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Title: Endurance performance is influenced by perceptions of pain and temperature: Theory, applications and safety considerations.

Running Head: Perceptions of pain and temperature influence performance

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Abstract

Models of endurance performance now recognise input from the brain, including an athlete's ability to cope with various non-pleasurable perceptions during exercise, such as pain and temperature. Exercise training can reduce perceptions of both pain and temperature over time, partly explaining why athletes generally have a higher pain tolerance, despite a similar pain threshold, compared to active controls. Several strategies with varying efficacy may ameliorate the perceptions of pain (e.g. acetaminophen, transcranial direct current stimulation and transcutaneous electrical stimulation) and temperature (e.g. menthol beverages, topical menthol products and other cooling strategies, especially those targeting the head) during exercise to improve athletic performance. This review describes both the theory and practical applications of these interventions in the endurance sport setting, as well as the potentially harmful health consequences of their use.

Key Points

*Athletes generally have a higher pain tolerance, despite a similar pain threshold, compared to active controls.

*Acetaminophen ingestion and transcutaneous electrical stimulation have been demonstrated to significantly decrease pain and improve endurance performance/capacity, but no data exist in elite populations.

*Endurance performance can be influenced by thermal perceptions independently of any changes in physical body temperature.

*Cooling strategies that induce large perceptual cooling effects and have practical application in endurance competition are ergogenic for athletes competing in the heat.

*Practitioners and athletes should deliberate on the ethical and safety considerations of strategies that override homeostatic controls before implementing them in competition.

1.0 Introduction

The mechanisms underpinning endurance capacity and performance have largely been defined in the exercise sciences with physiological concepts: a high maximal oxygen uptake, lactate threshold and exercise economy [1]. Recently, models of endurance performance have attributed greater value to the brain within exercise regulation [2-5], and specifically how athletes interpret what they 'feel' during exercise (hereafter referred to as 'perceptions'). Some describe the rating of perceived exertion (RPE) as the ultimate limiting factor to exercise tolerance [2], as it may be responsible for pacing, fatigue and exhaustion [3]. However, precisely what the RPE measures has been debated [6, 7]. Regardless, RPE likely incorporates aspects of effort, exertion and afferent sensory feedback, including the perceptions of pain and temperature [6].

Perceptions of pain and temperature during exercise have recently received increased research attention. They appear to be attenuated with normal exercise training [8, 9], and strategies manipulating these perceptions to improve endurance performance have also been investigated [10, 11]. While such research may drive advancements in knowledge around the relationship between psychology and physiology for endurance athletes, some aspects of the topic have been at the centre of intense international debate about the ethical and health considerations of manipulating the senses to override homeostatic controls during exercise. Therefore, the purpose of the current review is to summarise recent advancements in research surrounding the influences of pain and temperature perceptions during exercise, while also reiterating the message of athlete safety in relation to their applications.

2.0 Literature Search Methods

Searching was carried out within a range of databases including Web of Science, Scopus and MEDLINE, up to 9th October, 2017. Searching was conducted in English and included the terms: perception, sensation, pain, temperature, heat, exercise, endurance and performance. Various combinations of search clusters were used, and search results were limited to peer-reviewed content. Additional works from key authors were also included in the study. Inclusion criteria stipulated that investigations must have been peer reviewed and measured perceptions of pain and/or temperature. This review was focussed on endurance exercise, which reflects the majority of the literature available. Participants of all abilities were included within both the sport and occupational health settings.

3.0 Perceptions of Pain and Endurance Performance

3.1 Theory

Pain is defined by the International Association for the Study of Pain as “an unpleasant sensory and emotional experience that is associated with actual or potential tissue damage or described in such terms” [12]. The meaning and implications of pain are learnt in the early years of life, where the sensation is related to injury or tissue damage [13]. However, pain is always subjective and the perception of the sensation is not always proportional to the size of the nociceptive signal and given pain is always unpleasant, the perception of pain will also partly be an emotional experience [13].

These sensory and subjective principles are critical for understanding the role of pain in exercise and athletic performance [14].

During exercise, pain arises as a natural consequence of intramuscular pressure, muscle distortion and a build-up of deleterious metabolites in the muscle [15]. This ‘exercise-induced pain’ (EIP) starts as a localised perception in the primary exercising muscle or muscles, but spreads to other locations over time, with significantly increased levels of pain experienced in areas as central as the chest at the end of exhaustive running [16]. In cycling, EIP has been shown to increase linearly with both power output and physiological intensity [17], whilst in self-paced exercise EIP appears to increase linearly as a function of distance completed or time elapsed, with near maximal levels experienced at the end of exercise [10]. Consequently, an individual exerting an intense and sustained physiological intensity will experience a level of pain and discomfort that is extremely unpleasant [17]. This is important because pain is ultimately a protective function that serves as a warning of actual or impending tissue damage and therefore a stimulus to disengage with the action or behaviour that is causing it [18]. Therefore, the drive to disengage with the exercise task, or reduce intensity to reduce the level of pain, will become increasingly stronger as the exercise continues [14, 19].

