Placebo effects on cycling performance in virtual-reality and laboratory environments

by

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ABSTRACT

Placebo effects are a desirable outcome resulting from a person's expected and/or learned response to a treatment or situation In sport, most research has examined placebo effects by administering a placebo and informing athletes that they received an ergogenic aid, or via manipulating their expectations about an opponent. While previous research has revealed the magnitude of placebo effects during sport performance, it is limited in that they are often conducted in highly controlled environments, and opponents are often a replication of participants' own performance. Thus, it is unknown if placebo effects are induced outside of the laboratory and whether they can be induced when competing against real opponents. In this research programme, placebo effects induced via both ergogenic aids and opponents were examined when participants completed cycling time trials remotely on a virtual-reality software (i.e., Zwift) or in the laboratory. In Study 1 (N = 44), the reproducibility of 20-min cycling performance on Zwift was confirmed (CV = 3.7%). In Study 2 (N = 67), athletes completed two 20-min cycling time trials on Zwift, before completing a final time trial with the administration of one of four conditions as part of the balanced placebo design [1) told beetroot/given beetroot, 2) told beetroot/given placebo, 3) told placebo/given beetroot, and 4) told placebo/given placebo]). Findings showed no differences in power output (η_p^2 = .03) during any condition in comparison to baseline. In Studies 3 and 4, a deceptive intervention was adopted to investigate the effects of different competitive environments on cycling performance, whereby participants were either correctly informed about the nature of the opponent (accurate condition) or informed they received a performance-enhancing substance (deception). In Study 3, after a 20-min baseline time trial, participants (N = 12) competed twice against a virtual avatar replicating their previous baseline performance ($competition_{BSL}$) or against a virtual avatar riding at 2% higher power outputs than their best competitive performance (augmented feedback conditions; accurate and deception). Results showed that participants improved performance during $competition_{BSL}$ ($P < .001$) and accurate ($P = .036$) in comparison to baseline but not during deception ($P = .152$). In Study 4 (n = 14), participants competed against a real opponent of similar ability (± 2% difference achieved during baseline). Contrary to Study 3, performance during both accurate and deception conditions was similar to baseline (all $P \geq 0.134$). Collectively, this research has shown that placebo effects might not be as evident in remote-research designs than when conducted in the laboratory, which could be explained by the limited social contact between researchers and participants. These results have important implications for researchers and practitioners interested in placebo effects outside of the controlled environments, highlighting the importance of considering the exercise context. Virtual-reality software an innovative tool in which to conduct experimental designs in applied settings, including a geographically diverse sample, perhaps increasing the generalisability of findings.

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Sincerely,

Guilherme Matta.

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AUTHOR DECLARATION

I declare that this thesis represents my own original work, and that I conceived the rationale and procedures for each part of this research. I was responsible for the development of all testing procedures and carried out all the participants' recruitment, data collection, data input and statistical analyses. The research presented in this thesis was conducted under the supervision of Dr Philip Hurst and Professor Andrew Edwards and any assistance received during the research process has been appropriately acknowledged.

I acknowledge that the ethical considerations of the research have been addressed, and that the research was conducted in accordance with the ethical guidelines set out by the School of Psychology and Life Sciences at the Canterbury Christ Church University.

PUBLICATIONS ORIGINATING FROM THIS WORK

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Matta, G., Edwards, A., Roelands, B., Hettinga, F., & Hurst, P. (2022). Reproducibility of 20-min Time Trial Performance on a Virtual Cycling Platform. *International Journal of Sports Medicine, 43*(14), 1190-1195.

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Matta, G., Edwards, A., Roelands, B., Hettinga, F., & Hurst, P. Developing remote-design studies to investigate performance outcomes in sport and exercise sciences. *Postgraduate Research Forum in Psychology and Life Sciences (CCCU)*, Canterbury, UK, 21st of July, 2022.

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CHAPTER ONE

Introduction

INTRODUCTION TO THE RESEARCH PROGRAMME

Sports create highly competitive environments where marginal differences in performance might determine competition rankings. For example, the difference between first and second place during the 2023 Giro d'Italia was of only 14 seconds, even after 21 racing stages, involving more than 3,440 km in total. Such close, competitive situations have induced athletes to rely on a range of performance-enhancing practices, hoping to find an edge over their opponents. Dietary ergogenic aids (Maughan, Burke et al. 2018), for example, are extremely popular among athletes from all levels, and the reasons for their choices are usually linked to the expectancy of direct performance enhancement. However, performance benefits experienced by these athletes could also be associated with their inherent beliefs about a given supplement, i.e., placebo effects.

Placebo effects are any beneficial biological or psychological outcome that can be attributed to a placebo, or which solely occurs as a consequence of expectation or conditioning – the processes by which placebos are established (Benedetti, Mayberg et al. 2005), and which are often present in treatment conditions. Although placebo effects have been extensively studied in clinical settings, contemporary studies have demonstrated that placebo effects extend beyond clinical contexts and can manifest in sports settings as well (Beedie, Benedetti et al. 2018, Beedie, Benedetti et al. 2020, Hurst, Schipof-Godart et al. 2020, Raglin, Szabo et al. 2020, Brietzke, Cesario et al. 2022). More specifically, in a systematic-review of 32 experimental studies, Hurst, Schipof-Godart et al. (2020) observed small to moderate placebo effects when participants received a placebo described as a nutritional (e.g., caffeine, sodium bicarbonate, carbohydrates) or mechanical ergogenic aids (e.g., transcutaneous electrical nerve stimulation, kinesiology tape, ischemic preconditioning). In such contexts, although nutritional or mechanical ergogenic aids have commonly been used to induce placebo effects, other strategies such as manipulating sports equipment like tennis rackets (Guillot, Genevois et al. 2012) and rolling skis (Blumenstein, Abrahamsen et al. 2021). Recently, it has been proposed that opponents and teammates could act as social placebos by changing athletes' psychological outputs and beliefs in their ability versus those of their opponents, leading to improved performance (Davis, Hettinga et al. 2020).

Changes in performance associated with placebo effects have shown to occur through a variety of regulatory psychophysiological mechanisms, including the release of endogenous opioids (Benedetti and Amanzio 1997, Amanzio and Benedetti 1999), activation of the reward system in the brain (Schultz 2006, Colloca and Miller 2011) and changes in perception and expectations (Amanzio and Benedetti 1999, Humphrey 2002), which may share the same neurobiological pathways as the actual substance the placebo purports to be (Benedetti, Pollo et al. 2007, Benedetti, Amanzio et al. 2011,

Davis, Hettinga et al. 2020). Although the laboratory studies published to date have suggested that placebo effects influence performance (Benedetti, Pollo et al. 2007, Pollo, Carlino et al. 2008, Beedie, Benedetti et al. 2018, Brietzke, Cesario et al. 2022), its impact on applied settings is yet to be determined.

