Food and Chemical Toxicology 157 (2021) 112549

Contents lists available at ScienceDirect

Food and Chemical Toxicology

journal homepage: www.elsevier.com/locate/foodchemtox

Caffeine exposure from beverages and its association with self-reported sleep duration and quality in a large sample of Icelandic adolescents

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ARTICLE INFO

Handling Editor: Dr. Jose Luis Domingo

Keywords:
Energy drinks
Beverages
Caffeine
Adolescents
Sleep duration
Risk assessment

ABSTRACT

Previous risk assessments have concluded that adolescent's caffeine exposure from energy drinks (ED) are of limited concern. Recent surveys have, however, shown substantial increase in consumption. This cross-sectional survey conducted in 2020 estimated caffeine exposure from beverages among ~80% of all 13-15-year-old adolescents (n = 10358) relative to the European Food Safety Authority's level of no safety concern of (3.0 mg/kg bw) and level for effects on sleep (1.4 mg/kg bw). Associations with self-reported sleep duration and quality were also explored. ED consumers were more likely to exceed the limit of no safety concern (prevelance: 12–14%) compared to non-ED-consumers (1–2%). Exceeding the limit for effects on sleep was also higher among ED consumers (31–38%) than non-ED-consumers (5–8%). Across categories of low (<0.5 mg/kg bw) to high (>3.0 mg/kg bw) caffeine intake, the prevalence of participants sleeping <6 h increased from 3% to 24%, respectively. The corresponding adjusted Prevalence Ratio was 4.5 (95% CI: 3.6, 5.7) and mean decrease in duration of sleep was 0.74 h (95% CI: 0.65, 0.84). In conclusion, caffeine intake from beverages above the limit of no safety concern was largely confined to ED consumers. Consistent with effects from intervention studies in adults, caffeine intake was strongly associated with self-reported sleep duration in this representative population.

1. Introduction

Energy drinks are non-alcoholic beverages that contain a relatively high amount of caffeine compared to other soft drinks and are often marketed as boosting athletic performance or mental alertness. Concerns about energy drinks as determinant of high caffeine exposure in children have been raised due to possible adverse effects of caffeine on neurological and cardiovascular outcomes; as well as risk of acute toxicity at the extremes (Ehlers et al., 2019; Temple, 2009). In adults, mild symptoms of caffeine toxicity (at~0.75 g) include gastric symptoms, seizures and fever; and the lowest lethal dose recorded is ~5 g (OECD-SIDS, 2002). Due to differences in body weight (bw), the same effects will occur at proportionally lower intakes in children (EFSA, 2015), but poisoning events appear rare based on the few reports available (Ehlers et al., 2019; Seifert et al., 2013). Studies focusing on children are also scarce (Wikoff et al., 2017), but habitual intake has been linked with physical dependence, sleep- and mood disorders (Cusick et al., 2020; Jackson et al., 2013; Kristjansson et al., 2014; Owens et al., 2014; Pollak and Bright, 2003)

There are currently no specific guidelines on caffeine intake in the US for children, while Health Canada established in 2012 a recommended level of 2.5 mg/kg bw (Health Canada, 2012). Three years later the European Food Safety Authority (EFSA) published a risk assessment on caffeine where a single dose of caffeine of up to 200 mg (or ~3 mg/kg

Abbreviations: BW, body weight; ED, energy drinks; EFSA, European Food Safety Authority; CI, confidence intervals; PR, prevalence ratio.

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https://doi.org/10.1016/j.fct.2021.112549
Received 18 May 2021; Received in revised form 16 August 2021; Accepted 7 September 2021
Available online 10 September 2021

bw), and habitual daily caffeine intake of 400 mg (5.7 mg/kg bw) was set as the level of no safety concern for non-pregnant healthy adults (EFSA, 2015). It was also noted that a single dose of 100 mg (~1.4 mg/kg bw) consumed close to bedtime could affect sleep latency and duration. For pregnant or lactating women, the opinion stated that habitual caffeine intake up to 200 mg per day would not give rise to safety concerns. Citing lack of data, EFSA set as a precaution for children and adolescents, a level of no safety concern of 3 mg/kg bw per day for habitual caffeine consumption.

Until 2008 the maximum limit in Iceland for caffeine added to soft drinks was (150 mg/L) but gradually concentrations increased to ~320 mg/L and in 2017 energy drinks with a concentration of up to ~550 mg/L first appeared on the market. Coincidingly, nationwide surveys among adolescents showed that consumption of energy drinks had more than doubled between 2016 and 2018 (Guðmundsdóttir et al., 2019). Concerns about the possible deleterious effects of the aforementioned increase in energy drink consumption prompted a more detailed assessment of caffeine intake from beverages among all 13 to 15-year-old children in Iceland in 2020. The aim of this study was to assess possible risks associated with caffeine consumption from beverages relative to the level of no safety concern set by EFSA (EFSA, 2015); and to assess whether intake of caffeine from beverages might be adversely associated with sleep duration and quality in these children.

