BJSM Online First, published on August 23, 2017 as 10.1136/bjsports-2017-097971

Sugar addiction: is it real? A narrative review

James J DiNicolantonio,[1] James H O'Keefe,[1] William L Wilson[2]

[1]Saint Luke's Mid America Heart Institute, Kansas, USA
[2]Lahey Health and the Wilson Institute of Neurobiology, Burlington, USA

Correspondence to
Dr James J DiNicolantonio, Saint Luke's Mid America Heart Institute, Kansas City, USA; jjdinicol@gmail.com

Accepted 1 August 2017

ABSTRACT

In animal studies, sugar has been found to produce more symptoms than is required to be considered an addictive substance. Animal data has shown significant overlap between the consumption of added sugars and drug-like effects, including bingeing, craving, tolerance, withdrawal, cross-sensitisation, cross-tolerance, cross-dependence, reward and opioid effects. Sugar addiction seems to be dependence to the natural endogenous opioids that get released upon sugar intake. In both animals and humans, the evidence in the literature shows substantial parallels and overlap between drugs of abuse and sugar, from the standpoint of brain neurochemistry as well as behaviour.

It has been suggested that refined added sugars are habit-forming just like cocaine, nicotine, alcohol, tobacco and caffeine.[1–3] In fact, chronic smokers suppress their cigarette cravings better than their food cravings.[4] Some individuals report increased sweet cravings after giving up cigarettes,[5] likely accounting for the typical weight gain associated with quitting smoking.[6] In fact, oral glucose may even decrease tobacco cravings[7] and withdrawal discomfort.[5] One study in cocaine-addicted individuals noted that their liking and wanting for food was even greater than that for cocaine.[8] As sweet foods are the most craved foods, this suggests that the reward and cravings from added sugars might be comparable to that of addictive substances.

Indeed, food cravings have significant overlap with drug cravings,[1–3 9] and animal studies show that sweetness, such as sugar or saccharin, is preferred even over that of addictive drugs like cocaine.[10–14] Once sugar is introduced (even in lab rats already addicted to cocaine) the rats will almost always switch over to consuming sugar. This is because the reward from sugar surpasses that of even cocaine.[2] Consuming sugar produces effects similar to that of cocaine,[15–19] altering mood,[20] possibly through its ability to induce reward and pleasure,[2] leading to the seeking out of sugar.[2] Others have shown that foods high in sugar produce drug-like psychoactive effects.[2 21–23]

A natural reward from sugar is another evolutionary adaptation, as it would have driven humans to search out and consume sugar whenever it was found in the food supply.[10 24] The increased consumption of foods high in sugar (such as ripened fruit and honey) would have increased the chances for survival during periods of food scarcity, as sugar helps us to lay down fat, and when found in nature generally indicates foods that would have provided ample amounts of calories.[24] Those individuals with the greatest fat stores likely had a strong evolutionary advantage when it comes to survival during times of food scarcity. Thus sugar cravings likely imparted a strong evolutionary advantage.

Unfortunately humans never adapted to the intense reward that follows the consumption of highly refined added sugars, and the 24/7 availability of these sugars provides us with little reprieve. In other words, we can run from sugar but we cannot hide. The most common forms of added sugar are sucrose (table sugar) and high-fructose corn syrup. Each contains the simple sugars glucose and fructose. This unnatural reward from consuming sugar (surpassing that of drugs of abuse) over-rides our self-control mechanisms predisposing us to sugar addiction.[10] Indeed, sweet substances are extremely rewarding to humans and other mammals, but there does appear to be genetic differences in the strength of this preference for sweetness.[10 25–29] And with the recent 'sweetening of the world's diet', there has followed a dramatic rise in the consumption of sugar.[30–33] Added sugars have penetrated the food supplies of virtually every isolated corner of the world.

The reason why we may not be able to give up the sweet stuff is because sweet sensations are one of the most intense sensory pleasures that humans experience in the modern day.[10] Our seeking out of sugary substances exceeds any metabolic need.[10] And there is no physiological requirement for consuming a single gram of added sugar as there is technically no such thing as an 'essential carbohydrate' (unlike that for protein or fat).[34] Nonetheless as we previously discussed, fructose consumption played a critical role in human evolution. Although individuals can clearly thrive and survive without any added sugars, the human species likely would not have survived for very long without the craving and consumption of natural sources of fructose.