Placebo effects are widely recognized as being a socially-based phenomenon (Davis, Hettinga et al. 2020). Many aspects of sport, from the psychological boost of a supportive home crowd to the improved motivation of competing against opponents (McCormick, Meijen et al. 2015, Hettinga, Konings et al. 2017), are similarly rooted in social factors. These social effects have been studied extensively in fields ranging from social psychology to experimental physiology (Geers and Miller 2014, Evers, Colloca et al. 2018, Beedie, Benedetti et al. 2020, Brietzke, Cesario et al. 2022). Recent research in cognitive and evolutionary anthropology suggests that such social effects can be understood as a form of placebo effect. Davis, Hettinga et al. (2020), provided insights into the social aspects of placebo effects, suggesting that opponents, teammates and/or researchers act as social placebos and directly influence an athlete's performance through changes in psychophysiological responses such as motivation and decision-making. Indeed, Williams, Jones et al. (2015) investigated the psychological responses to different competitive environments, in which the performance of an opponent was deceptively manipulated, and showed changes in self-efficacy (Bandura 1977), ratings of perceived exertion (Borg 1982) and potentially increased motivation (Baron, Moullan et al. 2011). Although the social aspects of placebo effects induced by competitive environments have been previously studied extensively (Williams, Jones et al. 2014, Davies, Clark et al. 2016, Hettinga, Konings et al. 2017), most studies simulated competitions based on the participant's own individual performance, and not real competitions. Such simulated competitions, whereby cyclists compete against a virtual avatar representing their own performance or against a real opponent can provide important insights into the mechanisms associated with changes in performance.

It has been extensively shown that the distribution of effort across an exercise task (i.e., pacing) influences performance (Abbiss and Laursen 2008, Foster, Hendrickson et al. 2009, Edwards and Polman 2013, Roelands, de Koning et al. 2013). Pacing has been defined as "the goal-directed distribution and management of effort across the duration of an exercise bout" (Edwards and Polman 2013) and is suggested as crucial for endurance performance (Renfree, Martin et al. 2014, Renfree and Casado 2018). Several studies showed that altered pacing leads to different performance outcomes, whereby adopting an "optimal" work rate distribution to a given exercise demand is key to optimising performance (Foster, Hoyos et al. 2005, Hettinga, Konings et al. 2017). It is therefore

crucial that experimental research consider potential changes in how participants distribute their effort.

A few studies have previously reported changes in the pacing adopted by athletes induced by placebo effects from different interventions. For example, Hurst, Schipof-Godart et al. (2019) investigated the placebo effects induced by the hidden and overt administration of caffeine on pacing during 1000-m running time trials and found faster speeds during the initial 400-m when runners believed they ingested caffeine. In competitive contexts, previous studies have shown that the presence of opponents influences an athlete's pacing (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Davies, Clark et al. 2016, Hettinga, Konings et al. 2017, Konings and Hettinga 2018). In a previous meta-analysis, Davies, Clark et al. (2016) showed increased power output in the initial and middle parts of cycling time trials when athletes competed against a virtual opponent. Such findings suggest that placebo effects might improve athletes' motivation, influencing their goal-directed process of decision-making and how to approach time trials (Renfree, Martin et al. 2014, Hettinga, Konings et al. 2017). For example, if an athlete believes in the potential ergogenic effects of a substance, they might choose to adopt higher intensities at the start of a time trial, expecting an overall performance improvement. Similarly, when faced with opponents, the goal of winning a race or the decision of keeping up with a faster opponent might induce athletes to adopt higher initial exercise intensities. However, although the effects of opponents on pacing are more evident, there is a lack of studies investigating the placebo effects induced by ergogenic aids on pacing.

CHALLENGES FACED BY SPORTS AND EXERCISE SCIENCES RESEARCH

Since early 2020, most sport and exercise science laboratories around the world were forced to shut down and social distancing measures were implemented in response to the COVID-19 pandemic and to prevent the spread of the coronavirus (Harper, Kalfa et al. 2020, Omary, Eswaraka et al. 2020). As a result, the pandemic led to unprecedented challenges for athletes and coaches training for their respective sport (Washif, Farooq et al. 2021, Edwards and Hettinga 2023) as well as for researchers conducting scientific experiments reliant on laboratory-based testing. For example, a recent viewpoint (Souza, Bernardes et al. 2022) highlighted the many challenges faced by sports scientists to conduct meaningful research during that period, and discussed whether the scientific community can/should perform remote data collection.

Nevertheless, while this is challenging, it also presents opportunities to conduct research in different ways and perhaps to better consider the link between field (or remote) and laboratory work in terms of real-world sports applications. Using virtual-reality community platforms, that allow for social

distancing and competition could provide valuable insight into sports performance in an applied setting. It is conceivable that reproducible results, accurate performance monitoring, competition situations and even novel intervention-based research can be conducted in such a remote setting, although such information is scant.

THESIS STRUCTURE AND AIMS

This thesis comprises a literature review and four empirical, experimental studies investigating the placebo effects induced by various means such as a nutritional ergogenic aid (i.e., beetroot juice) and through different competitive environments on 20-min cycling time trial performance. A hybrid approach was implemented, incorporating three remote-study designs (i.e., on Zwift) and one laboratory-based study that would assist in understanding the physiological mechanisms induced by changes in performance associated with competitions. The 20-min time trial duration was chosen as cyclists usually rely on such time trial duration to assess performance and monitor training. Given that Zwift and other virtual-reality software are relatively new technologies and have not been extensively used as an alternative to laboratory-based studies, the first aim of this thesis was to assess the reproducibility of cycling time trial performance and pacing on Zwift (CHAPTER THREE). The results of this study would form the basis for the following three experimental studies. In the second remote study (CHAPTER FOUR), placebo effects induced by beetroot juice on performance were investigated, using a balanced placebo design and recruiting a large sample size. In the third study (CHAPTER FIVE), the effects of simulated competitions in the laboratory were investigated, in which athletes competed against a virtual opponent simulating different competitive settings. This study provided important insights into the physiological mechanisms behind potential changes in performance induced by competitions, in a more controlled environment. Finally, in the last study CHAPTER SIX the effects of head-to-head competitions on Zwift were investigated, involving different participants of similar performance levels.

CHAPTER TWO

Review of the literature

PLACEBO EFFECTS DEFINITIONS

Defining placebo effects is crucial to accurately understand and interpret the results of research studies. Although placebo effects have been extensively investigated in the scientific literature, previous studies have used different definitions of "placebo effects", leading to confusion and inconsistencies in the interpretation of results (Hróbjartsson 2002). Placebo effects research has commonly used the term "placebo" in combination with either "effects" or "response" interchangeably, but those terms have distinct meanings (Evers, Colloca et al. 2018). "Placebo effects" refers to the psychophysiological changes that occur in response to a placebo treatment. "Placebo response", in turn, refers to the overall response to the placebo treatment, including both the placebo effect and any other factor that may be contributing to the response, including natural healing processes, regression to the mean (the tendency for extreme values to return to the average over time), and the spontaneous improvements of a given symptom. Moreover, previous studies referred to the psychophysiological responses to an inactive treatment as "the" placebo effect, which implies that there is one single monolithic effect that applies to all placebo interventions. It is widely understood, however, that placebo effects can vary in magnitude, duration and mechanism and thus, are a complex phenomenon that can manifest in different ways, which is context dependent (Price, Finniss et al. 2008).