2. Materials and methods

2.1. Survey description

In January 2020, the *Icelandic Risk Assessment Committee for Food, Feed, Fertilizers and Seeds* under the *Ministry of Industries and Innovation* was asked to perform a quantitative assessment on caffeine intake from beverages. Data was collected using the *Youth in Iceland* survey; a biannual paper-and-pencil questionnaire survey, conducted by the *Icelandic Centre for Social Research and Analysis*, that collects social behavioural health information for policy, research and prevention (Kristjansson et al., 2016; Sigfusdottir et al., 2020). The survey was conducted in February of 2020 and was administered according to standard protocols (Kristjansson et al., 2013) to all 13-15-year-old children across 135 schools in Iceland. The full questionnaire, available in Icelandic and English, was designed to be completed within one 40 min class session.

All aspects of data collection, including participant involvement based on passive parental/caregiver consent, were in compliance with Icelandic law on the protection of human subjects that have been reviewed and deemed exempt by the Icelandic National Bio-Ethics Committee (similar to a National IRB; protocol # VSNb2017020009/04.01).

2.2. Study size

A total of 10778 children returned the questionnaire corresponding to ~80% of all 13-15-year-old children in Iceland. The present analyses were conducted with 10358 children who provided answers on caffeinated beverages (96% of responders). Due to missing values on the sleep duration and sleep quality questions, analyses of those data were based on 10225 to 10324 children (95–96% of responders).

2.3. Quantification of caffeine intake

Previous *Youth in Iceland* surveys have included questions on energy drinks, cola drinks, coffee and tea in categories of *never or number of servings per day*. For the purpose of our assessment, capturing a broader habitual intake was considered important but replacing existing questions would have hampered comparison with previous surveys. Existing questions were therefore kept but new questions on energy drinks, caffeinated protein sports drinks (mixed from powder) and cola drinks were added with a scale of *never, <1/week, 2–3/week, 4–6/week, 1/day, 2/day and ≥3/day*. For all beverages, the children were asked to report their current level of consumption. Total caffeine intake from beverages was then quantified based on the reported frequency of intake from the new questions as well as the original questions on coffee and tea. The justification for relying on the older questions for coffee and tea was that consumption of these beverages would, based on previous surveys, be low and limiting the number of added questions was important. Exact response categories and the frequency distributions for individual beverages are shown in Supplemental Table S1 and all questions from the survey (in Icelandic) relevant to the results presented in this paper are included in the online supplemental material.

The caffeine content in energy drinks was assessed with the following question: *"when you drink energy dinks what is the amount of caffeine content usually declared in mg on the can or bottle"*. Possible responses were ~80 mg, ~105 mg, ~180 mg, and "don't know". These options referred to the absolute amount of caffeine per serving based on the most frequent concentrations declared on energy drinks on the market in Iceland in 2019. This method for quantification was used as the absolute caffeine content (in mg) is usually clearly labelled on these beverages and is easier to understand than concentrations in mg/L which need to be considered in relation to serving size. The amount of caffeine in protein sports drinks mixed from powder was assumed to contain 50 mg/serving based on declaration from prevalent products on the market. The amount of caffeine assigned to coffee was 100 mg/serving averaged over all different types of coffee that vary in both serving size and concentration. For tea the caffeine concentration was estimated to be 28 mg/serving assuming a standard serving size of 150 mL and assuming a 50%/50% mixture of black (220 mg caffeine/L) and green (151 mg caffeine/L) tea. For cola beverages the caffeine concentration was estimated to be 36 mg/serving assuming caffeine concentration of 108 mg/L and standard serving size of 330 mL. These estimates were largely based on the values used to assess caffeine intake by EFSA (EFSA, 2015).

Based on these assumptions the total amount of caffeine from each beverage was estimated by multiplying the frequency of consumption for each individual with the estimated amount of caffeine from each beverage. The total amount of caffeine from beverages was then calculated as the sum of all the five beverages.

2.4. Questionnaire information

The *Youth in Iceland* survey contains several questions on sociodemographics, height and weight. Participants were also asked to self-rate their mental and physical health (as very good, good, adequate, poor or very poor); and to report their engagement in sports (frequency per week). Questions capturing their temperament and mental well-being were also included. In those questions participants were asked to report how frequently during the previous week they had experienced episodes of nervousness, anxiety, being angry and running into arguments. Questions on episodes of headaches and stomach pains during the previous week were also included. Participants were also asked to assess their duration and quality of sleep, in terms of 1) average duration in hours and 2) difficulties in falling asleep or staying asleep.

2.5. Main outcomes

To assess possible risks associated with caffeine intake from beverages, quantified intake was compared to the EFSA level of no safety concern set as 3.0 mg/kg bw for children and adolescents (EFSA, 2015). This level is primarily set on the basis of effects of caffeine on the cardiovascular system. Quantified intake of caffeine was also compared to the cut-off of 1.4 mg/kg bw, which EFSA has proposed as the threshold for a single dose that may affect sleep.