This association between pain and exercise no doubt provides the basis of long-held beliefs that pain tolerance is an important pre-requisite for athletic performance (i.e. no pain, no gain). It is important to note that pain tolerance (i.e. the maximum level of perceived pain that someone is able to tolerate, or the duration someone is willing to be exposed to a given pain intensity) is very different to pain threshold (the level at which a stimulus is initially perceived as pain), and the distinction between these should be emphasised and assessed with appropriate methods so that the role of pain in exercise performance is better understood. However, even when this distinction is made, the impact of pain on exercise performance can be difficult to empirically test, so that despite the clear reference to its significance by competitors [19, 20], the experimental evidence supporting this notion is surprisingly limited and often inconsistent. A meta-analysis examining pain perception differences between athletes and active controls showed that in most well-controlled studies, athletes exhibited a higher pain tolerance, despite similar pain thresholds [21]. This is logical, given that EIP tends to reach only moderate or strong levels, but must be tolerated for the duration of the exercise. A recent investigation demonstrated that specific tolerance to EIP was not only strongly correlated with endurance performance, but could also predict the completion time of a 10 mile cycling time trial [22]. Even when EIP tolerance was combined with traditional measures of endurance performance (maximal oxygen uptake, gas exchange threshold and peak power output), it was still able to explain some of the variance (7.5% variance, p=0.002) in time trial completion time [22]. It is likely that this increased tolerance of pain arises from particular physiological or psychological adaptations that occur as a result of exercise training [8, 21]. Indeed, an improvement in pain tolerance has been an outcome of aerobic training programs in previously untrained individuals [23-25], which the authors attributed predominantly to psychological adaptations to training (although this was not measured). The increased pain tolerance could have arisen as a result of diminished signalling in response to the noxious stimulus [26-28], but this desensitisation of the nociceptors is hard to measure and unlikely given that these studies also observed no change in pain threshold. A more likely explanation is that exposure to frequent and unpleasant sensory experiences during aerobic training permits the participants to develop a means of coping and a tolerance to these sensations. Indeed, coping skills can increase pain control [29] and the attitude of athletes towards pain has been shown to differ from that of normally active controls [30]. Recent evidence suggests that highly trained individuals (>10 h per week training and competing at, or above the top tier of their local competition) demonstrate significantly enhanced conditioned pain modulation compared with non-athletic controls [8]. This suggests that highly trained athletes have a higher endogenous pain inhibition ability, and that this may reduce the level of pain experienced at a given exercise intensity. However, it is not clear whether this is something that develops in response to training, or is an inherent characteristic that naturally predisposes these individuals to engaging in competitive sport.

Whilst the relationship between perception of pain and athletic performance is undoubtedly complex, the general consensus is that EIP forms an important part of endurance exercise [14]. At the very least, EIP likely provides important information for the exerciser regarding the current level of fatigue, and this information can subsequently be used to effectively pace an exercise bout [20]. Thoughts of pain and discomfort were shown to be prominent at the start of a 10 mile TT, but reduced towards the final sections of the race [20]. A similar observation was shown for thoughts relating to the monitoring or altering of pace, which may be indicative of the riders using the conscious feeling of pain and discomfort as a means to guide decisions on the appropriateness of their pacing strategy. This suggestion is supported by studies that have examined the effect of analgesia during exercise [10, 31, 32], where a decreased sensation of pain usually results in an increased power output being sustained and a significantly improved endurance performance (i.e. pacing strategy is adjusted when pain perception is moderated). When pain was completely blocked during exercise through the injection of intrathecal fentanyl, participants adopted an extremely positive pacing strategy, which resulted in very high levels of peripheral fatigue and a sub-optimal performance [33]. Whilst the purpose of this study was not to examine the effect of pain during exercise, it does support the notion that EIP is an important sensation in determining beneficial pacing during self-paced exercise.

3.2. Applications

Use of analgesics and/or their abuse in pursuit of athletic performance enhancement, or to mask injury to facilitate participation/competition, is not uncommon. The ethics and motivation for their use by athletes is beyond the scope of this review and has been discussed elsewhere [34-38], however their use and abuse appears rife within elite and recreational sport [39-43].

Although analgesia use appears widespread, empirical evidence supporting their use to augment athletic performance is sparse, particularly in elite populations (i.e. maximal aerobic power of 350-500 W and maximal aerobic capacity of 72-80 $mL \cdot kg^{-1} \cdot min^{-1}$ [44]). Trained but non-elite cyclists improved their 10 mile (16.1 km) time-trial completion time when ingesting 1.5 g of acetaminophen (paracetamol) compared to placebo [10]. Faster completion time was accompanied by elevated heart rate and blood lactate (increased intensity), yet perceived pain and exertion were not different to the placebo condition [10]. Indeed, augmented mean power output was seen across repeated anaerobic Wingate tests in response to the same dose of acetaminophen within a recreationally active population, again attributed to reduced EIP [32]. However, data from elite populations regarding analgesia use and their effects on exercise performance is lacking, despite their widespread use in sport [34, 35, 40-42].