The definition of "placebo" and "placebo effects", therefore, have caused controversy and dispute among the scientific community (Hróbjartsson 2002) due to its initial conceptualisation as an inert control agent, purely used as an ancillary measure in qualifying intervention effects of primary outcome measures in randomised controlled trials. Such a notion suggests that a placebo lacks inherent properties and cannot exert any effects, which we now know is incorrect, leading to contrasting opinions on the nature of the phenomenon. Irrespective of whether it is used in experimental designs or clinical practices, a placebo is essentially an inert agent or sham treatment that lacks any inherent biological, nutritional or mechanical constituents capable of yielding a biological or psychological benefit (Kirsch 1985). However, the seminal study of Beecher (1955) showed that around one-third of people respond to a placebo, involving a variety of therapeutical areas, such as pain relief (e.g., headache, wound pain), mood changes and anxiety. Such positive outcomes in response to a placebo have been termed placebo effects, which refers to a psychobiological phenomenon that follows the administration of an inert substance, or a sham treatment. For placebos to yield a response and induce placebo effects, they must be accompanied by verbal cues in an information exchange between the individual receiving the treatment (e.g., participants, patients) and the one delivering it (e.g., researchers, clinicians) (Theodosis-Nobelos,

Filotheidou et al. 2021), which essentially is responsible for manipulating the individual expectations about a given treatment (see "UNDERPINNING MECHANISMS ASSOCIATED WITH PLACEBO EFFECTS" section). Therefore, to avoid detection, placebos must be identical and indistinguishable from any active substance/treatment, matching the description, appearance, and mode of administration, differing only in the essential component (Colloca and Miller 2011, Beedie, Benedetti et al. 2020).

According to the American Psychological Association, placebo effects are defined as a "clinically significant response to a therapeutically inert substance or nonspecific treatment (placebo), deriving from the recipient's expectations or beliefs regarding the intervention.". As the early study of Beecher (1955) suggested, patients given a placebo supposed to relieve acute/chronic pain (e.g., headaches), may report reductions in pain intensity if they believe they received an active drug described as a pain reliever. However, it must be acknowledged that in some cases, there is no need to use a placebo to induce placebo effects: it can be induced by the administration of the actual treatment, which also includes the treatment context, individuals' expectancy about the treatment (both the one receiving and the one delivering the treatment), previous experiences and symbols (Carlino, Piedimonte et al. 2016). Perhaps a better definition of placebo effects is any beneficial biological or psychological outcome that can be attributed to a placebo, or which solely occurs as a consequence of expectation or conditioning – the processes by which placebos are established (Benedetti, Mayberg et al. 2005), and which are often present in treatment conditions. Such definition encompasses that placebo effects can occur in the absence of placebos, and suggests that conditioning and expectation assist in the efficacy of active treatments, including for example, pain medication (Benedetti and Amanzio 1997, Amanzio and Benedetti 1999). Placebo effects research is, therefore, fundamentally examining the psychosocial context behind the individual and the resulting effect that such context has on their experiences (Price, Finniss et al. 2008).

In contrast to placebo effects, the administration of a placebo accompanied by the expectation of negative outcomes may induce adverse responses or side effects, which has been termed nocebo effects (Benedetti, Lanotte et al. 2007, Carlino, Piedimonte et al. 2016, Evers, Colloca et al. 2018, Colloca and Barsky 2020). Although less studied than the placebo effects, nocebo effects have been reported in the literature, whereby harmful outcomes such as increased anxiety, pain or fatigue were induced when a placebo was administered coupled with explicit instructions that it may cause adverse responses (Benedetti, Lanotte et al. 2007, Colloca and Barsky 2020). Nocebo effects have been less studied mainly because of ethical concerns (Colloca and Miller 2011). When conducting research on the nocebo effect, the potential unnecessary harm that may be caused to participants or patients is

problematic. In this respect, if participants are deliberately misled into believing that a treatment will cause harm or negative side effects, they may experience unnecessary distress or harm. It may also be considered that some participants/patients may be more vulnerable to the nocebo effect, such as those with anxiety or health conditions, and may be more likely to experience negative symptoms as a result of their expectations and previous experiences.

In summary, placebo and nocebo effects are of utmost importance in different research fields, such as medicine, psychology, neuroscience and sports sciences. Placebo effects can produce significant improvements in clinical symptoms and health outcomes, whereas nocebo effects can lead to negative outcomes or exacerbate adverse symptoms. Understanding these effects can help researchers design better clinical trials, develop more effective treatments, and improve patient care. Additionally, placebo and nocebo effects can have significant implications for ethical considerations in clinical practice, such as informed consent, patient autonomy, and avoiding harm. Studying placebo and nocebo effects, therefore, can have wide-ranging implications for improving the effectiveness and ethicality of different experimental treatments, or even whether placebo effects themselves can lead to meaningful performance change without having to be in receipt of anything other than an inert performance-enhancing substitute.

HISTORICAL BACKGROUND

Placebo effects research has been a topic of great interest and debate in different fields, such as medicine, psychology, and neuroscience. A quick search on PubMed including the term “placebo effects” yields over 195.000 results, and although the origins of placebo effects research are not entirely clear, the first study that included the term “effect of placebo” seems to have been published in 1948 (Pillsbury, Perry et al. 1948). Although the study did not aim to investigate placebo effects *per se*, it reported that patients who received a placebo demonstrated improvements in symptoms related to cutaneous diseases.

Historically, "placebo" comes from the Latin word "placēbō," which means "I shall please". Its origins date back to the 13th century to describe a chant or prayer sung during the Catholic Mass for the dead and it can also be found in the first line of the antiphon Psalms 114:9. The word has later came to mean a sycophant (someone who deceptively praises people, usually to get an advantage from them), as some people attended the services and would “sing the Placebo”, hoping to be rewarded by the dead’s person relatives (Aronson 1999). Interestingly, the word placebo and its early connotations have a strong cultural link with Canterbury, where this thesis was developed: in the 14th century, the word placebo can be found in Chaucer’s Canterbury Tales (The Merchant’s Tale), in which the

character “Placebo” is a sycophantic pleasing courtier, who actively participates in a tale about disguise.

Although the origin of the word placebo dates back centuries, it was not until the 18th century that it became a medical jargon (Jütte 2013), when a medication with no therapeutic effect was administered and called a "placebo". The reasons for its use were mainly to satisfy the patient's demands and their expectations (“to please”), and not to necessarily yield any healing effect. Even so, early reports show that patients often experienced positive outcomes from its administration, which was later termed a “placebo effect”. Despite the initial scepticism surrounding the phenomenon, research has now established that the placebo effect is a measurable effect that can have significant implications for patient care or even human performance in sports settings (Rohsenow and Marlatt 1981, Beedie and Foad 2009, Hurst, Schipof-Godart et al. 2020, Brietzke, Cesario et al. 2022). The modern idea of the placebo effects stems from the seminal study developed by Beecher (1955), which provided critical insights into the power of suggestion in medicine. Beecher (1955) analysed data from 15 different clinical trials and found that roughly one-third of patients responded positively to a placebo. He also noted that the strength of the placebo effect was influenced by factors such as the patient's expectations, the experimenter’s behaviour, and the context in which the treatment was given. Beecher's study challenged the prevailing view at the time that the placebo effect was simply a psychological phenomenon and instead suggested that it had physiological underpinnings. That study paved the way for further research on the placebo effect and sparked a renewed interest in the use of placebos in clinical trials and medical practice.