Questions on duration of sleep (response categories <6, ~6, ~7, ~8, ~9, >9 h/day) and on difficulty falling asleep were used to assess possible influence of caffeine intake on the children's wellbeing. The reason for using these outcomes is that there is strong evidence for a causal link between caffeine consumption and reductions in sleep quantity and quality, especially when the caffeine is consumed in large doses and/or too close to bedtime (Drake et al., 2013; EFSA, 2015; Landolt et al., 1995a; Roehrs and Roth, 2008). Furthermore, it is also well established that poor sleep duration and quality can affect children's mental and physical health (Freeman et al., 2017; Shochat et al., 2014).

2.6. Statistical analyses

Prevalence of consumption for caffeinated beverages, defined as any intake above the zero category, was reported along with distributions of total caffeine intake in both absolute amount (mg) and relative to body weight (mg/kg bw). Percent of subjects above EFSAs level of no safety concern (3.0 mg/kg bw) and cut-off for sleep (1.4 mg/kg bw) was evaluated. Habits related to caffeine intake were described by comparing participants response to questions on engagement in sports, fitness level, mental health, and physical symptoms across categories of caffeine exposure (<0.5, 0.5–1.0, >1.0–1.4, >1.4–3.0, >3.0 mg/kg bw). The chi-square and the F-test were used to test for differences across categories for dichotomous and continuous variables, respectively.

Association between caffeine intake and sleep were examined for three outcomes: 1) having an average sleeping duration <6 h/night (binary outcome), 2) having difficulties in falling or staying asleep (binary outcome) and 3) mean duration of sleep (in hours/night, continuous outcome). To address possible reverse causation, e.g., that participants with poor physical or mental health or other conditions known to affect sleep might consume more caffeine to compensate, stratified associations across such conditions were examined. Associations with the two binary outcomes were evaluated by multivariate log-binomial regression as implemented in *proc genmod* in SAS (version 9.2) estimating prevalence ratios (Richardson et al., 2015) using low caffeine intake (<0.5 mg/kg bw) as referent. Relative change in sleep (in hours) was evaluated using multivariate linear regression using the same referent. In all analyses the following set of covariates were included: sex (binary variable, 0.5% missing), age (categorical, 3 levels, 0.6% missing), overweight (binary variable, 11% missing); and self-reported mental and physical health (categorical variables, 5 levels; 3.0% and 2.9% missing, respectively). Prevalence of overweight was assessed based on self-reported weight and height using age and gender specific cut-offs (Cole et al., 2000). Missing covariate information were imputed using multiple imputation (n = 5) as implemented in proc MI in SAS.

3. Results

Characteristics of study participants are shown in Table 1. Prevalence of energy drink consumption (any intake above the zero category) was comparable in both sexes and increased from 30% in 13-year-old boys to 47% in 15-year-old boys and from 26% in 13-year-old girls to 48% in 15-year-old girls. Prevalence of cola drink consumption varied less with age and was slightly more prevalent among boys (range: 73–75%) compared to girls (range: 60–64%). The prevalence for consumption of other caffeinated beverages was considerably lower (≤24%). The full frequency distribution for all these beverages is shown in Supplemental Table S1 and the mean contribution of each beverage to total caffeine intake among energy drink consumers and non-consumers is shown in Table 2.

Table 3 shows the distribution of total caffeine intake from beverages (in mg/day) for both sexes combined. The prevalence of subjects above the level of no safety concern (>3.0 mg/kg bw) ranged from 4% to 8% between the ages of 13–15 years. The number of subjects above the cut-off for sleep (>1.4 mg/kg bw) was around 3-fold higher, or 13%–22%, respectively. Among non-energy drink consumers, percentage consuming above the level of no safety concern and above the cut-off for sleep ranged between 1-2% and 5–9%, respectively. However, for energy drink consumers the corresponding numbers were 12–14% and 31–38%, respectively. The majority of energy drink consumers (≥90%) could identify the concentration of their preferred energy dinks, with 105 mg caffeine per serving being the most prevalent choice (Supplemental Table S2). Around 10% of boys and 5% of girls reported preferred consumption of energy drinks containing 180 mg caffeine per serving.

Higher consumption of caffeine (in mg/kg bw) was associated with worse physical and mental health compared to those with lower intake (Table 4). Those with higher intake were also less likely to engage in sports and were more frequently lonely, angry, nervous, and anxious. Episodes of headaches and stomach aches were also more common at higher caffeine intakes.

Across categories of low (<0.5 mg/kg bw) to high (>3.0 mg/kg bw) caffeine intake, the prevalence of subjects sleeping <6 h increased from 3% to 24%, respectively (Table 5). The corresponding adjusted Prevalence Ratio (PR) was 4.5 (95% confidence interval (CI): 3.6, 5.7) Similarly, the prevalence of having difficulty falling asleep increased from

Table 1
Characteristics of study participants in the Youth in Iceland survey 2020 (n=10358).