Transcranial direct current stimulation (tDCS) has shown some efficacy to reduce perceived pain (without the reliance on pharmacological analgesia), albeit in a cold pressor test within healthy recreationally active individuals [45]. This reduction in perceived pain was not seen in subsequent time to exhaustion (TTE) cycling exercise, i.e. EIP was unchanged as were performance metrics [45]. Similar findings of increased pain inhibitory capacity from high definition tDCS without enhancement of subsequent force production or attenuation of muscular fatigue have been reported elsewhere [46]. Indeed, the efficacy of tDCS to augment exercise performance, whether through favourable EIP modulation or otherwise, across various exercise modalities is currently ambiguous and the available evidence is often limited by poor ecological validity and experimental design [47-50]. Transcutaneous electrical nerve stimulation (TENS) has shown greater promise, whereby reduced EIP translated to increased TTE during isometric muscular contractions in healthy recreationally active participants [31]. However, the evidence pertaining to tDCS/TENS and EIP outlined above, relative to exercise performance, should be interpreted with caution. This is particularly the case when considering implementation of these findings in elite athletes (which the evidence above does not examine), given that such athletes have altered pain perception compared to their non-elite or recreational counterparts [8]. Indeed, evidence from such elite populations is required to inform practice, as is further discussion of any ethical/doping issues by germane authorities and medical support staff relative to tDCS/TENS use in an attempt to enhance athletic performance.

Although limited and from unfit [23] or healthy but relatively untrained populations [8, 25], evidence suggests that pain tolerance can be favourably enhanced by aerobic exercise training, whereas pain threshold remains unchanged. Triathletes have been shown to have greater tolerance and more efficient pain modulation than non-athletic controls [51]. But whether practitioners can evoke performance improvements in well-trained individuals by increasing their pain tolerance, in lieu of physiological adaptations, requires further evidence from studies with robust experimental designs. Practitioners should also be aware that acute psychological stress might remove such advantages in pain modulation [52]. Indeed, a dose response was seen between athlete susceptibility to psychological stress, magnitude of perceived stress and any reduction in their advantageous pain modulation capacity [52]. Practitioners may therefore wish to deploy psychological skills training to develop robust stress resilience and coping strategies in their athletes; this will in turn help them retain optimal pain modulation/resilience capacity [29], which has been shown to be conducive to optimal exercise performance [22, 31]. The research determining the effects of interventions acting on pain perception and exercise performance is summarised in Table 1.

Insert Table 1 near here

While there is evidence of acetaminophen being beneficial during exercise, this is within a well-controlled research setting where interactions with other medications and supplements (anti-inflammatory drugs, caffeine, etc.), other common conditions (redistribution of blood flow, hydration status, diet, etc.) and the intensity of exercise are explicitly controlled to ensure the safety of participants. Acetaminophen use during exercise where such robust controls are not in place must not be advocated; the risk of interaction with any of the stated factors is not known and may increase the danger of injury/damage to an individual.

4.0. Perceptions of Temperature and Endurance Performance

4.1 Theory

The perception of temperature (as measured by ratings of 'thermal sensation') and the perception of comfort associated with that temperature (as measured by ratings of 'thermal comfort') have been studied in exercising humans through psychometric scales since the late 1960s [53]. Warm and uncomfortable perceptions of temperature develop during prolonged exercise [54], and become exacerbated when exercise is completed in hot compared to cool environments [53, 55]. Thermal sensation and thermal comfort ratings should be treated separately however, as they are measured with separate scales, and do not always act in unison [56]. Original investigations demonstrated that at the onset of exercise, the increasingly hotter thermal sensation and thermal discomfort ratings are both associated with changes in the mean body temperature [53]. During steady state exercise of 30-40 minutes duration however, thermal sensation ratings can be attributed to skin and ambient air temperatures, while the thermal discomfort ratings can be attributed to the skin blood flow and the sweating response [53]. Thus, the psychophysiological basis of thermal sensation and discomfort ratings are likely governed by sensory and effector mechanisms, respectively. Detailed molecular, neuroanatomical, and neurophysiological mechanisms that allow humans to sense temperature have been described recently [57] and therefore this section will focus on relationships between ratings of thermal sensation, thermal discomfort and exercise performance. Lastly, it should be noted that the term 'sensation' (i.e. the process of a sensory receptor being stimulated) has been used incorrectly in this context, and this has become ingrained within the thermoregulation literature. The term thermal 'sensation' as it is described across the literature, is in fact a 'perception' (i.e. how one interprets how they feel). Considering that the term ‘thermal sensation’ is used as a measure of thermal perception (i.e. thermal sensation ratings) frequently in the current literature, we will continue to use it throughout this review (albeit erroneously) when discussing research that has measured these ratings of thermal sensation.

