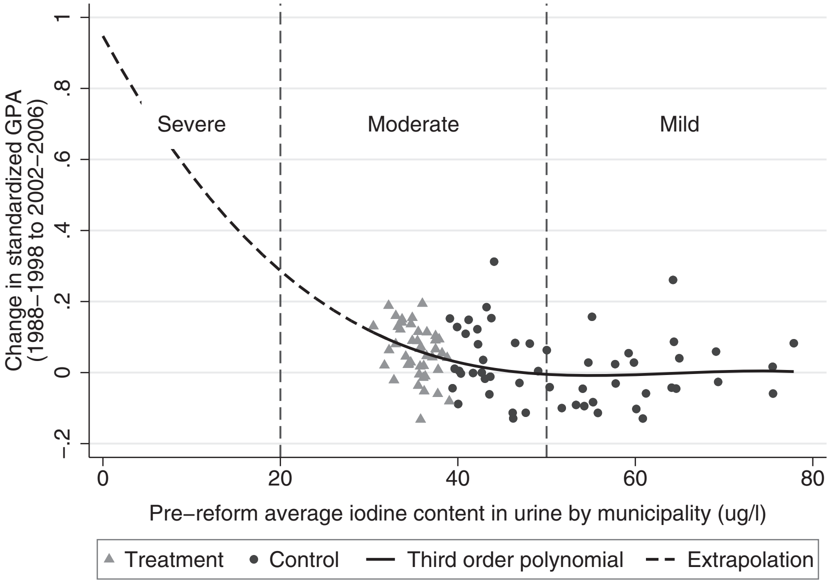
The results in this paper are specific to the degree of iodine deficiency present in Denmark prior to salt iodization. The Danish population was mildly to moderately iodine-deficient before the introduction of iodized salt. To give some indication of the benefits of salt iodization in other countries, I perform an extrapolation. I do this based on the relationship between the change in average GPA over time and the pre-existing level of iodine deficiency across municipalities, measured using the predicted iodine concentration in urine (see footnote 24).

This exercise is merely an illustration of the potential gains in other countries. I do not account for many factors that differ across countries, including the education system, institutions and the role of parents, which could influence the effect of salt iodization policies.

Figure 8 plots the results. The dots represent the change in average standardized GPA from 1988–1998 to 2002–2006 in each municipality in the treatment and control groups, relative to a mildly iodine-deficient (80 μg per liter) municipality. The solid black line in Figure 8 shows the predicted relationship between initial iodine deficiency and the increase in average GPA due to salt iodization, using a third-order polynomial. The dashed line is an extrapolation from this prediction.

In line with the findings of the paper, the predicted treatment effect in Figure 8 is increasing in the severity of iodine deficiency. Moreover, because Danes were mildly to moderately iodine-deficient prior to the reforms, the treatment effects observed in the paper are small compared with the prediction for more severely deficient populations. For moderate iodine deficiency, the predicted treatment effect is 0.09 standard deviations,

Figure 8. Predicted gains from correcting iodine deficiency by degree of deficiency



Notes: The figure plots the change in average standardized GPA from 1988–1998 to 2002–2006 for each municipality in the sample relative to a municipality with mild iodine deficiency (80 μg per liter). The x-axis shows the iodine concentration in urine (a measure of iodine intake) in each municipality as predicted by the iodine concentration in drinking water. The solid and dashed lines show the prediction and extrapolation, respectively, of a third-order polynomial. The vertical dashed lines represent thresholds for mild, moderate, and severe iodine deficiencies (see Andersson et al., 2012). For expositional purposes, I remove a small outlier, the municipality of Læsø, with an iodine concentration in urine of 105 μg per liter.

and in environments with severe iodine deficiency the predicted treatment effect is 0.58 standard deviations. While these predictions are not directly applicable to other countries, they suggest that the benefits of salt iodization are much larger in more deficient populations. Globally, 15.9 percent of school-age children are mildly iodine-deficient, 8.1 percent are moderately iodine-deficient, and 5.2 percent are severely iodine-deficient (Andersson et al., 2012).

7. Conclusion

The worldwide adoption of iodized salt over the past three decades is one of the most successful public health interventions in recent times. The focus of these efforts has been to prevent mental retardation caused by *in utero* exposure to maternal iodine deficiency. While this is the most severe consequence of iodine deficiency, my analysis shows that salt iodization policies benefit a much broader group of individuals.

Using the introduction of iodized salt in Denmark over the period 1998–2001, I find that salt iodization improves cognitive performance among adolescents. I show that this effect most likely arises from the contemporaneous effect of iodine deficiency on metabolic functioning and brain activity. As iodine is crucial for the metabolism in all stages of life, this suggests that similar benefits of salt iodization might be found for adults. If so, the aggregate societal benefits of salt iodization policies would be considerably larger than previously thought.

While the use of iodized salt has reduced the incidence of iodine deficiency dramatically, about one-third of the world's population remain iodine-deficient (Andersson et al., 2012). Hence, there is still a large untapped economic potential in eradicating iodine deficiency. My results are especially relevant for other European countries, where iodine deficiency is not considered a serious health concern, despite the region having one of the highest rates of deficiency and the lowest rate of salt iodization (WHO, 2007). In developing countries, where severe iodine deficiency is more prevalent, my estimates add to the already large expected benefits of salt iodization.

Supporting information

Additional supporting information can be found online in the supporting information section at the end of the article.

Online appendix
Replication files

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