Title: Can Taste be Ergogenic?

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Abstract

Taste is a homeostatic function that conveys valuable information such as energy density, readiness to eat, or toxicity of foodstuffs. Taste is not limited to the oral cavity but affects multiple physiological systems. In this review, we outline the ergogenic potential of substances that impart bitter, sweet, hot and cold tastes administered prior to and during exercise performance and whether the ergogenic benefits of taste are attributable to the placebo effect. Carbohydrate mouth rinsing seemingly improves endurance performance, along with a potentially ergogenic effect of oral exposure to both bitter tastants and caffeine – although subsequent ingestion of bitter mouth rinses is likely required to enhance performance. Hot and cold tastes may prove beneficial in circumstances where athletes' thermal state may be challenged. Efficacy is not limited to taste, but extends to the stimulation of targeted receptors in the oral cavity and throughout the digestive tract, relaying signals pertaining to energy availability and temperature to appropriate neural centres. Dose, frequency and timing of tastant application likely require personalisation to be most effective, and can be enhanced or confounded by factors that relate to the placebo effect, highlighting taste as a critical factor in designing and administering applied sports science interventions.

Keywords

Taste, Carbohydrate, Caffeine, Menthol, Capsaicin, Bitter

1. Introduction

Taste is a homeostatic function that aids in deciding what to eat, and acts as a precursor for digestion [1]. Human taste and preferences are evolved due to nutrient availabilities within our ancestral environments [2], where they conveyed information such as energy density, readiness to eat, or toxicity [1,3]. Despite being the area most densely populated with taste receptors, taste is not strictly confined to the oral cavity, but frequently incorporates other sensory inputs from the upper digestive tract and auditory, olfactory and visual systems [1,4-9]. This is most evident in those who suffer with ageusia (loss of taste), or anosmia (loss of smell), and still respond physiologically to tastes [3,10], demonstrating taste as a chemical interaction between a chemesthetic agent and receptors, which drives either ingestion or aversion and accompanying hedonic sensations.

Assessment of the physiological responses to taste has not escaped sports scientists, with many 'tastes' now investigated within the literature [11-15] with a view to attenuating fatigue or improving physical or cognitive performance. Depending upon the tastant investigated, impressions of energy availability [16,17], thermal perceptions [11,12,18] and central drive [15,19] may be altered. Secondary outcomes may also include modifications in autonomic function [20-22], thirst [23,24] and ventilation [25-27], with further downstream effects depending upon whether tastants are ingested or simply rinsed around the oral cavity and expectorated.

These outcomes are likely useful to athletes, but depend heavily upon their exercise modality, prior exposure to and preference for specific tastants, as well as the availability of tastants during an exercise bout. Placebo effects associated with tastants cannot be excluded, and indeed may be maximised by including a carefully chosen taste component in personalised sports nutrition interventions, or matching tastes of interventions to other sensory expectations such as colour [28,29]. Previous work has asked whether "the [central] governor has a sweet tooth" [14]; in this review, we explore the ergogenic potential of different tastes administered prior to and during exercise performance. We also raise the question of whether the ergogenic benefits of taste are attributable to the placebo effect. Recommendations for athletes and practitioners, and future research directions are also provided throughout.

2. Sweet and Bitter Tastants and Athletic Performance

2.1 Carbohydrate

The efficacy of carbohydrates as a means of supporting endurance performance is well established [30]. However, a clear, over-riding mechanism by which carbohydrate enhances performance is currently unknown; during exercise, only about a quarter of ingested carbohydrate enters peripheral circulation [31], with exogenous carbohydrate demonstrated to contribute only a small proportion of the carbohydrate oxidised during the late stages of prolonged exercise [32]. This lack of a clear metabolic mechanism lead to speculation that the consumption of carbohydrates during exercise may stimulate central pathways associated with sensations of reward or energy availability, which in turn has a performance-enhancing effect [33]. To test this hypothesis, researchers allowed subjects to rinse a carbohydrate solution around the mouth, but not ingest it, removing the metabolic effects of carbohydrate on performance. In the last decade, an exponential increase in research on this topic has been carried out, with a number of reviews [14,33-36] demonstrating a clear ergogenic effect of a carbohydrate mouth rinse on endurance performance, particularly in glycogen depleted participants.