Following the research developed by Beecher (1955), Levine, Gordon et al. (1978) published a ground-breaking study exploring the mechanisms associated with placebo effects. The authors conducted a series of experiments that suggested that placebo effects are a powerful phenomenon in clinical settings, even if patients are fully aware that they are receiving a placebo. Their main findings demonstrated that placebos could produce measurable physiological changes in the body, such as changes in blood pressure and heart rate, and could even ease symptoms of conditions such as asthma and angina. The study provided evidence that placebo effects were not just a psychological phenomenon but also had a physiological basis, which supported the early suggestions made by Beecher (1955). Levine and colleagues’ study has since become a classic in the field of placebo research and has contributed to our understanding of the complex psychophysiological responses in health, illness and fitness, having important implications for the way we think about medical treatment and the mind-body connection.

Following the work of Levine, Gordon et al. (1978), several placebo effects studies focused on pain, which is highly influenced by emotions and expectations (Benedetti and Amanzio 1997). More specifically, Benedetti and Amanzio (1997) provided a comprehensive overview of the neurobiological mechanisms associated with placebo effects in relation to analgesia—a phenomenon that occurs when the administration of a non-analgesic substance yields an analgesic response, when the individual is informed it is a painkiller. In their study, they identified the role of neurobiological mechanisms, such as the endogenous opioid system and cannabinoid receptors, as mediators of placebo effects. They demonstrated that the brain's endogenous opioid system plays a crucial role in placebo analgesia and found that the release of cholecystokinin, a neuropeptide involved in pain modulation, is increased during placebo administration. Benedetti, Pollo et al. (2007) later demonstrated it is possible to trigger robust placebo effects when after the repeated administration of an active painkiller it is replaced by an inert substance (a process known as conditioning), where the recipient still believes they are in receipt of such drug. In their study, the participants underwent a series of pharmacological conditioning trials in which they were given morphine repeatedly before being submitted to a painful stimulus. In a subsequent painful trial, the morphine was replaced by a placebo, which resulted in similar analgesic responses from the morphine trials. The findings from these studies highlight and support the importance of psychological and neurobiological factors associated with placebo effects, particularly in the context of pain management.

From the information provided in this section, it is clear that placebo effects research has an interesting history. It initially had a different meaning from our current understanding and was ignored in clinical trials; then it was recognised as having an effect and treated as a control artefact of randomised controlled trials; finally, it has been extensively studied in its own rights. Although placebo effects research has attracted the interest of different scientific fields, different experimental designs have been used to assess the efficacy of experimental interventions and their placebo effects, controlling for the potential expectations of the participants.

EVOLUTIONARY PERSPECTIVE

While placebo effects and their associated psychological/neurobiological mechanisms have been extensively studied in clinical settings (see the section below “Underpinning mechanisms associated with placebo effects”), it is currently unknown whether placebo effects have an evolutionary explanation. Arguably, if placebo effects are ubiquitous to humans, they evolved for a purpose.

Interestingly, in the book *The Placebo Effect* (Shapiro and Shapiro 1997), the authors questioned whether placebo effects are “an adaptive characteristic, conferring evolutionary advantages, and that

this allowed more people with the placebo trait to survive than those without it?". In a thought-provoking book chapter, Humphrey (2002) argued that there are two reasons for thinking that the evolutionary perspective might play a role in placebo effects. First, the human ability to respond to placebos must have played a significant role during evolution regarding our likelihood of surviving and reproducing, which in turn, may have been influenced by natural selection. Second, such ability to respond to placebos involves dedicated pathways linking the brain with healing systems, which seems to have been designed to play such a role. Humphrey (2002) then considered the adaptive significance of placebo effects and their social roots, arguing that they may have evolved as a way of enhancing social bonding and cooperation. He suggests that the ability to create and sustain strong expectations and beliefs may have helped early humans to form social groups and to coordinate their behaviour in pursuit of common goals.

Like all animals, humans developed the ability to adapt to different environments through learning processes, and as such, the modulation of endogenous systems and healing processes by learning would enhance survival (Colloca and Miller 2011). From the pain perspective, previous studies have suggested pain works as an "alarm system" that informs the individual of tissue damage, which leads to appropriate action (Steinkopf 2015). More specifically, in his book, Wall (1999) suggested that the placebo effects represent such appropriate actions, which leads the individual to believe that a given placebo treatment accounts for the appropriate action against pain. The need, therefore, to take action would have been fulfilled and then, the pain or injury diminishes. Although this is a theory that fits well with the evolutionary perspective of placebo effects, it accounts only for pain and placebo analgesia.

Humphrey (Humphrey 2002, Humphrey 2004) suggested the theory of "health management system'' or ''health governor". Rather than an automatic response to infection and injury, for example, self-healing and defence mechanisms should be used selectively based on an evaluation of costs and benefits. For example, if an injured individual is in direct danger from a predator, mechanisms related to pain management and swelling may need to be postponed. Similarly, a lack of food and bodily energy reserves may limit the body's ability to support a full immune response. Therefore, the regulation of self-healing should take into account costs, opportunity costs, and potential benefits. These factors are determined by an individual's subjective assessment of their environmental conditions, which is influenced by their expectations. In Humphrey's theory, placebo effects can modify such assessments by creating the impression that it will boost the immune system, improving the chances of a speedy recovery (which is related to the appropriate action mentioned in the previous paragraph). This would then create a feedback loop where the "health governor" assumes the

circumstances have improved and permits a full immune response. Such theory was further tested by Trimmer, Marshall et al. (2013) who developed mathematical models to investigate the trade-off between the costs and benefits of immune responses to challenging environments. They suggested that the immune system seems to have an on-off switch controlled by the brain, which is modulated by the environment. That said, under stress, animals seem to live longer if they are able to endure infections without a full immune response.

Similar to the previous theories, Harvey and Beedie (2017) argued that placebo effects have evolved in different organisms as a way to enhance the natural healing mechanisms of the body, allowing the organism to better cope with survival-relevant situations. For example, when an animal is injured or sick, it may experience pain, discomfort, or other negative symptoms that can impact its ability to survive and reproduce. Placebo effects can then help to alleviate these symptoms, allowing the animal to recover and increase its chances of survival. If pain sensations can be tolerated for longer it might allow the animal to produce greater muscle force. This in turn could lead to improved running speed allowing them to successfully capture prey or even avoid predation. Their study suggested that by studying the placebo effect in model organisms, such as rats or mice, researchers can gain a better understanding of how this phenomenon works in humans and whether it indeed is an evolutionary trait.

The evolutionary perspective of placebo effects suggests that this phenomenon is not simply a result of human psychology, but rather a fundamental aspect of biology that has evolved over millions of years. By studying placebo effects in model organisms, researchers may be able to explore new insights into how this phenomenon works and potentially assist in the development of new treatments that harness psychological and neurobiological mechanisms.