The issue of attractiveness of sweets in humans is further complicated by the fact that individuals perceive sweetness differently. The tendency to experience addiction to refined sugars is likely rooted in both the sweet taste perception and the preference of each individual, likely reflecting genetic factors.[35] Thus although humans have the ability to become addicted to sugar, the tendency to do so is likely multifactorial.

DOES SUGAR BEHAVE LIKE A DRUG?

Nowadays, sugar has been refined to the state of a chemical-like substance. Indeed, when sugar cane is crushed and drained of all its liquid contents, boiled down to a syrup, shaken and then stripped of all its vitamins, minerals and molasses, we are left with pure white crystals. This extraction and refinement process is similar to that of other addictive white crystals, that is, cocaine from the coca leaf, and opium from the poppy seed/pod.[36] Thus, it is the

To cite: DiNicolantonio JJ, O'Keefe JH, Wilson WL. *Br J Sports Med* Published Online First: [*please include* Day Month Year]. doi:10.1136/bjsports-2017-097971

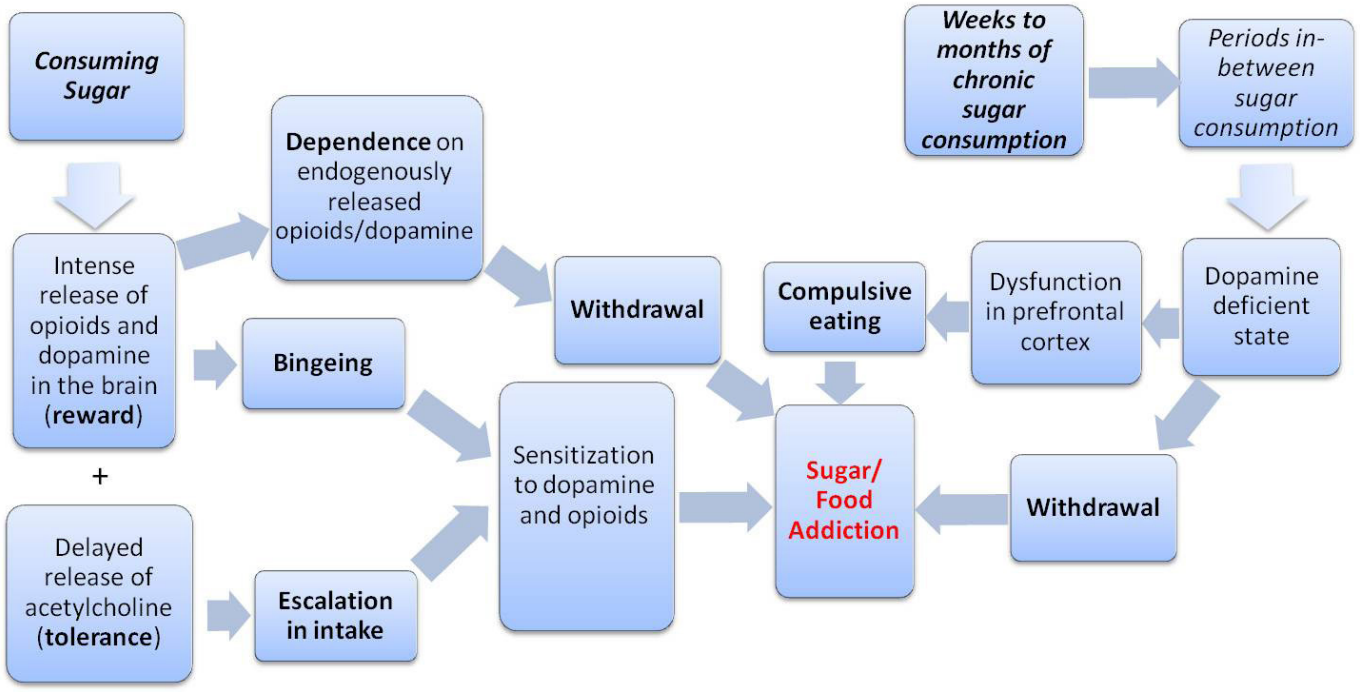

Figure 1 Schematic of sugar addiction

refinement of sugar that significantly adds to its addictive properties.