Given that little carbohydrate is absorbed in the oral activity during mouth rinsing, the mechanism(s) by which carbohydrate mouth-rinses enhance performance are likely central in nature [14]. The tongue contains a number of taste receptors capable of detecting sweet stimuli [37] and these taste receptors when stimulated activate dopaminergic pathways and reward centres within the brain [17,38]. In turn, this increase in reward may enhance motivation to exercise, allowing the athlete to self-select higher exercise intensities, and reducing the impact of peripheral fatigue-associated signals under both the Central Governor [39] and psychobiological [40] models of fatigue. There may also be a feed-forward effect, whereby the activation of oral carbohydrate receptors suggests that energy is being consumed, allowing for an increase in exercise intensity, although this hypothesis has yet to be experimentally tested.

At present, it appears that the ergogenic effects of a carbohydrate mouth-rinse are not taste related *per se*. This is demonstrated by the fact tasteless carbohydrates, such as maltodextrin, are ergogenic in a mouth-rinse solution [35], and also activate brain regions similarly to sweet tasting carbohydrates such as sucrose [17]. Similarly, artificial sweeteners provide a sweet taste, but a far smaller activation of key brain regions compared to sucrose [41]. Accordingly, it seems likely that it is the carbohydrate binding to as-of-yet unidentified oral carbohydrate receptors, as opposed to taste itself, that drives the ergogenic effects of a carbohydrate mouth rinse [14].

2.2 Bitter tastants

Building on the potential ergogenic effects of a sweet taste, as mediated by carbohydrate rinsing (detailed in section 2.1), Gam and colleagues explored the use of bitter tastants on exercise performance (reviewed in Gam et al., [19]). The potential relationship between bitter taste and enhanced exercise performance has a strong molecular underpinning, given that bitter tastants activate similar areas of the brain as sweet tastes [42], with these brain areas being implicated in aspects such as motor control and the processing of emotions [19].

In their first study exploring the ergogenic effects of a bitter tastant, Gam and colleagues [43] administered 14 competitive male cyclists with a bitter solution containing 2 mM quinine, which was rinsed in the mouth for 10 seconds, and then ingested. The quinine solution enhanced mean power output in a 30-second maximum cycle by 2.4% compared to an aspartame (sweet taste) mouth, and by 3.9% compared to water. In a subsequent study [44], a stronger concentration (10 mM) of quinine was utilised, but the solution was only rinsed around the mouth, and not ingested. In this scenario, there was no ergogenic effect of the bitter solution on a 30-s cycle sprint, suggesting that the ingestion of the bitter solution is potentially important. The proposed mechanism underpinning the need for ingestion is that there are an increased number of bitter taste receptors beyond the oral cavity in the upper gastrointestinal tract [45] which are not activated following mouth rinse only. Outside the work of Gam and colleagues [43,44,46], there is little additional research exploring the ergogenic effects of a bitter tastant, and so

114 further research in this area is warranted. This would be particularly pertinent from a practical approach,
115 with strong bitter tastants—such as those used in the research by Gam and colleagues—able to induce
116 nausea in some subjects upon ingestion [43]; given this information, further research exploring the
117 optimal intensity of the bitter taste would likely be very useful.