PLACEBO EFFECTS AND EXPERIMENTAL DESIGNS

An increasing number of studies have acknowledged the significant role of participants' expectancies in determining the efficacy of different experimental interventions (Rohsenow and Marlatt 1981, Theodosis-Nobelos, Filotheidou et al. 2021). To control these for such effects, the usual "gold standard" experimental methodology employed is the double-blind placebo-controlled design. In this design, the participant receives either the actual drug or a placebo without knowledge about the true nature of the substance. However, the major drawback of this design is the inadequate determination of pharmacologic effects in comparison to expectancy effects. The pharmacologic effect is presumed to be assessed by subtracting the effects of the placebo from the effects of the actual drug, but this method does not allow for the assessment of the uncontaminated effects of the drug. Additionally,

participants' expectancies may vary depending on their potential previous experiences with a given substance/intervention, leading to inconsistent results. In double-blind placebo-controlled trials, it is also rare for the researcher to assess the actual blindness of either participant or experimenter, of which both of them may accurately guess whether a drug or placebo had been administered.

A common alternative to double-blind placebo-controlled trials is the crossover Latin square design. Such design involves administering one of three doses or a placebo to each participant in different trials, which the order of these trials being counterbalanced to prevent bias. However, this design also poses issues in terms of participants' expectations if they are able to accurately guess which treatment they received (i.e., placebo or active treatment). To address this issue, Carpenter (1968) proposed the "antiplacebo" design, where both active treatments and placebos are administered with instructions that the subject is receiving an inert substance. In this design, any differences between groups would be attributed purely to pharmacological effects rather than expectancy. However, this design does not allow for the assessment of the effects of drug expectancy or the interaction between pharmacology and expectancy. The optimal way, therefore, to differentiate expectancy effects from pharmacological action is the balanced placebo design (Rohsenow and Marlatt 1981) (Figure 1). In this 2 x 2 design, expectancy is manipulated independently of pharmacology, with half of the participants receiving the active treatment and half receiving a placebo, but the information the participants receive in each group is different. That said, such design would consist of 4 different groups: 1) receive the active treatment and are told that they are receiving the active treatment; 2) receive the active treatment but are told that they are receiving a placebo; 3) receive a placebo but are told that they are receiving the active treatment; and 4) receive a placebo and are told that they are receiving a placebo. Ross, Krugman et al. (1962) first described this design for drug research, and later used an extension where subjects were administered different drugs with congruent instructions (Lyerly, Ross et al. 1964). The balanced placebo design has been used in placebo effects research, allowing the investigation of the effects of expectancy and pharmacological action, but also the interaction effects of both (Beedie, Foad et al. 2015, Hurst, Schipof-Godart et al. 2019).

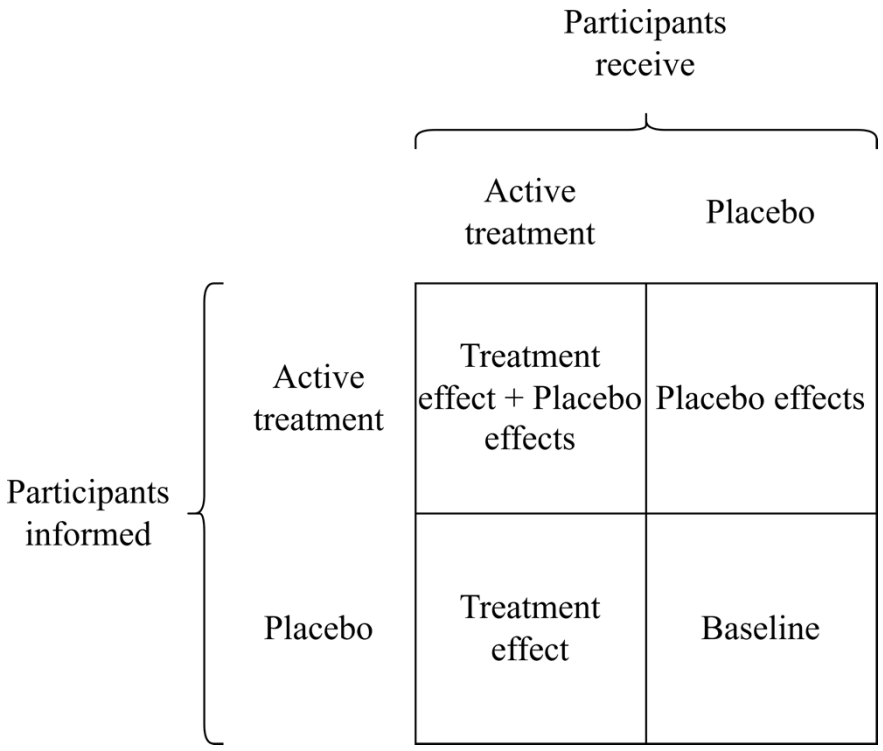


Figure 1. The balanced placebo design; adapted from Rohsenow and Marlatt (1981).

UNDERPINNING MECHANISMS ASSOCIATED WITH PLACEBO EFFECTS

The previous section reported the importance of placebo effects and how different experimental approaches allow researchers to further investigate the mechanisms that underpin the psychobiological responses associated with placebo effects. With advances in technology and methodological considerations (Meissner, Bingel et al. 2011), placebo research has been able to identify several of the psychological and neurobiological mechanisms behind placebo effects. It is clear that there is not a single placebo effect, but there are many, with different mechanisms of action, which act in different parts of the brain depending on the experimental intervention and environment.

Psychological mechanisms. Two key psychological mechanisms that underlie placebo effects have been established from previous research: expectancy (Shaibani, Frisaldi et al. 2017) and classical conditioning (Wickramasekera 1980, Colloca and Miller 2011). Understanding these psychological mechanisms can provide important insights into why placebo effects occur, and how they can be harnessed for therapeutic/performance benefit. More specifically, expectancy refers to the individual beliefs that a given treatment will have a positive effect (Shaibani, Frisaldi et al. 2017) and can result from verbal instructions (Benedetti, Lanotte et al. 2007, Carlino and Benedetti 2016), environmental cues (Theodosis-Nobelos, Filotheidou et al. 2021), emotional arousal (Jennings, Okine et al. 2014),

previous experiences with that treatment (Carlino, Guerra et al. 2016) and interaction with others (Benedetti 2013, Davis, Hettinga et al. 2020). Positive expectations have been shown to reduce anxiety, which in turn can affect different symptoms, such as pain (Amanzio and Benedetti 1999, Carlino and Benedetti 2016, Carlino, Guerra et al. 2016). Moreover, positive expectations of a beneficial outcome may induce feelings that increase the reward mechanism in the brain, such as dopamine (Benedetti 2013). On the other hand, negative expectations induce feelings that increase threat-related areas of the brain, such as cholecystokinin (Benedetti 2013).