During our evolutionary history we only had access to fructose in honey, fruits and certain vegetables, and in these sources fibre and other substances are present that slow and limit the absorption of the fructose. With low levels of fructose consumption typical of our evolutionary history, about half is converted to glucose and a quarter is converted to lactate. Very little fructose is converted into fat when consumption is at a low level and fatty acid synthesis is also not upregulated. Thus throughout our evolutionary history humans consumed a small amount of fructose on a regular basis and this did not cross the fat storage threshold. It is only when they occasionally binged on fructose after finding a beehive or large supply of ripened fruit would they store extra fat. Importantly, the natural antioxidants contained in these natural foods would have decreased the formation of 'inflammatory' fat stores (unlike that with the consumption of added sugars).

But does sugar behave like a drug of abuse? It has been noted that the same increase in dopamine D1 receptor binding and decreased D2 receptor binding in the striatum that occur with cocaine administration also occur with intermittent access to sugar or glucose.[17] Rats with intermittent access to sugar also have the same decrease in D2 receptor mRNA in the nucleus accumbens that occurs with morphine and cocaine. Moreover, the same increase in μ-receptor binding that occurs with cocaine and morphine occurs with intermittent sugar intake. And finally the same release of dopamine and reduction in extracellular acetylcholine in the nucleus accumbens (indicating tolerance) that occurs with injecting morphine occurs with bingeing on sugar.[17] Figure 1 provides a schematic of sugar addiction.

The sugar–drug connection goes even further as 'addiction transfer' may occur between sugar and drugs of abuse and alcohol.[37] Some overweight patients may transfer their addiction to high-sugar foods over to addictive drugs after weight loss surgery. In one study, weight loss surgery patients who reported preweight loss surgery problems with high-sugar foods were the most likely to have new-onset substance use disorders after surgery.[37] Box 1 summarises how added sugars (refined sugar and high-fructose corn syrup) behave like drugs of abuse.

In order to understand if sugar is addictive, we need to understand drug addiction. Take for example opiate addiction, which can be diagnosed if naloxone (an opiate antagonist) produces subsequent withdrawal signs. Shockingly, this is exactly what occurs when animals are fed sugar and then given naloxone. More importantly, the withdrawal that occurs with naloxone in these animals eating sugar is similar to that found with nicotine or morphine. Sugar addiction seems to be a dependence on the body's own natural endogenous opioids that get released on sugar intake.[38] Indeed, there are substantial parallels and overlap

Box 1 How added sugars behave like addictive drugs of abuse

- Behaves like a chemical or drug—due to its 'pure' white crystalline form, which is readily absorbable leading to unique metabolic harms[1]
- Habit-forming just like alcohol, tobacco, cocaine, nicotine, tea, coffee and chocolate[1–3]
- Induces reward and cravings comparable to addictive drugs, being more rewarding than cocaine[3]
- Alters mood,[4] induces reward and pleasure,[3] leading to the seeking out of sugar[3]
- Produces drug-like psychoactive effects[3 5–7]
- Produces cravings comparable to that of cocaine, sex and cigarettes[3 8 9]
- Can produce dependence/addiction (eg, bingeing, withdrawals and cravings) indicating sugar can be addictive[10]

between drugs of abuse and sugar, from the standpoint of brain neurochemistry as well as behaviour.