118

119 *2.3 Caffeine*

120 Given the demonstrated ergogenic effects of an ingested bitter tastant [43,46], Pickering [15] recently
121 reviewed whether caffeine—itself a bitter tastant [47] that has been shown to activate bitter taste
122 receptors located in the oral cavity [48]—exerted some of it's well established ergogenic effects [49]
123 via its bitter taste. A small number of studies [50-56] have utilised a caffeine mouth rinsing protocol as
124 a method to enhance performance. Studies that demonstrated an ergogenic effect employed a repeated
125 6-s Wingate sprint protocol [50,53], or a self-paced endurance effort over 30-minutes [56]; whereas
126 investigations that showed no effect employed either fixed work rate [51], progressive running [55] or
127 repetitions to failure [52] models. Whilst the results are currently equivocal, there is a trend for no
128 demonstrated performance enhancement when caffeine is rinsed around the mouth for both endurance
129 and high-intensity exercise [15]. The reasons for this are currently unclear; it may be that caffeine's
130 bitter taste is not ergogenic, that the caffeine solutions utilised were not sufficiently bitter to evoke an
131 ergogenic effect, or that like quinine [44], ingestion of caffeine is required for its bitter taste to be
132 ergogenic [54]. However, caffeine mouth rinses have been demonstrated to improve cognitive function
133 during exercise [57] and limit mental fatigue [58] suggesting that there might be psychological
134 ergogenic effect of caffeine mouth rinses—and therefore potentially caffeine's bitter taste—for future
135 research to uncover.

136

137 *2.4 Sweet and Bitter Tastes Section Summary*

138 Based on the research discussed here, there is a clear ergogenic effect of carbohydrate mouth rinsing on
139 endurance performance [14], along with a potentially ergogenic effect of oral exposure to both bitter

tastants [19] and caffeine [15] – although in the latter two cases, subsequent ingestion of the mouth rinse is likely required to enhance performance. Regarding bitter tastants, it is believed that this subsequent ingestion is required in order to further stimulate bitter taste receptors in the upper gastrointestinal tract [44]. These bitter taste receptors are not necessarily linked to gustatory neurons [59], meaning that this activation is not associated with "tasting" the bitterness. Additionally, tasteless carbohydrates evoke an identical ergogenic effect as sweet carbohydrates in a mouth rinse [35], whilst sweet tasting artificial sweeteners do not [33]. As such, it is important to note that the sensation of a particular taste may not be driving these ergogenic effects, but instead it is likely the stimulation of other receptors, which in turn act centrally to enhance performance [14].

3. Thermal Tastants and athletic performance

3.1 Chilli and Capsaicin

For millennia, humans have included spices such as chili peppers in their diets, experiencing and often enduring the associated pungent sensation of oral heat [60,61]. Mechanistically the sensation of increased temperature derives from the interaction between the compound capsaicin (8-methyl-N-vanillyl-6-nonenamide), and transient receptor potential vanilloid-1 proteins (TRPV1) [62]. TRPV1 is also stimulated when temperatures are elevated [63], hence foods containing capsaicin are perceived as being hot [62]. This perceptual heat is not limited to taste, with capsaicin also used in topical ointments, patches and sprays as a temporary but targeted analgesic [61]. The application of which is widely used by recreational and elite athletes to reduce joint and muscle pain, whereas the possible ergogenic properties of capsaicin taste and ingestion is an emerging field.

To date only four studies have investigated the ergogenic properties of capsaicin ingestion [64-66] or mouth swilling [12] in humans, and as such an array of protocols, dosages and performance measures have been assessed. Three studies have investigated the effect of acute supplementation of capsaicin (12mg), 45-minutes prior to athletic performance; 1500m running time trial [65], four sets of 70% 1RM

repeated squats to failure [13], and time to exhaustion during repeated 15 second treadmill running at 120% VO_{2Peak} with 15-second rest intervals [66]. Capsaicin supplementation improved 1500-m time trial performance (CAP 371.6 ±40.8 seconds vs. Pla 376.7 ± 39 seconds), total mass lifted (CAP 3,919.4 ± 1,227.4 kg vs. Pla 3,179.6 ± 942.4 kg) and time to exhaustion (CAP 1530 ± 515 seconds vs. Pla 1342 ± 446 seconds) compared to placebo. RPE was also significantly lower, although no differences in blood lactate were shown [13,65]. Researchers suggested that capsaicin supplementation may have stimulated activation of TRPV1 in skeletal muscle increasing calcium release at the sarcoplasmic reticulum; a phenomenon seen in rodent studies [67]. This increased influx of calcium may have resulted in greater actin and myosin interactions leading to improved performance. Alternatively, capsaicin has been shown to have an analgesic effect [61], which may have lowered RPE values and facilitated performance [13]. Increased endurance capabilities may also be facilitated by spared glycogen and concomitant increases in lipolysis through capsaicin ingestion [68-70].