Classical conditioning is another psychological mechanism that can contribute to placebo effects (Colloca and Miller 2011). It involves the pairing of an active treatment (e.g., painkillers, anti-depressants) with a positive outcome, such as pain relief or symptom improvement, and then replacing it with a placebo. Conditioning mechanisms are crucial elements of placebo effects, because previous experiences with a given treatment may lead to strong placebo effects (Benedetti and Amanzio 1997, Benedetti, Pollo et al. 2007). Over time, the individual may associate the treatment with a positive outcome, and experience positive outcomes simply from receiving the treatment, even when it is replaced by a placebo. For example, if a patient is repeatedly given a painkiller that is coupled with feelings of pain relief, they might associate the administration of the medication with reductions of pain. Over time, after being conditioned to the repeated positive effects of the medication, they may experience a placebo effect when the drug is replaced by a placebo. That said, classical conditioning can be particularly effective in cases in which an individual has previously experienced positive outcomes from a particular treatment or medication. In such cases, the individual would develop a strong association between the treatment and the positive outcome (i.e., framed as a learning phenomenon), making it more likely that they will experience a placebo effect in the future.

It is important to note that expectancy and conditioning are not mutually exclusive (Stewart-Williams and Podd 2004), as conditioning can lead to the reinforcement of different expectations about a given treatment. They may, therefore, overlap in some situations, although it is not entirely clear how they are involved in different types of placebo effects. Although placebo effects have been extensively investigated from the lens of both expectancy and conditioning, some studies argued that those two mechanisms are not exhaustive enough to fully explain it (Geers and Miller 2014) and it is likely that other factors might play a role. However, most of placebo effects research has manipulated those factors using different designs and found that they can account for most of the reported results. It must be acknowledged that although those psychological mechanisms are an important way to manipulate participants' expectancy about a treatment, which may also include a conditioning procedure and a

resultant observed effect, they are also accompanied by neurobiological responses. That said, both psychological and biological factors play a role in placebo effects, highlighting its complex nature.

Neurobiological mechanisms. As mentioned previously in this section and elsewhere in this thesis, the study developed by Levine, Gordon et al. (1978) highlighted that placebo effects are not merely a psychological phenomenon, but that it also affects neurobiological responses. They showed that the placebo effects on pain could be reversed by the administration of the opiate antagonist naloxone, suggesting that the neurobiological mechanism of placebo analgesia shares similar pathways as those expected with an active treatment. Their study is considered the landmark when the neurobiology of placebo effects was born (Amanzio and Benedetti 1999). Several more recent studies were published since the work of Levine, Gordon et al. (1978) demonstrating that expectation and conditioning (see above) induce placebo effects which operate via different neurobiological pathways (Benedetti, Mayberg et al. 2005, Beedie, Benedetti et al. 2018). Such body of research has demonstrated that there are several neurobiological mechanisms behind placebo effects, including the mediating role of endogenous opioid and dopaminergic pathways.

Several brain regions are involved in placebo effects (Benedetti, Carlino et al. 2011). The prefrontal cortex, for example, is a region involved in cognitive processes such as attention, decision-making and memory, which play a crucial role in placebo effects (Colloca, Benedetti et al. 2008). It also seems that the prefrontal cortex is involved in the top-down modulation of pain perception, which is affected during placebo analgesia (Crawford, Mills et al. 2021). The amygdala, which is an important brain region involved in emotional processing, might also influence pain perception through interactions with the prefrontal cortex, and reductions in its activity are linked with placebo analgesia.

The role of endogenous opioid and dopaminergic pathways play a key role in pain perception, reward processing and emotional regulation (Benedetti, Mayberg et al. 2005, Beedie, Benedetti et al. 2018). The opioid system is a complex network of receptors and neurotransmitters in the brain that play an important role in pain regulation, reward and addiction. Several studies have shown that the administration of placebos can activate these neurobiological pathways, which have important implications for health, illness or fitness (Amanzio and Benedetti 1999, Brietzke, Cesario et al. 2022, Shafir, Israel et al. 2023). For example, the study developed by Amanzio and Benedetti (1999) aimed to investigate the underlying neurobiological mechanisms of placebo-induced analgesia. Their results showed that the participants' expectations of pain relief from the administration of a placebo, activated the opioid system in the brain, which in turn resulted in pain reduction. However, placebo effects were blocked when the opioid antagonist naloxone was administered, evidencing the role of the endogenous opioid system. Their findings and others (Benedetti and Dogue 2015) demonstrated that placebo

effects trigger neurobiological responses, similar to an actual treatment and that the specific mechanisms depend on contextual cues that affect self-regulatory systems.

Previous studies have suggested that cannabinoid receptors also play an important role as a mediator of placebo analgesia (Benedetti, Amanzio et al. 2011). Such mechanism is mediated by psychological factors such as expectancy and conditioning, which activate the opioid system and the cannabinoid receptors, respectively (Amanzio and Benedetti 1999). Amanzio and Benedetti (1999) showed that naloxone blocked placebo analgesia induced by morphine expectations, whereas placebo analgesia induced by conditioning with the cannabinoid receptor agonist ketorolac, was insensitive to naloxone. Benedetti, Amanzio et al. (2011) showed that the cannabinoid receptor antagonist rimonabant had no effect on opioid-induced placebo analgesia with morphine but reversed placebo analgesia following non-opioid conditioning with ketorolac. Those findings, and others (Jennings, Okine et al. 2014), suggest that placebo analgesia can be mediated by both opioid and cannabinoid receptors, which is also dependent on participants' previous experiences with a given treatment (e.g., pharmacological drugs).

As mentioned above, given that expectancy and conditioning influence placebo effects, which foresee a positive outcome, they might be considered reward expectations (Theodosis-Nobelos, Filotheidou et al. 2021), indicating the significant role of dopamine in the reward system of the brain (Lidstone, Schulzer et al. 2010). The reward system is a complex network of neural pathways that plays a crucial role in the regulation of behaviour, motivation, and learning (Schultz 2006, Brietzke, Cesario et al. 2022), which induces pleasurable feelings associated with rewards. The reward system emerged due to the connection between brain regions associated with placebo expectations and reward, which induce the release of endogenous opioids in the brain, potentially producing a sense of well-being and pleasure (Lidstone, Schulzer et al. 2010). When an individual receives a placebo treatment, their brain may interpret the experience as a positive reward, triggering the release of endorphins and other neurotransmitters, which can lead to an improvement in symptoms.

Although much of the previous research has focused on clinical settings providing interesting insights, few studies investigated the neurobiological responses to placebo effects in sport and exercise settings. In a study mentioned previously in this section, Benedetti, Pollo et al. (2007) induced robust placebo effects from morphine administration simulating a sport situation, simulating a competitive environment. Apart from the performance outcomes reported, when participants received the opioid antagonist naloxone, the positive effects of morphine preconditioning were completely blocked, highlighting the activation of endogenous opioids after placebo administration. Their study has

important implications, showing that pharmacological conditioning has long-lasting effects, that could potentially affect performance during training or competition.

PLACEBO AND SPORTS PERFORMANCE

Placebo effects research has long been associated with clinical settings, where a patient's belief in the effectiveness of a treatment can lead to an improvement in their symptoms. However, recent research has shown that placebo effects are not limited to clinical settings and can also be observed in sports settings. For example, athletes who believe they are using a performance-enhancing substance, even if it is a placebo, may experience an improvement in their performance. This highlights the importance of beliefs and understanding placebo effects from various contexts and populations, including elite or recreational sport. It also raises important ethical questions about the use of placebos in sport and the potential for deception in the pursuit of athletic success. The following paragraphs provide a comprehensive review of the studies published to date that investigated placebo effects in sports contexts, induced by different strategies.