So back to the question, is sugar addictive? The term addiction is generally reserved for drugs of abuse (ie, cocaine, heroin, morphine, nicotine and alcohol) and is many times used synonymously with dependence.[17] The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) defines 'substance use disorder' (ie, addiction) if at least two to three criteria (symptoms) exist from a list of 11. This was a change from DSM-IV, which categorised both substance abuse and substance dependence as separate disorders, and substance abuse only required one criterion. In DSM-5 these two categories have been combined into 'substance use disorder'. It is also interesting to note that binge eating disorder has been added to DSM-5. Sweet and high-fat foods are preferred by those with binge eating disorders and that those preferences are mediated by the endogenous opioid system.[39]

In animal models, sugar produces more symptoms (eg, cravings, bingeing, tolerance and withdrawal) than is required to be considered an addictive substance.[36] So we can be quite confident that sugar is indeed addictive in animal models. In fact, animal data demonstrate significant overlap between the consumption of added sugars and drug-like effects,[10 40–42] producing (1) *bingeing*, (2) *craving* (a strong desire to 'use'), (3) *tolerance* (gradual escalation in intake with repeated use), (4) *withdrawal* (adverse physiological signs with discontinuation of use), (5) *cross-sensitisation* (increased response to drugs of abuse), (6) *cross-tolerance* (animals become tolerant to the analgesic effects of morphine after chronic intake of sugar and saccharin),[43 44] (7) *cross-dependence* (suppression of withdrawal symptoms with certain drugs),[38 45 46] (8) *reward*[47 48] (intense dopamine release in the brain),[17 49–51] and (9) *opioid effects,* such as the release of endogenous opioids on consuming sweet substances,[44 46 52] symptoms of narcotic withdrawal when an opiate blocker is given, and other neurochemical changes in the brain.[17 36]

A person may become addicted to sugar due to dependence on his or her own endogenously released opioids.[38] This is particularly revealing when looking at patients with anorexia who may be 'addicted to starvation' by the same dependence pathway that occurs when eating sugar (ie, addiction to endogenously released opioids that occurs during starvation).[53] If anorexia can be classified as a disease, and is apparently the body's addiction to its own endogenously released opioids, then sugar addiction (dependence to endogenously released opioids on consumption of sweets) should also be able to fall under the classification of a disease.

IS SUGAR ADDICTIVE IN HUMANS?

In the purest sense, addiction is simply a psychological dependence, but also a physiological dependence to sugar.[17] While there is not a universal agreement for the definition of addiction, certain characteristics must be present in order to diagnose an addiction (ie, cravings, tolerance and withdrawal), otherwise known as the 'addiction triad'. In order for sugar to be truly considered addictive, it must be able to induce a withdrawal. And in order for humans to have withdrawals from sugar, a threshold must be reached. Thus, a certain dose of sugar needs to be consumed for a certain of time whereby neurochemical changes occur in the brain. This period of time likely varies from person to person based on genetic differences.

It just so happens that after several weeks to months of chronic sugar intake, the period in between sugar intake may cause 'dopamine deficiency' in the brain due to downregulation of the dopamine D2 receptors and a reduction in binding of dopamine to those receptors.[54] But why is dopamine deficiency in the brain a problem?

When the brain is low in dopamine, this can then lead to withdrawals. And it is the withdrawal that can lead to continued perpetual sugar intake leading to addiction. But the withdrawals from sugar are less obvious compared with addictive drugs. Indeed, people are not visibly 'strung-out' on sugar, nor do they have life-threatening or even physically apparent withdrawal signs. But this does not mean that sugar withdrawal does not exist in the brain. In fact, the lack of dopamine in the brain during periods between sugar consumption has been suggested to lead to attention deficit hyperactivity disorder (ADHD)-like symptoms such as, hyperactivity, attention-deficit, distraction and decreased performance.[54] In essence, ADHD-type symptoms could be a sign of 'withdrawal' from eating refined added sugars.

In fact, obesity, ADHD and drug addiction to cocaine and heroin all share the same downregulation of the dopamine D2 receptors in the brain. This suggests that all three conditions have the same underlying issue (dopamine deficiency). During periods off sugar, a mild state of depression may ensue due to dopamine deficiency, which can be temporarily relieved by consuming more sugar (hence the term 'sugar fix'). This leads to an endless and vicious cycle of dopamine highs and lows, perpetuating continued sugar intake and dependence on its intake.