The above literature suggests that ingesting capsaicin as a capsule is effective for improving sport performance. However, when capsaicin is ingested as food, the ergogenic effects are not consistent. A 7-day ingestion of cayenne herbal supplement totalling 25.8 $mg.day^{-1}$ of capsaicin, did not result in improved 30m sprint times, nor a reduction in RPE or muscle soreness scores [64]. Whereas, Lim *et al.*, [71] showed the ingestion of 10g of hot red peppers 2.5 hours prior to exercise (150w cycling for 60 minutes) significantly elevated both respiratory quotient and blood lactate levels at rest and during exercise, suggesting increased carbohydrate oxidation. The differences in supplementation type (cayenne vs. red peppers), dose amount (25.8 vs. 12 mg) and protocol (repeated vs. acute) likely contributed to the variation in efficacy; the higher dose in particular, may negatively influence GI motility[13]. This is supported by a rodent study that found swimming endurance was optimal when mice were supplemented with 10mg/kg, 2 hours prior to performance [72]. This dose and ingestion timing appear to be a ‘sweet-spot’, with doses or timings that fall below or exceed these values proving ineffective or deleterious to performance, respectively [73]. It should be noted that a similar dosage in

192 a human diet would equate to 100g of red chilli pepper consumption [74], which would be impractical
193 and likely cause serious gastrointestinal (GI) discomfort [69].

194

195 As TRPV1 receptors are found in the oesophagus, stomach, intestine and colon [75], the possibility of
196 GI discomfort is increased following capsaicin consumption. In a study where participants ingested
197 capsaicin capsules, moderate visceral pain was reported following a median dose of 1mg [76]. Opheim
198 & Rankin's [64] repeated sprint study reported GI distress symptoms increased 6.3 times compared to
199 placebo and resulted in 3 participants withdrawing from the study [64], thus capsaicin induced GI
200 discomfort may deleteriously affect performance. A possible solution may be the use of a unique variety
201 of chili pepper, CH-19 Sweet, which contains capsiate, a non-pungent capsaicin analogue that has been
202 shown to activate TRPV1 [69,77] and return similar responses as capsaicin, including improving time
203 to exhaustion in rodent studies [69,74]. Haramizu et al., [69] also observed no aversion to capsiate
204 ingestion; like carbohydrate, efficacy of capsaicin supplementation may be less about the taste of the
205 intervention, and more about the activation of desired receptors.

206

207 In each of the aforementioned human studies [64-66], capsaicin was delivered via a capsule. As
208 a result, receptors in the oral cavity were by-passed, eliminating capsaicin's pungent oral
209 sensation. Recently, Gibson *et al*., [12], employed a 0.2% capsaicin mouth swill every 10-minutes
210 during repeated 6-second cycle ergometer sprints in the heat (40°C, 40% relative humidity). This
211 delivery method (mouth swill) directly targets TRPV1 channels in the mouth and reduces possible GI
212 discomfort; yet, results showed no difference in peak power, work performed or RPE across
213 experimental groups (control, placebo, menthol and capsaicin mouth swills). Interestingly, thermal
214 perception (comfort and sensation) was not altered after capsaicin mouth swill compared to control and
215 placebo, but menthol trials reported significant improvements in thermal comfort [12].

216 Despite many reported health benefits from the regular consumption of capsaicin (e.g. improved
217 cardiovascular function, diabetes control, etc. [61]), the effect of capsaicin on sports performance is

limited. It would appear that acute supplementation (45-minutes prior to exercise) of low dose capsaicin (12mg) may induce an ergogenic response in near maximal exercise [65,66]. Further investigation on precise timing, dosage and delivery methods are required. Minimising GI discomfort should be a primary consideration for researchers while still effectively stimulating TRPV1 channels.