The exercise, heat stress, and cooling literature has demonstrated associations between thermal perceptions, body temperatures and endurance exercise capacity or performance [56, 58-62]. However, reviews and models based on early thermoregulation research predominately implicated an elevated core body temperature as the direct cause of fatigue and impaired performance in the heat [63-66], while the role of thermal perceptions in pacing, fatigue and performance received little attention in comparison. However, Cheung [67] presented three forms of evidence to describe a possible relationship between thermal perceptions and exercise performance. Evidence included: a) alterations in pacing during exercise with heating and cooling interventions [68, 69]; b) the observation of reduced thermal perceptions following aerobic conditioning [9] and; c) the capacity for psychological skills training to improve running performance in the heat [70]. Nevertheless, the clarity of any relationship between thermal perception and exercise performance was still limited by the inability to separate thermal perception from thermal state (i.e. body temperatures) during exercise. Recently however, the use of the cooling compound menthol (which acts on cutaneous thermoreceptors to induce perceptions of coolness) has allowed the separation of thermal perceptions and thermal state within research, although the core temperature can be altered by menthol in some instances where it is applied to a large body surface area [71, 72]. Pre-cooling (i.e. cold water immersion, ice slurry ingestion, etc.) cannot reduce thermal perceptions without simultaneously reducing the thermal state (reductions in physical body temperatures e.g. various tissue temperatures). Hence, placebo controlled research that shows performance improvement with menthol application alone can be attributed to thermal perception only, as body temperatures generally remain unchanged [73-75].

In the first study to use menthol to separate thermal perceptions and thermal state, Schlader et al. [60] demonstrated that under heat stress, cooling of the face via both thermal (forced convection) and non-thermal (menthol gel) methods significantly increased power output in a RPE-clamp cycling protocol compared to a control. Hence, both the facial temperature and the perception of that temperature were demonstrated to be involved in the regulation of exercise (via alterations in the RPE). Another comparison between a menthol mouth rinse (that lowered thermal sensation ratings) and an ice slurry beverage (that lowered core body temperature) revealed that only the menthol intervention significantly improved running performance in the heat [76]. Hence, not only does thermal perception play a role in endurance pacing and performance, but this role may in fact be more influential than the physical temperature of the body in some circumstances of mild-moderate heat stress.

Thermal perceptions are strongly influenced by the temperature of the face and head [77, 78], especially during heat exposure, where facial warming is most uncomfortable and facial cooling is most comfortable compared to other body segments [78]. As such, focused cooling of the face and/or head during exercise has significantly increased cycling time to exhaustion [79], cycling work rate at a fixed RPE [60] and 5 km running performance time [80], all alongside a significantly cooler thermal sensation and/or increased thermal comfort rating. In an alternative model that required cyclists to control their work rate to maintain thermal comfort in cold conditions, facial warming and cooling significantly decreased and increased work rate, respectively [81]. Such changes may be explained by the combination of a greater density of thermal afferents in the face along with processing mechanisms in the central nervous system [77, 78]. Considering these interventions did not influence core body temperature, it is evidence for peripheral temperatures modulating endurance exercise performance, likely via mechanisms involving thermal perception [82].

Adjustments in pacing during exercise in the heat have also been observed prior to a physical change in the core body temperature [69, 83, 84], which suggests the involvement of afferent feedback and psychological factors in the regulation of endurance exercise performance in the heat. Thermal perception is not the ultimate afferent modulator of exercise performance however, since when the skin temperature was altered from cold to hot and vice-versa during a 60 minute cycling time trial, changes in the work-rate did not mirror changes in thermal perception across the trial [85]. Instead, the exercise intensity was more closely associated with the RPE, which is likely influenced by thermal perception [86, 87], but to a greater extent by the combination of whole-body feedback [88], exercise end-point [89] and feed-forward processes in the brain (corollary discharge) [7]. Hence, a previous review of the this evidence [82] proposed that during exercise in the heat, elevated skin temperature and the associated thermal perceptions are responsible for a self-selected reduction in work-rate in order to maintain the RPE and allow the completion of an exercise task without hyperthermia.

Studies whereby exercise performance was altered following application of menthol interventions allow confirmation that exercise performance is influenced by temperature perception [60, 76]. Such influence is maximised when cooling or heating interventions are targeted to the face and/or head [60, 79-81, 85], due to the high alliesthesial thermosensitivity of these areas [77]. Such afferent feedback is but one piece of the puzzle with an influence on the overall RPE, pacing and endurance performance, particularly relevant during exercise heat-stress. Lastly, it should be noted that this cooling research is limited by both the dominance of research participants being male (data on females are needed), as well as the difficulty in implementing a robust placebo condition relative to the experimental designs, and hence, future researchers should address these limitations. Another interesting avenue for future research would be to discriminate the relative contributions of thermal sensation and comfort ratings to endurance performance.