	13 years	14 years	15 years
	Mean (standard deviation), or %		
Boys	n = 1825	n = 1721	n = 1654
Weight, kg	56 (11)	63 (11)	68 (11)
Height, cm	168 (9)	173 (8)	178 (7)
% overweight[a]	16%	15%	15%
Consumers of caffeinated beverages[b]			
Energy drinks	30%	39%	47%
Caffeinated protein sports drinks	11%	13%	20%
Cola drinks	75%	78%	73%
Coffee	6%	8%	12%
Tea	21%	20%	15%
Girls	n = 1813	n = 1689	n = 1656
Weight, kg	54 (10)	58 (9)	61 (9)
Height, cm	164 (7)	165 (6)	167 (6)
% overweight[a]	15%	15%	15%
Consumers of caffeinated beverages[b]			
Energy drinks	26%	35%	48%
Caffeinated protein sports drinks	6%	7%	13%
Cola drinks	64%	62%	60%
Coffee	7%	7%	11%
Tea	24%	21%	20%

[a] Age specific cut-off for overweight as defined by Cole TJ et al. (Cole et al., 2000).
[b] Any intake reported above the zero category based on participants response to questions on their current consumption of these beverages. The exact frequency distribution for the participants responses are shown in Supplemental Table S1

Table 2
The average (in mg) and relative (in %) contribution of the different caffeinated beverages to total caffeine intake. The results are shown for energy drink consumers[a] and non-consumers separately.

	Mean caffeine intake in mg (%of total)	
	Energy drink consumers (n=3821)	*Non-consumer* (6537)
Total from all beverages	94 mg (–)	23 mg (–)
energy drinks	46 mg (49%)	0 mg (0%)
cola drinks	15 mg (16%)	8 mg (35%)
caffeinated sports drinks	4 mg (4%)	1 mg (<1%)
Coffee	20 mg (21%)	6 mg (26%)
Tea	9 mg (10%)	7 mg (30%)

[a] Any intake reported above the zero-category based on participants response to questions on their current consumption of these beverages.

Table 3
Distribution of caffeine intake (in mg/day) from beverages and prevalence of subjects above the reference value for effect on sleep (1.4 mg/kg bw)[a] and level of no safety concern (3.0 mg/kg bw)[a]. Youth in Iceland survey 2020 (n = 10358).

	mg of caffeine/day 5, 10, 25 50, 75, 90 and 95th percentile	Above cut-off for sleep (>1.4 mg/kg bw)	Above Level of no safety concern >3.0 mg/kg bw
All subjects			
15 years (n=3310)	0, 0, 3, 26, 78, 158, 238	22%	8%
14 years (n=3410)	0, 0, 3, 13, 48, 128, 196	16%	5%
13 years (n=3638)	0, 0, 3, 13, 37, 101,146	13%	4%
Non-energy drink consumers			
15 years (n=1761)	0, 0, 0, 5, 28, 74, 126	9%	2%
14 years (n=2156)	0, 0, 0, 5, 26, 54, 103	6%	1%
13 years (n=2620)	0, 0, 0, 5, 28, 41, 87	5%	1%
Energy drink consumers			
15 years (n=1549)	10, 11, 25, 58, 132, 231, 327	38%	14%
14 years (n=1254)	10, 11, 21, 49, 113, 216, 311	33%	13%
13 years (n=1018)	8, 10, 20, 41, 98, 187, 295	31%	12%

[a] as established by EFSA 2015: Scientific Opinion on the safety of caffeine (EFSA, 2015).

13% to 31% across categories from low (<0.5 mg/kg bw) to high (>3.0 mg/kg bw) caffeine intake with adjusted prevalence ratio of 1.7 (95% CI: 1.4, 2.0). The corresponding mean decrease in duration of sleep was 0.74 h (95% CI: 0.65, 0.84).

When comparing high (>3.0 mg/kg bw) versus low (<0.5 mg/kg bw) caffeine intake in stratified analyses (Table 5) relatively strong association with sleeping <6 h were observed in strata of those reporting either good or very good [PR: 8.2 (95%: 5.4, 12.7)] or adequate, poor and very poor mental health [PR: 3.7 (95%CI: 2.9, 4.9)]. In absolute terms the proportion of participants affected was larger among those with adequate, poor or very poor mental health (34% at >3.0 mg/kg - 7% at <0.5 mg/kg = 27%) compared to those with good or very good mental health (12% at >3.0 mg/kg - 1% at <0.5 mg/kg = 11%). To test the stability of our findings in these stratified analyses we also examined the influence of excluding those reporting adequate health from the strata of those with adequate to very poor mental health. After exclusion, the mean reduction in sleep duration when comparing those with caffeine intake >3.0 mg/kg vs. <0.5 mg/kg was 0.86 h (95%CI: 0.64, 1.07), which is near identical to the estimate reported in Table 4 when the adequate group was included [0.87 h (95%CI: 0.73, 1.01)]. As further stability analysis, associations with sleeping <7 h were also examined (Supplemental Table S3) and the results concur with our primary analyses in Table 5.