3.2 Menthol

Menthol imparts its familiar minty flavour via stimulation of transient receptor melastatin 8 (TRP-M8) receptors. These sodium voltage gated ion channels are especially concentrated in the trigeminal nerve , which innervates the oral cavity, and when stimulated mimic a 'cold' temperature range (8-28ºC; [78]), feeling and tasting 'cool'. The effects of menthol are inversely proportional to the thickness of the stratum corneum [11,79], hence application to the oral cavity often confers a greater stimulatory effect than topical menthol application [11,80]. Menthol can be experienced by anosmic individuals [81], emphasising its neurological mechanism [82,83], but the ability to detect menthol has been shown to decline with age [84] suggesting higher menthol concentrations may be required to elicit ergogenic effects in masters athletes.

Menthol application to the oral cavity can be individualised by using a preferred menthol concentration and may be enhanced by using colour [29]. A relative dose is yet to be administered to athletes, but an experimental dose of 30mg/kg was prescribed by food scientists investigating the effects of carbonation and menthol upon oral cooling [85]. Partnering menthol's chemosensory cooling effects with physiological coolants such as ice slurries may further enhance its efficacy [86-88], but there is an increased risk for overstimulation of the trigeminal system potentially resulting in "brain freeze" [89-91].

Performance literature to date has assessed the effects of menthol mouth swilling upon cycling in intermittent [12] and time to exhaustion [25,26,92] models, as well as running time trial performance [27,93]. Intermittent performance was not improved, however time to exhaustion and time trial performance demonstrate *trivial-moderate* improvements (Hedge's *g*: 0.40; 0.04 – 0.76 [18]).

Concomitant improvements in thermal comfort and thermal sensation are noted following menthol exposure [12,25,27,92,93], with an increase in ventilation also reported [25-27]. These effects are likely mediated by TRP-M8 expression and stimulation of jugular and nodose neurons which provide interoceptive feedback from the alimentary organs and the cardiorespiratory system [94,95]. This may explain the increase in ventilation seen with menthol mouth swilling. The rate and volume of airflow passing through the nasal canal also increase TRP-M8 activity and ventilation [96-98]. Whilst this can be contrived in the laboratory, it is likely that this effect is more apparent in ecologically valid settings with faster wind and performance velocities.

Despite participants reporting feeling cooler, no changes in body temperature have been reported to date following the oral application of menthol exclusively [12,25-27,92,93]. An emerging secondary effect of menthol use is an attenuation of thirst [23], however the potential ergogenic and contextual relevance of this is unknown as of yet, highlighting that menthol should be applied to sport cautiously. Thirst, more so than taste, conveys a homeostatic message regarding hydration status [99,100]; however, thirst can also be quenched by carbonated and cool/cold products [85,100-103] emphasising the role of TRP-M8 receptors in our somatosensory interpretation of cool and refreshing [104-107] and the potential for deception driven dehydration if water intake is attenuated in an event where hydration status is performance limiting e.g. ultramarathon [108,109], or in athletes with abnormally high sweat rates [110].

3.3 Thermal Tastants Section Summary

Whilst the research pertaining to the TRP channel afferents capsaicin and menthol is in its infancy, in comparison to caffeine and carbohydrate, these thermal tastes may prove ergogenic under certain circumstances and likely serve to disrupt an athlete's perception of their thermal state, which may be ergogenic of itself. Individual sensory thresholds for effective doses likely exist, and timing of administration requires further elucidation, with the potential impact of these strategies on GI discomfort an important consideration. What is clear though, is that if capsaicin and menthol are to be

supplemented, attaining meaningful doses via wholefoods would either be impractical or ineffective [73,111]

4. The sweet taste of placebo

The ergogenic effect of taste could be influenced by the placebo effect. The placebo effect is a desirable outcome resulting from a person's expected and/or learned response to a treatment or situation [28]. Placebo effects have shown to improve sport performance [112-114], with a systematic review reporting small to moderate effects for nutritional (d = 0.35) and mechanical (d = 0.47) ergogenic aids [115]. Placebo effects are often created within a psychosocial context that influences a person's response to a placebo. These include the interaction between the person receiving the placebo and the person administering it (e.g. participant and researcher), the environment in which it is delivered (e.g. laboratory) and sensory processes, such as colour, smell and taste [28]. The placebo effect is therefore a response to a signal, or set of signals, which convey information that trigger self-regulatory mechanisms.