Sugar and high glycaemic carbohydrates also have an effect on brain serotonin. After consuming a meal high in sugar or carbohydrates, there is a surge in brain serotonin. In other words, people may overconsume sugar because it makes them feel better. Over time this may lead to depletion of serotonin in the brain perpetuating sugar dependence. As we have discussed, these patients also tend to be dopamine-deficient with downregulation of dopamine receptors. This combination may well explain the association of obesity with many other brain disorders like depression, anxiety disorders, bipolar disorder and ADHD.[55]

After consuming large amounts of sugar, a drop in blood glucose may cause further sugar dependence. Throughout our evolutionary history, low blood glucose levels meant 'it's time to eat', and if given the chance it made perfect sense to eat something with sugar or starch, the fastest way to restore normal glucose levels. Ramped up hunger and sweet cravings were Mother Nature's means of accomplishing this critical task. But today with a constant supply of added sugar readily available, advocating the consumption of sugar as a treatment of low blood glucose levels may make the situation worse. Since it is now estimated that around 110 million Americans have insulin resistance,[56] much of the population could be at particular risk for sugar addiction.

SUGAR ADDICTION MIGHT PREDISPOSE TO DRUG ADDICTION

Sugar produces drug-like effects that may increase the risk for drug addiction.[17] Indeed, sugar may have a 'gateway effect' as it cross-sensitises with drugs of abuse.[17] However, these effects are not always reproducible and more work in humans is required to fully elucidate these effects. The consumption of sugar has even caused an increase in the intake of alcohol during periods of sugar abstinence.[17] Rats given daily amphetamine injections become hyperactive after tasting sugar.[17] And this occurs even when low doses of amphetamine are used. Sugar has also been found to cross-sensitise with cocaine,[17] and can lead to sensitisation to the dopamine agonist quinpirole.[17] These data suggest

that sugar consumption may sensitise the brain dopamine system, contributing to addiction and polysubstance abuse.[17] Moreover, animals that prefer sweetness will self-administer cocaine at a greater rate,[17] which may be due to sugar's dopaminergic, cholinergic, opioid-mimicking effects and stimulant-mimicking effects like dexamphetamine, methylphenidate and modafinil (although smaller in magnitude).[17]

Postingestive glucose can activate the brain dopamine reward circuit independently of sweet taste,[57] and that sweet appetite may even be stimulated by the presence of glucose in the gastrointestinal tract.[58]

Unlike drug or alcohol addiction, in general sugar addiction has little direct negative social impact on individuals or their families. Sugar addiction does have one clear impact on our collective health—it makes us fat and metabolically sick. The fructose in sucrose, honey, high-fructose corn syrup and fruits has little impact on fat storage when it is consumed in small amounts.[59] This was clearly how humans interacted with simple sugars most of the time in the past. Our ancient ancestors would binge on fruit or honey when it was available, but these episodes were clearly sporadic. In today's world with the 24/7 availability of highly processed food loaded with added sugars, these episodes of craving and bingeing would almost be constant, leading to a markedly increased intake of fructose. Excessive consumption of fructose promotes fat storage especially in the liver .[60] This supports the old adage 'the dose makes the poison'.

Based on the aforementioned evidence, sugar meets many of the criteria for a substance of abuse and could be potentially addictive in humans. Changes that occur in the brain neurochemistry with drugs are similar, although smaller in magnitude, to those that result from sugar intake. Because of the nature of addiction, simply telling people to consume less sugar is unlikely to be successful. The focus of the medical profession should be on finding treatments that suppress or eliminate these cravings. Varenicline (Chantix) is approved by the Food and Drug Administration as an aid to quitting cigarette smoking, and it also markedly decreases cravings for sugar.[61] There are a few case reports suggesting that varenicline might be effective for weight loss.

Certain supplements such as chromium picolinate and L-glutamine have been reported to curb sweet cravings, but to date research on these supplements has been limited. Chromium picolinate appears to be especially effective for patients with binge eating disorder and depression.[62] Unfortunately as is the case of many supplements, at the present time we are lacking large controlled studies using these supplements.

In conclusion, now is the time to kick the habit and say goodbye to the sweet stuff for good. Hopefully in the future we will have more effective medical treatments that will help us in this critical endeavour.

What is already known?