Similar patterns of consistent associations between caffeine consumption and sleep duration were also observed across strata of several other self-reported conditions that might affect sleep duration (Table 6).

4. Discussion

In a nationwide survey of Icelandic adolescents with ~80% population coverage, the prevalence of energy drink consumption was ~30% in 13 year old adolecents but increased to ~50% at age 15 years. Energy drink consumers were more likely to exceed the caffeine limit of no safety concern (prevalence: 12–14%) set by EFSA, compared to non-consumers (prevalence: 1–2%). The proportion of those exceeding the limit for effects on sleep duration and latency was also much higher among energy drink consumers (31–38%) than non-consumers (5–9%). Total caffeine intake from beverages was strongly associated with self-reported measures of both poor sleep duration and difficulty falling asleep and this association was stable across conditions and behaviours known to affect sleep.

National legislations and recommendations on caffeine vary considerably (Reyes and Cornelis, 2018). In Iceland, the limit for caffeine in soft drinks was previously set at 150 mg/L but in 2007 the European Commission filed objections to this low value citing free movement of goods within the EU (MAST, 2019). The EFSA opinion from 2015 (EFSA, 2015) was intended to provide more scientific clarity as such opinions provide scientific basis for policies and legislative decisions on food safety in the EU. In their opinion EFSA established a level of no safety concern for caffeine, which is a threshold below which no

Table 4
Self-reported mental health, physical form, and conditions reflecting wellbeing of participants according to their caffeine intake from beverages. Youth in Iceland survey 2020 (n = 10358).

	mg/kg body weight					P-value[a]
	<0.5	0.5–1.0	>1.0–1.4	>1.4–3.0	>3.0	
Mental health						
How do you describe your mental health						<0.0001
Very good	32%	24%	21%	21%	18%	
Good	38%	40%	37%	31%	30%	
Adequate	20%	23%	25%	28%	28%	
Poor	7%	10%	13%	13%	15%	
Very poor	3%	4%	5%	7%	9%	
Physical form and sports						
Sports ≥3/wk.	86%	84%	84%	76%	74%	<0.0001
How do you describe your physical condition						
Very good	40%	32%	27%	24%	22%	<0.0001
Good	39%	41%	39%	39%	38%	
Adequate	18%	22%	27%	29%	29%	
Poor	3%	4%	5%	7%	9%	
Very poor	0%	1%	2%	1%	2%	
Feeling unwell[2]						
Frequent headaches	11%	15%	18%	19%	22%	<0.0001
Frequent stomach aches	10%	14%	15%	18%	19%	<0.0001
Relations and friendship[a]						
Often lonely	10%	14%	13%	18%	18%	<0.0001
Temperament [2]						
Often angry	3%	5%	7%	7%	11%	<0.0001
Frequently nervous	9%	10%	11%	14%	13%	<0.0001
Often anxious	7%	8%	11%	13%	14%	<0.0001
Frequent arguments	4%	6%	8%	12%	15%	<0.0001
Sleeping habits						
Difficulty falling asleep	13%	18%	20%	25%	31%	<0.0001
Sleeping <6 h	3%	5%	7%	11%	24%	<0.0001
	mean (standard deviation)					
Length of sleeping (hours)	7.8 (1.1)	7.6 (1.2)	7.3 (1.2)	7.1 (1.2)	6.8 (1.4)	<0.0001

[a] Chis-square test; [2] In the questionnaire it was asked, "How often did you feel or experience any of the following feelings or conditions during the previous week?". The reported percentages refer to those who answered yes to these conditions occurring "often "or "frequently."

Table 5
Caffeine intake from beverages and its association[a] with sleep duration and difficulty falling asleep. Results are presented for all subjects and stratified by participants self-reported mental health. Youth in Iceland survey 2020 (N = 10225–10324)[b].