While there are many theories to propose the underpinning mechanisms of the placebo effect (e.g. expectancy theory, classical conditioning), in this paper we adopt a broader and general conception that the placebo effect of taste could be explained through an anticipation on resource allocation. Beedie *et al.*, [116] recently argued that the brain modulates and anticipates the relationship between a signal (e.g. taste) and the body, which regulates subsequent resource allocation. Based on this understanding, the taste of glucose, for example, signals to the brain that resources will soon be available, which in turn, regulates the resources allocated. Theoretically, if a placebo tastes like glucose, the brain would anticipate that glucose has been received and subsequently offloads more resources. In short, the placebo effect may impact the ergogenic effect of taste through its application of signalling to the brain

that more resources are available, which sets in motion a chain of self-regulatory responses that produce an improvement in performance[1].

Research into taste and the placebo effect on sport performance is limited. However, early research into the placebo effect provides compelling evidence of the significant role taste can have for inducing placebo effects and influencing physiological responses. Ader and Cohen [119] administered a distinctly flavoured drink followed by a toxic agent capable of suppressing the immune system. After repeat administrations of the drink and toxic agent, the taste of the drink alone resulted in an immunosuppression response. Similarly, Olness and Ader [120] reported a clinical case study of a child with lupus erythematosus (an autoimmune disease) after administering cyclophosphamide paired with taste and smell stimuli similar to Ader and Cohen [119]. After initial pairings of the drug with the sensory stimuli, the taste alone was administered and the patient's symptoms improved after 12 months. The publication of these studies resulted in a proliferation of similar taste aversion research [121], which has demonstrated the influence of taste and anticipatory responses in inducing placebo effects.

It is likely that placebo effects of taste are mediated by neurobiological pathways. While there are many neurobiological pathways associated with the placebo effect, a large amount of research has investigated the role of the endogenous opioid system [122]. This is not surprising given that μ-opioid receptors are located throughout the brain are critical for the reduction of pain [123]. Amanzio and Benedetti [124] exposed participants to a conditioning procedure of the opioid drug buprenorphine and measured pain tolerance and endogenous opioid release in the brain. After repeat trials of the opioid drug, when replaced with saline, pain tolerance significantly increased compared to baseline, which was mediated by increases in activation of the endogenous opioid system. Similar results have been reported

[1] Providing an explanation for why this occurs is outside the scope of the paper, but we refer the reader to the work of Humphrey [117] and Miller, Colloca and Kaptchuk [118], who offer a more thorough explanation.

313 elsewhere [125,126], and highlight the significant mediating role the endogenous opioid system has for
314 inducing placebo effects.