- Substances of abuse are acknowledged throughout the medical community to have the potential to be addictive.
- Sugar consumption has increased in parallel with its introduction in the food supply.
- Sugar may drive increased food consumption, obesity and diabetes.

What are the findings?

- Animal studies have confirmed that the reward for sugar can surpass that of cocaine.
- In animal studies, sugar produces more symptoms than is required to be considered an addictive substance.
- In animal studies there is overlap between the consumption of added sugars and drug-like effects (eg, bingeing, craving, tolerance, withdrawal, cross-sensitisation, cross-tolerance, cross-dependence, reward and opioid effects).
- Sugar addiction may be a dependence to the natural endogenous opioids that get released on sugar intake.
- In both animals and humans there are substantial parallels and overlap between drugs of abuse and sugar, from the standpoint of brain neurochemistry as well as behaviour.

Contributors JJD performed the literature search and wrote the initial manuscript. JHO'K and WLW reviewed, edited and wrote sections of the final manuscript.

Competing interests JJD is the author of The Salt Fix and operates the website thesaltfix.com WLW sells a supplement that contains both L-glutamine and chromium picolinate. JHO'K owns and operates a nutraceutical company.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1 Lustig RH. Fructose: metabolic, hedonic, and societal parallels with ethanol. *J Am Diet Assoc* 2010;110:1307–21.
2 Ahmed SH, Guillem K, Vandaele Y. Sugar addiction: pushing the drug-sugar analogy to the limit. *Curr Opin Clin Nutr Metab Care* 2013;16:434–9.
3 Snow HL. Refined sugar: its use and misuse. *The Improvement Era Magazine* 1948:51.
4 Kober H, Mende-Siedlecki P, Kross EF, *et al*. Prefrontal-striatal pathway underlies cognitive regulation of craving. *Proc Natl Acad Sci* 2010;107:14811–6.
5 Toll BA, Katulak NA, Williams-Piehota P, *et al*. Validation of a scale for the assessment of food cravings among smokers. *Appetite* 2008;50:25–32.
6 Aubin H-J, Farley A, Lycett D, *et al*. Weight gain in smokers after quitting cigarettes: meta-analysis. *BMJ* 2012;345:e4439.
7 West R, May S, McEwen A, *et al*. A randomised trial of glucose tablets to aid smoking cessation. *Psychopharmacology* 2010;207:631–5.
8 Goldstein RZ, Woicik PA, Moeller SJ, *et al*. Liking and wanting of drug and non-drug rewards in active cocaine users: the STRAP-R questionnaire. *J Psychopharmacol* 2010;24:257–66.
9 Nair SG, Adams-Deutsch T, Epstein DH, *et al*. The neuropharmacology of relapse to food seeking: methodology, main findings, and comparison with relapse to drug seeking. *Prog Neurobiol* 2009;89:18–45.
10 Lenoir M, Serre F, Cantin L, *et al*. Intense sweetness surpasses cocaine reward. *PLoS One* 2007;2:e698.
11 Augier E, Vouillac C, Ahmed SH. Diazepam promotes choice of abstinence in cocaine self-administering rats. *Addict Biol* 2012;17:378–91.
12 Cantin L, Lenoir M, Augier E, *et al*. Cocaine Is low on the value ladder of rats: possible evidence for resilience to addiction. *PLoS One* 2010;5:e11592.
13 Kerstetter KA, Ballis MA, Duffin-Lutgen S, *et al*. Sex differences in selecting between food and cocaine reinforcement are mediated by Estrogen. *Neuropsychopharmacology* 2012;37:2605–14.
14 Morales L, Del Olmo N, Valladolid-Acebes I, *et al*. Shift of circadian feeding pattern by high-fat diets Is coincident with reward deficits in obese mice. *PLoS One* 2012;7:e36139.
15 Ifland JR, Preuss HG, Marcus MT, *et al*. Refined food addiction: a classic substance use disorder. *Med Hypotheses* 2009;72:518–26.
16 Gearhardt AN, Grilo CM, DiLeone RJ, *et al*. Can food be addictive? public health and policy implications. *Addiction* 2011;106:1208–12.
17 Avena NM, Rada P, Hoebel BG. Evidence for sugar addiction: behavioral and neurochemical effects of intermittent, excessive sugar intake. *Neurosci Biobehav Rev* 2008;32:20–39.
18 Brown RJ, Rother KI. Non-nutritive sweeteners and their role in the gastrointestinal tract. *J Clin Endocrinol Metab* 2012;97:2597–605.
19 Grayson BE, Seeley RJ, Sandoval DA. Wired on sugar: the role of the CNS in the regulation of glucose homeostasis. *Nat Rev Neurosci* 2013;14:24–37.
20 Pretlow RA. Addiction to highly pleasurable food as a cause of the childhood obesity epidemic: a qualitative internet study. *Eat Disord* 2011;19:295–307.
21 Rose N, Koperski S, Golomb BA. Mood food: chocolate and depressive symptoms in a cross-sectional analysis. *Arch Intern Med* 2010;170:699–703.