As mentioned earlier, placebo effects are a result of social interactions between the individual administering the placebo (e.g., coaches, researchers, practitioners) and the one receiving the placebo (e.g., athletes, study participants) (Davis, Hettinga et al. 2020). Although the most prevalent strategy of inducing placebo effects in sports and exercise sciences is through nutritional ergogenic aids (e.g., caffeine, sodium bicarbonate and anabolic steroids), other different strategies have been reported in the literature (Hurst, Schipof-Godart et al. 2020). For example, studies have shown that interventions, such as transcutaneous electrical nerve stimulation and ischemic preconditioning (i.e., termed mechanical ergogenic aids), might also induce placebo effects. Moreover, few studies reported placebo effects induced by the manipulation of sports equipment, such as tennis rackets (Guillot, Genevois et al. 2012), rolling skis (Blumenstein, Abrahamsen et al. 2021) or running shoes (Hunter, McLeod et al. 2019). It has been proposed recently that opponents and teammates might even act as social placebos by altering athletes' psychological outputs and beliefs in their ability vs. the qualities of the opponents and can improve performance (Davis, Hettinga et al. 2020). Taking this into perspective, Davis, Hettinga et al. (2020) proposed that competitors, teammates, coaches and/or researchers might act as social placebos and induce improvements in athletes' performance that, at least in part, share the same neurophysiological pathways as placebo effects induced by active substances. Such an idea comes from the fact that the presence of others might alter athletes' psychological outputs, such as motivation, perceptions of pain, fatigue and perceived exertion, which are features similar to that of placebo effects (Schiphof-Godart and Hettinga 2017, Konings and Hettinga 2018, Konings, Parkinson et al. 2018, Brietzke, Cesario et al. 2022). Indeed, studies have

shown that the mere presence of a passive observer improves performance through social facilitation (Triplett 1898, Uziel 2007, Edwards, Dutton-Challis et al. 2018), whereas opponents additionally affect athletes' performance inducing changes in perceptions of effort and motivation during exercise (Schiphof-Godart and Hettinga 2017, Konings and Hettinga 2018).

In the aforementioned systematic review (Hurst, Schipof-Godart et al. 2020), the authors showed that placebo effects induced by a purported anabolic steroid had the largest effects on performance. For instance, Ross, Gray et al. (2015) reported significant improvements in running performance when participants self-administered subcutaneous saline injections (i.e., placebo), believing it to be "OxyRBX", a made-up substance supposed to yield similar effects to recombinant human erythropoietin (EPO). The participants reported reductions in physical effort, increased motivation, and improved recovery in receipt of the placebo injections. Other studies also investigated placebo effects induced by mimicking substances such as caffeine (Beedie 2010, Hurst, Schipof-Godart et al. 2019), beta-alanine (Bellinger and Minahan 2016), sodium bicarbonate (McClung and Collins 2007, Higgins and Shabir 2016), amino acids (Kalasountas, Reed et al. 2007) and carbohydrates (Clark, Hopkins et al. 2000, Hulston and Jeukendrup 2009) on exercise performance. Performance changes, resulting purely from the belief of ingesting a purported ergogenic aid, ranged from -1.9% to 25.9% in comparison to a baseline trial for a series of different sports including weightlifting, endurance, and sprinting,

Hurst, Schipof-Godart et al. (2020) also provided an overview of 12 studies that investigated the placebo effects induced by mechanical ergogenic aids. These involved transcutaneous electrical nerve stimulation (TENS), magnetic wristband, cold-water immersion, ischemic preconditioning, and kinesiology tape. They found moderate to large effects induced by TENS, including a total of 113 participants. In the four studies analysing placebo and nocebo effects induced by TENS on force production by the right index and leg extension, performance changes ranged from -12.9% to 14.4%. Other studies further investigated the effects of kinesiology tape on muscle function and force production (Poon, Li et al. 2015, Cai, Au et al. 2016, Cheung, Yau et al. 2016) and failed to report any significant changes in performance compared to a baseline trial or a placebo. The placebo effects induced ischemic preconditioning was investigated in a few studies (Marocolo, Da Mota et al. 2015, Ferreira, Sabino-Carvalho et al. 2016, Sabino-Carvalho, Lopes et al. 2017, Cheung, Slysz et al. 2020) and Marocolo, Da Mota et al. (2015) reported an improvement of 0.9% in swimming performance when the placebo was administered in comparison to a control trial. However, Ferreira, Sabino-Carvalho et al. (2016) failed to find any significant differences between the placebo and control (0.1% change), although they found significant improvements after ischemic preconditioning (1.2%). One

study investigated the effects of magnetic wristbands, which were supposed to improve balance, strength and flexibility (Brazier, Sinclair et al. 2014) and failed to find any differences in performance over different tests. Broatch, Petersen et al. (2014) investigated the physiological responses to cold-water immersion and compared it against a placebo intervention. They found that the placebo intervention was superior to thermoneutral-water immersion (control) in the recovery of muscle strength, and it was similar to cold-water immersion. The results were attributed to improved readiness for exercise, pain and vigour, suggesting that the benefits associated with cold-water immersion are at least partially, induced by placebo effects.

A few studies investigated the placebo effects induced by sports equipment on performance. Guillot, Genevois et al. (2012) analysed how a modified tennis racket, purported to enhance performance, affected tennis serve accuracy scores. They found that the 'placebo rackets' enhanced accuracy performance by 5.7%, in comparison to the control group. In another study, Blumenstein, Abrahamsen et al. (2021) investigated whether hypothetical differences in rolling-skis resistance affected junior cross-country skiers' performance over a time trial. Although the rolling resistance was kept constant, participants performed worse when they believed the roller skis had higher resistance, thus their mistaken belief was that this would impede performance (i.e., negative effect – nocebo). The combined results of both studies suggest that athletes' beliefs and perceptions about their equipment may also affect their performance. These results are particularly important at the moment, as recent men's and women's world records in long-distance running have been broken by runners wearing new running shoes that are purported to increase performance by ~4% (Poon, Li et al. 2015). It is likely that the new shoes, which are composed of a full-length carbon-fibre plate embedded within the shoes' foam, deliver a mechanical advantage (Hoogkamer, Kipp et al. 2018, Barnes and Kilding 2019, Hunter, McLeod et al. 2019), but the potential placebo effects cannot be disregarded until full placebo-controlled trials are published.

Due to the potential for performance improvements, it is perhaps unsurprising that coaches and athletes might adopt placebo interventions during their training programme to enhance outcomes (Szabo and Müller 2016) by exploring untapped psychological potential (Beedie and Foad 2009). Szabo and Müller (2016) investigated coaches' attitudes toward placebo interventions and found that nearly half of the coaches included in the study (n = 96) admitted to giving a placebo of some kind to their athletes. While it may be considered part of the training method for coaches to psychologically influence the beliefs of their athletes, some authors (Benedetti, Pollo et al. 2007) have expressed ethical concerns about the use of such placebo interventions. Benedetti, Pollo et al. (2007) raised such debate by demonstrating it is possible to induce robust placebo effects after the repeated

administration of a drug/substance is replaced by an inert substance, where the recipient still believes they are in receipt of such drug/substance. Their study suggested the analgesic effects of morphine could last beyond the period in which morphine was administered through the use of a placebo. This effect is particularly important given that, according to the latest 2023 WADA Prohibited List, substances such as morphine are banned only during competitions, but athletes are allowed to administer it while training. The placebo effects induced by morphine administration, therefore, could perhaps last through to cover competition when timed appropriately.