315 Like placebo effects, taste receptors can also mediate the release of endogenous opioids [127,128].
316 Although the magnitude of the effect can depend on age and gender[129], the sweet taste of glucose
317 and sucrose can modulate the production of endogenous opioid release [130], whereas administration
318 of sucrose directly to the stomach has no effect [131]. This suggests that sweet taste can have analgesic
319 effects. However, where the ergogenic effects of taste tend to report pain relieving effects, placebo
320 effects are often the result of similar mechanisms e.g. pain, fatigue and perception of effort
321 [113,114,132]. While taste could have direct neurobiological mechanisms, there is evidence that
322 placebo effects can mimic the neurobiological pathways of a treatment [133]. It could be suggested that
323 the same pathways activated by taste are also activated by the administration of a placebo. We are by
324 no means implying that the ergogenic effects of taste are the result of a placebo effect, but we, like
325 others [28,134,135], are suggesting that the mechanisms in which a nutritional ergogenic aid exerts it
326 effect is likely to be a combination of both. As with most treatments and interventions on sport
327 performance, the ergogenic effect of taste will be influenced via the placebo effect (see Beedie, Foad &
328 Hurst [134]). It is likely that they are both components of a self-regulatory system that act as signals to
329 the brain for resource allocation, which are likely mediated by neurobiological pathways, such as the
330 endogenous opioid system. However, there is a lack of research in sport explicitly examining whether
331 the ergogenic effect of taste and the placebo effect activate shared or distinct mechanisms. To help
332 develop knowledge and understanding in this area beyond speculation, empirical research is needed
333 that examines whether the placebo effect of taste is partially or fully responsible for its ergogenic effect.

334 **5. Practical Recommendations**

335 Tastants have the potential to be employed as ergogenic strategies during sport and exercise
336 performance, with tentative evidence supporting the efficacy of sweet [14], bitter [19], spicy [65], and
337 cooling [11] tastants. However, consideration of event demands, nutritional state of the athlete and
338 athletes' performance environment are strongly recommended to successfully employ taste related
339 strategies in athletic settings. Developing taste related strategies with regular input from athletes also

allows for maximisation of other sensory factors such as colour and odour, which may confer further psychological and performance benefits through placebo effects. At present, given the evidence discussed, we can tentatively suggest that athletes undertaking aerobic endurance and/or repeated high intensity efforts may benefit from the use of sweet-tasting carbohydrate or bitter-tasting beverages, with the addition of caffeine. Similar to carbohydrate and bitter tastants, athletes may benefit from menthol supplementation during endurance exercise, whereas capsaicin ingestion may be of use during activities that are near maximal in nature. Menthol may be administered as a mouth rinse, at concentrations between 0.01% and 0.1% [29] and can be employed throughout the exercise bout. Capsaicin may be ingested as a capsule containing a 12mg dose, 45 minutes prior to maximal effort exercise. All strategies should be trialled prior to use in competition, and the potential for GI disturbance using a validated tool [136]. In using these beverages, there may be additional advantages—and no obvious negatives—gained by the athlete from rinsing the liquid around the oral cavity prior to ingestion. Furthermore, augmented ergogenic effects may occur if the athlete recognises a taste as performance-enhancing via expectancy and placebo effects [15].

6. Future Research Directions

Future research in taste and athletic performance should consider investigating differences between tasting, swilling and ingesting, and their subsequent effects upon performance; this is especially important given the emerging research that ingestion of bitter tastants such as quinine and caffeine is required to maximise their ergogenic effects above those demonstrated through mouth-rinse only [15] Each strategy exposes tastants to different densities and volumes of taste receptors, and may be accompanied by other sports nutrition strategies, so the inclusion of tastants need to be weighed against established ergogenic strategies such as maintaining carbohydrate availability during an event. The optimal dose of each tastant, including their physiological tolerance and associated side-effects, also represent an important practical avenue for future research. Similarly, habituation to tastants is also worthy of investigation, as we must understand the time course of these strategies to maximise their efficacy. It is acknowledged that there is likely a strong genetic underpinning to preference and responses to tastes [137,138]. Some work has already begun in caffeine [139,140], carbohydrate

[141,142] and TRP-M8 [143], but understanding the genetic contributions to liking, or tolerance for, thermal tastes and bitterness may confer further benefits beyond athletic populations.

7. Conclusion

This review synthesises the evidence from a variety of tastes that have shown ergogenic promise with respect to athletic performance. This efficacy is not limited to taste *per se*, but extends to the stimulation of targeted receptors in the oral cavity and throughout the digestive tract, which relay signals pertaining to energy availability and temperature to appropriate neural centres. Timing of tastant application, dose and frequency of application likely require personalisation to be most effective, and can be enhanced or confounded by factors that relate to the placebo effect.

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