4.2 Applications

Thermal perception and comfort, as outlined above, can be important relative to exercise pacing and performance [60, 69, 80]. Heat adaptation (HA) through acclimation/acclimatisation, provides robust protection [90] to thermally mediated reductions in endurance [91] and repeated sprint [92] exercise performance, and against heat illnesses [93]. Relevant to thermal perception and this review article, appropriate HA has efficacy to improve ratings of thermal sensation/comfort in team sport and endurance athletes during subsequent training and competition in the heat [90, 94-96]. However, these HA-mediated thermal sensation rating changes are not seen in resting values but rather at comparative time-points or as a mean value across an exercise/training bout, when comparisons are made pre- to post-HA [90]. An empirically rationalised [90] attainment of a heat acclimated phenotype may be practically challenging however, as only 13% of long distance athletes at the 2015 World Athletics Championships (where hot conditions were expected) followed a HA regime [97]. Therefore, while HA is recommended to favourably alter thermal sensation ratings during heat-strain, it may not be practically viable for all athletes.

Exercise training *per se* and increasing ‘fitness’ has been shown to dissociate physiological and perceptual (i.e. thermal sensation ratings) exercise heat-stress, specifically a dampening of perceptual relative to physiological heat-strain [67]. Thus attainment of high-levels of fitness appears an important counter-measure to reduce perceived temperature during exercise. However, practitioners should exercise caution with highly-trained athletes given their dampened interpretation of thermal perception and ability to produce sustained highly elevated core temperatures [67]; this potentially places these populations at heat illness risk, especially when appropriate HA has not been performed [91]. Moreover, high body mass-index with low running ability also predisposed Marine Corps recruits to heat illness [98], indicating that practitioners should adopt individualised practice across populations of all fitness levels engaging in exercise heat-stress.

Aside from increasing ‘fitness’ and procurement of a HA phenotype, there are acute strategies which can positively alter ratings of thermal sensation/comfort prior to [99] and during exercise [11, 100] with subsequent ergogenic performance effects. Challenges whereby delineation of changes in thermal sensation rating without concomitant core body temperature rise have been overcome, demonstrating that a pre-exercise change in the rating of thermal sensation alone (no change in core temperature, only skin temperature) can beneficially alter subsequent athletic performance [101]. A pre-exercise cooling strategy with efficacy to reduce body temperatures can create a 'heat-sink' [102], i.e. a larger heat storage capacity [99] which delays the attainment of an individualised high body temperature at which performance decrements begin to occur. Similarly, a mid-exercise alteration in the rating of thermal sensation via facial water spraying (without change in core body temperature) has been demonstrated to be equally as ergogenic to running performance as pre-cooling by cold water immersion [80]. Therefore, evidence for strategies that reduce the rating of thermal sensation, rather than the core body temperature only, to enhance endurance performance may drive their use by practitioners and athletes [11, 76, 80, 99, 100, 102].

Practitioners should employ evidence-based practice regarding their choice of thermal perception orientated mid-cooling strategies and the tissue to be targeted, relative to attempts to improve exercise performance. This evidence must be considered carefully, given that few laboratory investigations have applied realistic facing wind speeds, without which, artificially high body temperatures are seen along with over-estimates of the beneficial effects of a cooling intervention (thermal perception or body temperature orientated), thus translation from the laboratory to the 'field' may be lacking [100]. The following recommendations are therefore based on the criteria that an appropriate facing winding speed was employed, a time-trial rather than time-to-exhaustion performance measure was used and the mid-cooling strategy employed was highly practical (i.e. frozen items were not consumed or applied to the body). Menthol mouth rinse and/or facial water spray mid-cooling has proven ergogenic to 5 km running time trial performance at ~33°C and ~46 % relative humidity [76, 80]. Indeed, lowering rating of thermal sensation via menthol mouth rinse during exercise improved running performance whereas pre-cooling via ice slurry (which lowered core temperature) did not [76]. Even when pre-cooling was administered through cold water immersion (which lowered core temperature), its ergogenic performance effect was matched by mid-cooling (which lowered rating of thermal sensation rather than core temperature) via facial water spray [80]. Practitioners should therefore seek to either utilise menthol mouth rinse and/or facial water spray in an attempt to improve endurance performance via thermal perception. Practitioners should avoid the temptation to use menthol as a gel or spray to the skin/clothing, as exercise performance is not enhanced concomitantly alongside ratings of thermal sensation [73, 103, 104], likely due to the capacity of menthol to reduce sweat rate and vasoconstrict blood vessels, ultimately promoting heat storage when applied to a large surface area of the body [11]. Alterations of thermal sensation rating through menthol use during exercise appear most beneficial to performance when applied internally via a beverage containing menthol or through mouth rinsing [11]. Relative to mid-cooling via facial water spray, it is important for practitioners to consider that the skin on the torso demonstrates lower alliesthesial thermosensitivity compared to the face [57]. Indeed, cooling of the face can be up to five times more effective than cooling of other body surfaces relative to maintenance of thermal comfort [77]. However, it must be noted that further research is required in this regard, for example, currently there is no evidence whether menthol mouth rinse can be combined with facial water spray to elicit an additive performance effect. Furthermore, optimised and field compatible mid-cooling strategies will evidently be discipline specific according to what might be practical and within the rules of the different sports.