Caffeine intake *mg/kg body weight*	Sleeping less than 6 h[c]		Difficulty falling asleep		Change in duration of sleep (hours) [c]
	no. cases (%)/N	*PR (95%CI)*	*no. cases (%)/N*	*PR (95%CI)*	*mean (95%CI)*
All					
<0.5	192 (3%)/6307	1.00	782 (13%)/6249	1.00	referent
0.5–1.0	88 (5%)/1725	1.5 (1.1, 1.9)	302 (18%)/1707	1.2 (1.1, 1.4)	−0.20 (−0.26, −0.15)
>1.0–1.4	36 (7%)/541	1.6 (1.0, 2.2)	109 (20%)/538	1.3 (1.1, 1.6)	−0.30 (−0.40, −0.21)
>1.4–3.0	129 (11%)/1147	2.5 (2.0, 3.1)	281 (25%)/1134	1.4 (1.3, 1.7)	−0.49 (−0.55, −0.42)
>3.0	143 (24%)/604	4.5 (3.6, 5.7)	184 (31%)/597	1.7 (1.4, 2.0)	−0.74 (−0.84, −0.65)
P for trend[e]		<0.0001		<0.0001	<0.0001
Very good or good mental health[d]					
<0.5	61 (1%)/4437	1.00	283 (6%)/4392	1.00	referent
0.5–1.0	20 (2%)/1080	1.4 (0.8, 2.3)	100 (9%)/1069	1.3 (1.1, 1.7)	−0.19 (−0.26, −0.13)
>1.0–1.4	6 (2%)/315	1.3 (0.5, 3.0)	30 (10%)/312	1.4 (1,0, 2.2)	−0.35 (−0.47, −0,23)
>1.4–3.0	25 (4%)/599	2.8 (1.8, 4.5)	69 (12%)/593	1.8 (1.4, 2.3)	−0.48 (−0.57, −0.39)
>3.0	35 (12%)/288	8.2 (5.4, 12.7)	41 (14%)/286	2.2 (1.6, 3.1)	−0.64 (−0.77, −0.52)
P for trend[e]		<0.0001		<0.0001	<0.0001
Adequate poor or very poor mental health[d]					
<0.5	131 (7%)/1870	1.00	499 (27%)/1857	1.00	referent
0.5–1.0	68 (11%)/645	1.5 (1.1, 2.0)	202 (32%)/638	1.1 (1.0, 1.4)	−0.24 (−0.34, −0.13)
>1.0–1.4	30 (13%)/226	1.6 (1.0, 2.5)	79 (35%)/226	1.3 (1.0, 1.6)	−0.26 (−0.43, −0,10)
>1.4–3.0	104 (19%)/548	2.4 (1.8, 3.1)	212 (39%)/541	1.3 (1.1, 1.6)	−0.52 (−0.63, −0.41)
>3.0	108 (34%)/316	3.7 (2.9, 4.9)	143 (46%)/311	1.5 (1.3, 1.8)	−0.87 (−1.01, −0.73)
P for trend[e]		<0.0001		<0.0001	<0.0001

Abbreviations: PR, prevalence ratio; CI, confidence interval.
[a] adjusted for sex, age, overweight and self-reported mental and physical health.
[b] N = 10324 for sleeping less than 6 h and duration of sleep; N = 10225 for difficulty falling asleep.
[c] This outcome is based on the question: "How many hours do you sleep on average per night" with responses of <6, ~6, ~7, ~8, ~9 and > 9 h.
[d] The participants were asked to rate their mental health as: very good, good, adequate, poor, and very poor.
[e] Caffeine intake in mg/kg body weight entered as continuous variable in the regression model using the median values for each category. T-test for duration of sleep, otherwise Chi-square test.

Table 6
Caffeine intake from beverages and its association[a] with duration and difficulty falling asleep stratified by self-reported symptoms of physical, social, and mental conditions that may affect sleep quality. Youth in Iceland survey 2020.

	Caffeine	Sleep <6 h		Change in duration of sleep (hours)
	mg/kg bw	No cases/N	PR (95% CI)	mean (95%CI)
Physical health[b]				
Good	≤1.0	121 (2%)/6163	1.0	Referent
	>1.4	104 (10%)/1086	3.7 (2.8, 4.8))	−0.52 (−0.59, −0.46)
Adequate/poor	≤1.0	159 (9%)/1869	1.0	Referent
	>1.4	168 (25%)/665	2.4 (1.9, 3.0)	−0.52 (−0.62, −0.41)
Engagement in sports				
≥3/week	≤1.0	196 (3%)/6856	1.0	Referent
	>1.4	180 (14%)/1323	3.1 (2.5, 3.8)	−0.53 (−0.59, −0.47)
<3/week	≤1.0	84 (7%)/1092	1.0	Referent
	>1.4	92 (22%)/528	2.5 (1.8, 3.3)	−0.48 (−0.61, −0.35)
Frequent stomach- or headaches[c]				
No	≤1.0	158/(2%)/6579	1.0	Referent
	>1.4	141 (11%)/1269	3.2(2.5, 4.0)	−0.50 (−0.56, −0.44)
Yes	≤1.0	122 (8%)/1453	1.0	Referent
	>1.4	131 (27%)/482	2.4 (1.8, 3.1)	−0.56 (−0.68, −0.44)
Often lonely[b]				
No	≤1.0	184 (3%)/7148	1.0	Referent
	>1.4	180 (12%)/1444	3.4 (2.7, 4.2)	−0.52 (−0.58, −0.46)
Yes	≤1.0	96/11%)/884	1.0	Referent
	>1.4	92 (30%)/307	2.2 (1.6, 2.9)	−0.55 (−0.71, −0.39)
Frequently angry, nervous, anxious, or arguing[b]				
No	≤1.0	138 (2%)/6710	1.0	Referent
	>1.4	125 (10%)/1239	3.5 (2.7, 4.5)	−0.48 (−0.54, −0.42)
Yes	≤1.0	137 (11%)/1245	1.0	Referent
	>1.4	145 (29%)/505	2.1 (1.7, 2.7)	−0.58 (−71, −0.45)