22 Dallman MF. Stress-induced obesity and the emotional nervous system. *Trends in Endocrinology & Metabolism* 2010;21:159–65.
23 Spring B, Schneider K, Smith M, *et al*. Abuse potential of carbohydrates for overweight carbohydrate cravers. *Psychopharmacology* 2008;197:637–47.
24 Johnson RJ, Andrews P, Benner SA, *et al*. Theodore E. Woodward Award: the evolution of obesity: insights from the mid-miocene. *Trans Am Clin Climatol Assoc* 2010;121:295–308.
25 Steiner JE. Human facial expressions in response to taste and smell stimulation. *Adv Child Dev Behav* 1979;13:257–95.
26 Drewnowski A. Taste preferences and food intake. *Annu Rev Nutr* 1997;17:237–53.
27 Berridge KC. Food reward: brain substrates of wanting and liking. *Neurosci & Rev* 1996;20:1–25.
28 Sclafani A. Oral and postoral determinants of food reward. *Physiol Behav* 2004;81:773–9.
29 Keskitalo K, Knaapila A, Kallela M, *et al*. Sweet taste preferences are partly genetically determined: identification of a trait locus on chromosome 16. *Am J Clin Nutr* 2007;86:55–63.
30 Bray GA, Nielsen SJ, Popkin BM. Consumption of high-fructose corn syrup in beverages may play a role in the epidemic of obesity. *Am J Clin Nutr* 2004;79:537–43.
31 Bray GA, Popkin BM. Dietary sugar and body weight: have we reached a crisis in the epidemic of obesity and diabetes?: health be damned! Pour on the sugar. *Diabetes Care* 2014;37:950–6.
32 Malik VS, Popkin BM, Bray GA, *et al*. Sugar-sweetened beverages and risk of metabolic syndrome and type 2 diabetes: a meta-analysis. *Diabetes Care* 2010;33:2477–83.
33 Popkin BM, Nielsen SJ. The sweetening of the world's diet. *Obes Res* 2003;11:1325–32.
34 Westman EC. Is dietary carbohydrate essential for human nutrition? *Am J Clin Nutr* 2002;75:951–3.
35 Reed DR, McDaniel AH. The human sweet tooth. *BMC Oral Health* 2006;6:S17.
36 DiNicolantonio JJ, Lucan SC, Season S. *It's Everywhere and Addictive*: The New York Times, 2014.
37 Fowler L, Ivezaj V, Saules KK. Problematic intake of high-sugar/low-fat and high glycemic index foods by bariatric patients is associated with development of post-surgical new onset substance use disorders. *Eat Behav* 2014;15:505–8.
38 Colantuoni C, Rada P, McCarthy J, *et al*. Evidence that intermittent, excessive sugar intake causes endogenous opioid dependence. *Obes Res* 2002;10:478–88.
39 Yanovski S. Sugar and fat: cravings and aversions. *J Nutr* 2003;133:835s–7.
40 Kelley AE. Memory and addiction: shared neural circuitry and molecular mechanisms. *Neuron* 2004;44:161–79.
41 Levine AS, Kotz CM, Gosnell BA. Sugars: hedonic aspects, neuroregulation, and energy balance. *Am J Clin Nutr* 2003;78:834s–42.
42 Volkow ND, Wise RA. How can drug addiction help us understand obesity? *Nat Neurosci* 2005;8:555–60.
43 D'Anci KE, Kanarek RB, Marks-Kaufman R. Duration of sucrose availability differentially alters morphine-induced analgesia in rats. *Pharmacol Biochem Behav* 1996;54:693–7.
44 Lieblich I, Cohen E, Ganchrow JR, *et al*. Morphine tolerance in genetically selected rats induced by chronically elevated saccharin intake.*Science* 1983;221:871–3.