A high variance in the efficacy of psychological skills training has been demonstrated relative to several interrelated agendas appropriate to exercise performance optimisation, including tolerance to environmental extremes and pain [70, 105, 106]. However, there is evidence [70] that psychological skills training (including goal setting, arousal regulation, mental imagery and positive self-talk) can augment distance covered during a 90-min treadmill run in the heat (30°C; 40% relative humidity). Recently, a specific form of psychological skills training, motivational self-talk, also enhanced endurance and cognitive function during cycling based exercise heat stress [105]. Positive performance effects were attributable to the two week motivational self-talk intervention allowing participants to tolerate a longer duration near or at a maximal intensity (i.e. ≥ RPE 19) and a higher terminating core temperature without difference in heart rate or oxygen uptake (i.e. greater psychological tolerance to thermophysiological strain) compared to the control group without motivational self-talk, demonstrating that even in well-trained individuals, enhanced psychological tolerance to thermal or exercise discomfort is trainable and pliable via motivational self-talk [105]. Practitioners may consider adding appropriate exercise heat-stress orientated psychological skills training to their athlete's training regime, but whether or not such psychological skills training could provide an additive effect to the above outlined ergogenic thermal perception orientated interventions/approaches requires further research. The research determining the effects of interventions acting on temperature perception and exercise performance is summarised in Table 2.

Insert Table 2 near here

5.0. Interconnections Between Pain and Temperature Perception

While acetaminophen is best known as a pain reliever, it can also be used to treat fever [107] and hence, it may play a role in thermoregulation and temperature perception. In athletes, an acute dose of acetaminophen can delay the increase in body temperature during exercise in the heat [108, 109] and has also been demonstrated to significantly lower thermal sensation rating and improve cycling time to exhaustion in the heat [109]. However, no such changes were observed following ingestion of acetaminophen when cycling at a fixed rate of metabolic heat production [110].

Another interconnection between pain and temperature perception is evident when considering the use of a cold stimulus as a widespread treatment for pain [111]. Research on menthol application may also allow separation between the physical and perceptual effects of a cold stimulus when considering pain responses. Menthol has been added to commercially available medical creams targeting musculoskeletal pain as it may have an analgesic effect for sports injuries, delayed onset muscle soreness and arthritis [112, 113]. Menthol has been demonstrated to cool not only through the transient receptor potential cation channel subfamily M member 8 (TRPM8), but also to inhibit the transient receptor potential cation channel, subfamily A, member 1 (TRPA1), which is a mediator of inflammatory pain [114]. While topical application of menthol decreased perceived pain and improved physical function in patients with knee osteoarthritis [115], research to date has not investigated the analgesic effects of menthol during exercise in athletes.

6.0. Safety Considerations

Athletes who attempt to override the perceptions of pain during intense endurance exercise may be at risk of serious injury. Given that pain serves as a protective function for the body, it could be suggested that moderating the naturally occurring EIP signals during exercise poses a danger to the individual. While no participants suffered long-term damage as a result of a complete afferent (and consequently pain) block [33], suggesting any regulation of intensity arising from EIP is likely minimal, the risks of such methods in all athletic situations are largely unexplored. It should also be noted that harmful side effects have been reported with analgesic use during and relative to sport, including gastrointestinal damage, as well as liver and kidney failure [39, 116-118]. Therefore, this article does not condone the use of analgesics to mask the pain from injury during competition, nor in the pursuit of performance enhancement. Use of analgesic strategies must be considered carefully by the athlete and under guidance from their medical support team/physician.

The perception of temperature may also be a protective mechanism to preserve against exertional heat illness and hyperthermia. The ability to perceive the temperature of the environment and adjust behaviour accordingly is undoubtedly a vital attribute in humans that has ensured long-lasting survival [57]. These perceptions may also play a similar role during endurance exercise (especially in the heat) to encourage the exerciser to slow down or stop when it may be otherwise dangerous to continue [82, 119]. Therefore, application of menthol or cooling methods that target perception should be avoided close to the onset of hyperthermia, to allow perception of symptoms associated with high levels of heat stress, adjustment to self-selected exercise intensity and the prevention of heat injury.

While no specific evidence of serious health complications from the use of these strategies has been described within the literature to date, it is wise to exercise the cautions described above. Indeed, the absence of such evidence is likely due to a lack of specific designs to test such hypotheses, which would be mostly unethical in humans.