Abbreviations: PR, prevalence ratio; CI, confidence interval.
[a] Adjusted for sex, age, overweight and self-reported mental and physical health.
[b] The participants were asked to rate their physical health as: very good, good, adequate, poor, and very poor.
[c] In these questions asked, "How often did you feel or experience any of the following feelings or conditions during the previous week?".

health risk is expected (EFSA, 2015). This is a more uncertain value compared to other health-based guidance values set for substances intentionally added to foods (e.g. Acceptable Daily Intake), where exceedance is more clearly linked to adversity. We can therefore only conclude that between the ages of 13–15 years, caffeine intake among 4%–8% of our participants may pose some risks to their health.

Although documented cases of acute toxicity are rare (Seifert et al., 2013), such events may become more frequent with rapidly rising prevalence of excessive consumption and increased availability of products with high caffeine content. Despite restrictions in Iceland on selling heavily caffeinated energy drinks (180 mg/serving) to children (<18 years), around 10% of energy drink consumers in our study reported both preference for, and consumption of, such beverages. However, focusing on toxicological outcomes alone overlooks other health aspects, including effects on sleep and the fact that part of those who drink caffeinated beverages on regular basis develop caffeine dependency and experience withdrawal symptoms, including headache, fatigue, and anxiety that for some can last several days (Bernstein et al., 1998; Juliano and Griffiths, 2004). This is not the case for any other substances intentionally added to foods. Intentional enrichment of soft drinks and other foods with caffeine that can be marketed and sold unrestricted to children, which may result in physical dependency, largely appears to fall outside the remit of food safety as defined by the general EU food law (European Parliament, 2002), which primarily focuses on protecting consumers from foods that are "injurious to health". Under such remit effects on physical dependency and sleep that are well established in adults may, from a toxicological point of view, not meet the definition of being adverse or "injurious to health". Existing risk assessments (EFSA, 2015; VKM et al., 2019) have however, largely bypassed the question whether these same effects could be adverse (or not adverse) in children.

Concerning sleep, intervention studies in adults have shown significant effects on sleep disruption at doses corresponding to the equivalent of ~4 cups of coffee (400 mg) 6 h before bed-time (Drake et al., 2013), ~1 cup of coffee (100 mg, ~1.4 mg/kg bw) before bedtime (Landolt et al., 1995a) and even at ~2 cups (200 mg) of coffee administered early in the morning (Landolt et al., 1995b). One limitation of existing interventions focusing on caffeine and sleep in adults is that they are typically conducted in few selected healthy individuals (n ~10–20) with only few doses tested (Drake et al., 2013; Drapeau et al., 2006; Landolt et al., 1995a, 1995b). One strength of our study is that it provides a more direct measure of the biological gradient (or dose-response) between habitual consumption of caffeine and self-reported sleep in the general adolescent population. The clear reduction in sleep duration observed in our study is entirely in line with the above-mentioned results from interventions in adults. Although we lacked information on timing of intake, consumption is likely to tilt towards the afternoon as use of energy drinks is prohibited at schools. Still, our use of the 1.4 mg/kg bw cut-off for sleep requires balanced interpretation as exact timing of consumption relative to bedtime was lacking and one can only assume that exceedance of this limit close to bedtime may have occurred for some but not all of those participants.

Previous risk assessments and opinion by health authorities have largely ignored observational findings on sleep in children, citing use of self-reported measures, lack of prospective studies and risk of bias (COT, 2018; EFSA, 2015; VKM et al., 2019). In the case of caffeine, lower risk of bias would not be expected for prospective studies as the effects of caffeine on sleep are measured in hours but not days, weeks or years. Concerning other limitations, the Committee of Toxicity (COT) suggested in their statement from 2018 that risky behaviour among energy drink consumers and "*confounding by other dietary and life-style factors as well as psychological effects such as expectation*" might account for such findings on sleep in children (COT, 2018). Although some confounding can be expected, this statement overlooks the fact that associations reported between caffeine and sleep among children (Cusick et al., 2020; Pollak and Bright, 2003) are fully in line with effects observed in experimental studies in adults, which makes it less plausible that these associations are fully explained by such biases alone. As with all observational studies some confounding may occur, for example, through higher caffeine intake among children who have sleeping difficulties due to behavioural problems or being exposed to difficult conditions at home or in school. In our study we could address this concern in some detail by exploring associations with sleep across strata of conditions that reflect children's behaviours or well-being that could affect sleep. In those analyses we observed consistent associations, measured in both relative and absolute terms, across these strata. The consistency of our findings across these strata makes confounding by factors affecting the children's life-style, behaviour or their well-being seem less likely.