45 Rudski J, Billington CJ, Levine AS. A sucrose-based maintenance diet increases sensitivity to appetite suppressant effects of naloxone. *Pharmacol Biochem Behav* 1997;58:679–82.
46 Kanarek RB, Mathes WF, Heisler LK, *et al*. Prior exposure to palatable solutions enhances the effects of naltrexone on food intake in rats. *Pharmacol Biochem Behav* 1997;57:377–81.
47 Volkow ND, Fowler JS, Wang GJ, *et al*. Imaging dopamine's role in drug abuse and addiction. *Neuropharmacology* 2009;56:3–8.
48 Dopamine WRA. learning and motivation. *Nat Rev Neurosci* 2004;5:483–94.
49 Hajnal A, Smith GP, Norgren R. Oral sucrose stimulation increases accumbens dopamine in the rat. *Am J Physiol Regul Integr Comp Physiol* 2004;286:31R–7.
50 Pontieri FE, Tanda G, Orzi F, *et al*. Effects of nicotine on the nucleus accumbens and similarity to those of addictive drugs. *Nature* 1996;382:255–7.
51 Di Chiara G, Imperato A. Drugs abused by humans preferentially increase synaptic dopamine concentrations in the mesolimbic system of freely moving rats. *Proc Natl Acad Sci U S A* 1988;85:5274–8.
52 Cohen E, Lieblich I, Bergmann F. Effects of chronically elevated intake of different concentrations of saccharin on morphine tolerance in genetically selected rats. *Physiol Behav* 1984;32:1041–3.
53 Aravich PF, Rieg TS, Lauterio TJ, *et al*. β-endorphin and dynorphin abnormalities in rats subjected to exercise and restricted feeding: relationship to anorexia nervosa? *Brain Res* 1993;622:1–8.
54 Johnson RJ, Gold MS, Johnson DR, *et al*. Attention-deficit/hyperactivity disorder: is it time to reappraise the role of sugar consumption? *Postgrad Med* 2011;123:39–49.
55 Wurtman RJ, Wurtman JJ. Brain serotonin, carbohydrate-craving, obesity and depression. *Obes Res* 1995;3:477S–80.
56 DiNicolantonio JJ, O'Keefe JH, Lucan SC. Added fructose: a principal driver of type 2 diabetes mellitus and its consequences. *Mayo Clin Proc* 2015;90:372–81.
57 Tellez LA, Han W, Zhang X, *et al*. Separate circuitries encode the hedonic and nutritional values of sugar. *Nat Neurosci* 2016;19:465–70.
58 Han W, Tellez LA, Niu J, *et al*. Striatal dopamine links gastrointestinal rerouting to altered sweet appetite. *Cell Metab* 2016;23:103–12.
59 Sun SZ, Empie MW. Fructose metabolism in humans – what isotopic tracer studies tell us. *Nutr Metab* 2012;9:89.
60 Schwarz JM, Noworolski SM, Erkin-Cakmak A, *et al*. Effects of dietary fructose restriction on liver fat, De Novo Lipogenesis, and insulin kinetics in children with obesity. *Gastroenterology* 2017.
61 Shariff M, Quik M, Holgate J, *et al*. Neuronal nicotinic acetylcholine receptor modulators reduce sugar intake. *PLoS One* 2016;11:e0150270.
62 Brownley KA, Boettiger CA, Young L, *et al*. Dietary chromium supplementation for targeted treatment of diabetes patients with comorbid depression and binge eating. *Med Hypotheses* 2015;85:45–8.

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Br J Sports Med published online August 23, 2017

Notes