7.0. Conclusion

New research developments have demonstrated that the perceptions of pain and temperature can both influence endurance exercise performance. These findings highlight the importance of the brain in the development of endurance training adaptations, and in the development of fatigue during acute exercise. While interventions are available to modify the perceptions of pain and temperature to improve performance in endurance-trained populations, these interventions may have serious health consequences when used during intense exercise and/or in thermally challenging environments and as such, a medical practitioner should supervise any use of such interventions closely to ensure the safety of the athlete.

Compliance with Ethical Standards

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Table 1: Research determining the effects of interventions acting on pain perception and exercise performance.

Study	Participants	Intervention	Testing Protocol	Testing Conditions	Outcomes
Mauger et al. 2010 [10]	13 males, VO_2max = 65 ± 5 $mL \cdot kg^{-1} \cdot min^{-1}$	Oral ingestion of 1.5 g acetaminophen, 60 min prior to TT	16.1 km cycling TT	Not stated	↓ TT time by 30 s (2%) ↑ Mean PO by 10 W (4%) ↔ EIP, ↔ RPE, ↑ HR, ↑ BLa
Astokorki and Mauger, 2017 [31]	Part 1: 11 males, 7 females. Part 2: 14 males, 8 females, VO_2max = 53 ± 7 $mL \cdot kg^{-1} \cdot min^{-1}$	Biphasic TENS applied unilaterally to BF muscle (Part 1) or bilaterally to VL muscle (Part 2) in a continuous pattern with pulse width of 300 μs and frequency of 100 Hz	Part 1: 20% MVC of biceps flexion held at 90° isometrically until exhaustion. Part 2: 16.1 km cycling TT	Not stated	Part 1: ↑ TTE by 3 min (38%) ↓ EIP, ↔ RPE Part 2: ↓ TT time by 33 s (2%) ↓ EIP, ↔ RPE, ↑ HR, ↑ BLa
Foster et al. 2014 [32]	9 males, VO_2max = 47 ± 6 $mL \cdot kg^{-1} \cdot min^{-1}$	Oral ingestion of 1.5 g acetaminophen, 30 min prior to test	8 x 30 s Wingate tests, with 2 min active rest intervals	Not stated	↑ Mean PO by 19 W (5%) ↔ EIP, ↔ Peak PO, ↔ HR
Angius et al. 2015 [45]	Part A: 9 males, VO_2max = 48 ± 7 $mL \cdot kg^{-1} \cdot min^{-1}$ Part B: 7 males	tDCS applied to the left motor cortex at an intensity of 2 mA for a period of 10 min.	Part A: Cycling TTE at 70% peak PO Part B: CPT with right hand submerged in iced water (0-1°C)	20°C, 50% RH	Part A: ↔ TTE, ↔ EIP ↔ RPE, ↔ HR, ↔ VO_2, ↔ VE ↔ BLa Part B: ↔ pain tolerance, ↓ pain intensity
Flood et al. 2017 [46]	12 males, recreationally active	High definition tDCS applied to the hand motor cortex at an intensity of 2 mA for a period of 20 min.	30% MVC of knee extensor flexion held at 90° isometrically until exhaustion	Not stated	↔ TTE or maximal force production ↑ conditioned pain modulation

↔ = no change, BLa = blood lactate concentration, BF = biceps femoris, CPT = cold pressor test, EIP = exercise induced pain, HR = heart rate, MVC = maximal voluntary contraction, PO = power output, RH = relative humidity, RPE = rating of perceived exertion, tDCS = transcranial direct current stimulation, TENS = transcutaneous electrical nerve stimulation, TT = time trial, TTE = time to exhaustion, VE = volume of expired air, VL = vastus lateralis, VO_2max = maximal oxygen uptake.

Table 2: Research determining the effects of interventions acting on temperature perception and exercise performance.