Previous surveys among adolescents vary considerably by design and reporting, making direct comparison difficult (EFSA, 2015; Vercammen et al., 2019; Verster and Koenig, 2018; VKM et al., 2019). Based on the National Health and Nutrition Examination Survey (NHANES) the prevalence of daily energy drink consumption among US adolescents (12–19 years, n = 9 911) increased from 0.4% in 2003 to 2.3% in 2016 (Vercammen et al., 2019). In comparison a total of 4.2% of our 13-15-year-old participants reported to drink at least one energy drink per day. In another large (n ~32000) survey among adolescents across 14 European countries the prevalence of energy drink consumption, defined as having one energy drink over the past year or more, was 68% (EFSA, 2015). Based on this broad definition, the mean caffeine intake from energy drinks among energy drink consumers was 24 mg/day compared to 46 mg/day in our study, where consumers were not defined as broadly.

When assessing the impact of energy drinks, the use of average intake estimates can lead to spurious conclusions. For example, by averaging consumption of different caffeine containing beverages (EFSA, 2015), EFSA concluded that the relative contribution of energy drinks to total daily caffeine exposure among adolescents across 14 different European countries was marginal (median across all countries: 0%, range: 0–13%) compared to chocolate drinks (29%, 8–92%) coffee (19%, 3–53%), tea (22%, 1–65%) and cola drinks (17%, 0–42%). This approach, which has also been used in a recent risk assessment from Norway (VKM, 2019) and in a review on caffeine intake among US adolescents (Ahluwalia and Herrick, 2015), has contributed to the widespread opinion that the contribution of caffeine from energy drinks is neglectable, and reduction in intake can best be achieved by targeting other beverages (COT, 2018; Verster and Koenig, 2018). Such use of statistics to characterise intake is, however, misleading for skewed data. That is, for energy drinks, there is a large group of non-consumers where other dietary sources fully explain caffeine intake. However, for the minority of regular energy dink consumers, relative sources of intake will inevitably differ, and conclusions on relative contributions of different caffeine sources should be evaluated specifically for this group but not diluted over the whole population. Regardless of how others have interpreted their data (EFSA, 2015; VKM et al., 2019), simple calculations show that for children and adolescents one to two servings of energy drinks per day, depending on body weight, result in exposure above the limit of no safety concern, regardless of other caffeine sources (Seifert et al., 2011).

Our study is subject to several limitation. The quantification on caffeine intake is subject to assumptions on both serving sizes and caffeine concentrations that vary considerably. Self-reported intakes are also prone to recall bias. However, the uncertainty in our estimates should be similar to those used in previous risk assessments (EFSA, 2015; VKM et al., 2019) or reviews that are either based on 24 h recalls, questions on frequency of intake as in our study, or both. At least for adults, the two methods have been shown to be relatively strongly correlated (r~0.7) (Schliep et al., 2013). Reasonable correlation (r~0.6) between self-reported caffeine intake and some metabolites of caffeine in urine (Rybak et al., 2015) have also been reported. Concerning our measures on sleep, a study in 9–17 year old US children (n = 285) comparing self-reported measures of sleep with polysomnography reported intraclass correlation of 0.7 and 0.5 for sleep duration and latency, respectively (Combs et al., 2019). Compared to the polysomnography, the children systematically overestimated their sleep duration (mean ~30 min). Although these results suggest reasonable degree of validity for self-reported sleep duration, the assessment was based on recall for a single day but not questions on average over several nights as in our study. Acknowledging the uncertainties associated with our self-reported measures, the exact values of our estimates should be interpreted with some caution.

In conclusion, in a large nationwide survey on caffeinated beverages we observed strong association between total caffeine intake and self-reported duration and difficulty falling asleep among 13 to 15-year-old Icelandic adolescents. In contrast to conclusions from previous risk assessments high caffeine intake above the limit for effects on sleep and level of no safety concern was largely explained by consumption of energy drinks. In the case of children, access and availability to many commercial products and services are restricted if they are suspected to adversely affect their well-being. Given the known dependencies and withdrawal symptoms experienced by some regular caffeine users as well as documented effects of poor sleep on children's well-being, a question can be raised concerning the intentional addition of caffeine to beverages and foods marketed to, and specifically directed at, children. This issue appears to fall outside the scope of existing food safety regulations and the fact that previous risk assessments have largely ignored this issue perhaps reflects the limitation of relying on pure toxicological principles for addressing children's wellbeing.

Authors contributions

All authors contributed actively to the design and implementation of this study. ALK, ITh and IDS were responsible for the data collection. ThiH conducted the statistical analyses. ThiH, ALK, ITh and HG contributed to the first draft of the manuscript. All authors then critically reviewed and approved the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by funding from the Icelandic Ministry of Industries and Innovation. The Ministry had no role in study design, data collection, data analysis, data interpretation, or reporting.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fct.2021.112549.

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