Study	Participants	Intervention	Testing Protocol	Testing Conditions	Outcomes
Schulze et al. 2015 [56]	7 males, VO_2max = 62 ± 3 $mL \cdot kg^{-1} \cdot min^{-1}$	Ingestion of 15 $g \cdot kg^{-1}$ ice slurry + ice towels on legs and torso in 30 min + *ad-libitum* ingestion of ice slurry during TT	20 km cycling TT	34°C, 80% RH	↔ Mean power during TT ↑ Mean power by 9 W (1%) during pre-load ↓ TS, ↑ TC, ↓ T_{CORE}, ↓ T_{MS}
Schlader et al. 2011 [60]	12 males, untrained	Topical application of menthol gel on the face (0.5 $g \cdot 100\ cm^2$ at 8% prior to protocol)	Cycling TTE RPE clamp protocol at 16 'hard-very hard' in a WPS to ↑ heat stress	20°C, 48% RH	↑ Total work by 39 kJ (21%) ↓ TS, ↑ TC
Kenny et al. 2011 [61]	10 males, untrained	Ice vest worn under NBC	Walking TTE (or 120 min) at 3 $mi \cdot h^{-1}$ in NBC	35°C, 65% RH	↑ TTE by 12 min (12%) ↓ TS, ↓ T_{CORE}, ↓ T_{MS}, ↓ HR, ↓ RPE
Luomala et al. 2012 [62]	7 males, VO_2max = 56 ± 3 $mL \cdot kg^{-1} \cdot min^{-1}$	Ice vest worn after 30 min of cycling	Cycling TTE (9 min at 60%, 1 min at 80% VO_2max)	30°C, 40% RH	↑ TTE by 13 min (22%) ↓ TS, ↑ TC, ↓ T_{CH}, ↓ T_{UB}
Booth et al. 1997 [68]	5 males, 3 females, VO_2peak = 63 $mL \cdot kg^{-1} \cdot min^{-1}$	Cold-water immersion for 30 min at 24-29°C	30 min running TT	32°C, 60% RH	↑ TT distance by 304 m (4.2%) ↑ TC, ↓ T_{CORE}, ↓ T_{MS}, ↓ HR
Barwood et al. 2008 [70]	18 males, untrained	Psychological skills training involving goal setting, arousal regulation, mental imagery and positive self talk	90 min running TT	30°C, 40% RH	↑ TT distance by 1.2 km (8%) ↔ T_{AU}, ↔ T_{MS}, ↔ SR, ↔ IL-6, ↔ PRL
Barwood et al., 2015 [71]	8 males, untrained	Menthol sprayed on the cycling jersey (100 mL at 0.2% after 10 km of TT)	16.1 km cycling TT	34°C, 33% RH	↔ TT time ↓ TS, ↑ TC, ↓ RPE
Flood et al. 2017 [72]	8 males, VO_2peak = 55.4 $mL \cdot kg^{-1} \cdot min^{-1}$	Menthol mouth rinse (25 mL at 0.01% every 10 min)	Cycling TTE RPE clamp protocol at 16 'hard-very hard'	35°C, 48% RH	↑ TTE by 99 s (7.6%) and ↑ Power by 6 W (3.6%) ↓ TS, ↔ TC, ↔ T_{CORE}, ↔ T_{MS}, ↔ SR
Stevens et al. 2016 [75]	11 males, 5 km run time of 18-22 min	Menthol mouth rinse (25 mL at 0.01% every 1 km)	5 km running TT	33°C, 46% RH	↓ TT time by 0.7 min (3%) ↓ TS, ↑ VE, ↑ PRL, ↔ SR
Stevens et al. 2016 [79]	9 males, 5 km run time of 18-22 min	Facial water spray (every 1 km)	5 km running TT	33°C, 46% RH	↓ TT time by 0.6 min (3%) ↓TS, ↓ T_F, ↑ iEMG, ↔ SR
Sunderland et al. 2008 [93]	17 females, trained in team sports	4x30-45 running training sessions (30°C, 27% RH)	Loughborough Intermittent Shuttle Test	30°C, 27% RH	↑ distance by 2.5 km (33%) ↑ TC, ↓ T_{CORE}, ↔ progesterone, ↔ aldosterone, ↔ cortisol

Kelly et al. 2016 [94]	14 males, professional AF players	5x27 min cycling training sessions (39°C, 34% RH)	30 min cycling at 60% VO_2peak	38°C, 29% RH	↑ TC, ↓ RPE, ↓ BLa ↔ VO_2, ↔ T_{CORE}, ↔ T_{MS}
James et al. 2017 [95]	17 males, mean 5 km perf time 20:51	5x90 min running training sessions (36.6°C, 59% RH) to target T_{CORE} 38.5°C	5 km running TT	32°C, 60% RH	↓ TT time by 98 s (6.2%) ↓ TS, ↓ T_{CORE}
Wallace et al. 2017 [104]	14 males and 4 females, trained	2-weeks of motivational self-talk training	30 min cycling at 60%, then TTE at 80% peak power output	35°C, 50% RH	↑ TTE by 192 s (40%) ↑ executive function ↔ HR, ↔ VO_2, ↔ RPE

↔ = no change, AF = Australian Football, BLa = blood lactate concentration, HR = heart rate, iEMG = integrated electromyography, IL = interleukin, NBC = nuclear biological chemical suit, PRL = blood prolactin concentration, RH = relative humidity, RPE = rating of perceived exertion, SR = sweat rate, T_{AU} = aural temperature, TC = thermal comfort, T_{CORE} = core temperature, T_{CH} = chest skin temperature, T_F = forehead skin temperature, T_{MS} = mean skin temperature, T_{UB} = upper back skin temperature, TS = thermal sensation, TT = time trial, TTE = time to exhaustion, VE = volume of expired air, VO_2max = maximal oxygen uptake, VO_2peak = peak oxygen uptake, WPS = water perfused suit.