PLACEBO EFFECTS AND EXERCISE DEMANDS

The previous section illustrated the different ways of inducing placebo effects reported in the literature. However, it is important to consider how different exercise demands are affected by placebo effects. The following sections represent a comprehensive summary of the results of different studies that investigated placebo effects induced by different ergogenic aids on endurance, sprinting and muscle strength performance. For a clear comparison, the placebo effects induced by social interventions, such as the presence of opponents, are summarised further below in a separate section. Placebo effects induced by nutritional ergogenic aids received more attention, given that the placebo effects induced by mechanical ergogenic aids were summarised previously and that the small number of studies does not allow for clear comparisons.

Applied outcomes: endurance performance. The first study to investigate the placebo effects on endurance performance appears to have been developed by Clark, Hopkins et al. (2000). In their study, 43 endurance cyclists performed two 40-km cycling time trials and ingested a drink containing either carbohydrates or a placebo before the experimental time trial. The authors found that when participants received a placebo described as carbohydrates, performance increased by 4.3%. However, Hulston and Jeukendrup (2009) did not find any placebo effects induced by a placebo solution described as carbohydrates, whereas performance was increased by 10.6% when they ingested the carbohydrate drink before a ~60 min time trial completed after a 120-min fixed-intensity cycling task. The disparities between both studies might be regarded by key differences in the experimental protocols. Although the time trial duration was similar (~60 min), the study by Hulston and Jeukendrup (2009) included a period of 120 min of fixed-intensity cycling before the time trial, which depleted the glycogen stores, and these were at least partially replenished when they ingested the carbohydrate drink. Given that carbohydrate availability might not limit performance during the relatively short exercise duration adopted by Clark, Hopkins et al. (2000), it is possible that placebo effects accounted for the ergogenic effects found in their study.

Some studies further investigated the placebo effects induced by caffeine ingestion on endurance performance. Beedie, Stuart et al. (2006) reported a mean increase of 3.1% in power output over a 10-km cycling time trial when participants believed they ingested a capsule containing 9.0 $mg.kg^{-1}$ of caffeine, even though they received a placebo. In a study adopting a balanced-placebo design, Foad, Beedie et al. (2008) reported mean increases of 2.3% and 2.9% in power output over a 40-km time trial, during the overt and hidden administration of caffeine, respectively. Saunders, de Oliveira et al. (2017) found that when athletes received a placebo perceived as caffeine, their performance increased by 1% during a fixed-work time trial lasting ~30 min. They also showed that the participants who believed they ingested a placebo decreased performance by -1.4%. Similarly, Pires, Dos Anjos et al. (2018) found that caffeine and placebo perceived as caffeine improved peak power output by 11.2% and 11.9%, and time to exhaustion by 15.4% and 17.4%, respectively, during a maximal incremental test. Collectively, the results of these studies suggest robust placebo effects induced by the belief of ingesting caffeine in a range of different endurance exercises, even when different protocols were adopted. In placebo effects experimental interventions, it is crucial that researchers are able to induce positive beliefs about the purported treatment. Caffeine is one of the ergogenic aids with the largest amount of evidence showing a positive effect on performance (Grgic, Grgic et al. 2020), which might contribute to induce strong positive beliefs when the active substance is replaced by a placebo.

Other studies reported placebo effects induced by the administration of sodium bicarbonate, beta-alanine or a placebo injection described as an anabolic steroid. More specifically, McClung and Collins (2007) reported that when runners ingested sodium bicarbonate or a placebo described as sodium bicarbonate before a 1000-m time trial, performance was improved by 1.7% and 1.5%, respectively. However, when participants received sodium bicarbonate expecting a placebo, performance changed by -0.3%, suggesting that benefits associated with sodium bicarbonate ingestion are based on the expectancy of receiving an ergogenic aid. Bellinger and Minahan (2016) reported improvements in performance during 1 km cycling time trials from the overt (2.4%) and hidden (1.8%) administration of beta-alanine, although the differences were not significant. Given the small number of studies investigating placebo effects induced by such substances, more evidence is needed to elucidate the mechanisms behind changes in performance. Interestingly, Ross, Gray et al. (2015) investigated the effects of an injected placebo during 3000-m running time trials. In their study, participants were informed they would receive an injection of "OxyRBX" before the time trial, which was described as a drug purported to have similar effects to recombinant human erythropoietin. They found that runners improved their performance by 1.2% when they received the placebo injection in comparison to the control trial, and their participants reported a reduction in physical effort, increased motivation and improved recovery. As highlighted in their study, the differences between the gold

medal and the fourth place in all running events from the 1,500 m to the 10,000 during the 2012 Olympics was less than 1%, suggesting that, indeed, properly timed and administered placebo effects could influence competition rankings.

Applied outcomes: multiple athlete competitive performance. As mentioned in a previous section of this chapter, the mere presence of a passive or active observer is known to augment aerobic and anaerobic performances (Uziel 2007, Edwards, Dutton-Challis et al. 2018). This is, in effect, a social placebo in action and might suggest that all 'observed' laboratory-controlled studies are, to some extent, influenced towards a positive (rather than negative) performance outcome. The addition of multiple athletes/opponents adds further complexity and the opportunity to induce a meaningful performance effect on top of anything achievable by social facilitation alone. The effects of opponents on endurance performance have attracted the interest of sports scientists for over 100 years. For example, Triplett (1898) was the first to analyse how different cycling environments affected performance during individual time trials and/or competitions. This was the first study to demonstrate that athletes are able to ride faster when competing against an opponent and suggested that, in the author's words, "the bodily presence of another contestant participating simultaneously in the race serves to liberate latent energy not ordinarily available". Several years after the seminal work of Triplett (1898), Wilmore (1968) developed a very interesting study investigating the physiological responses to head-to-head cycling competitions, in an attempt to better understand the mechanisms behind performance improvements. He was probably the first to hypothesize that if performance improvements during competition are linked purely to psychological constructs, such as the ability to "tolerate anaerobic metabolism", there would be no changes in respiratory responses in comparison to individual exercise tasks. To test this hypothesis, their participants completed 3 time-to-exhaustion tests on a cycling ergometer, composed of 2 individual and 1 competitive trial. During the competition trial, participants were matched based on the performance achieved during the individual trials and cycled alongside each other, in an attempt to induce a simulated competition between them. They showed that time to exhaustion and work were higher during competition than when participants cycled individually, and that there were no concomitant increases in mean $\dot{V}O_2$, $\dot{V}_E$ and heart rate, accounting the improvements in performance to higher motivation. The results of the studies of Triplett (1898) and Wilmore (1968) still have implications to this day, and it is possible that their findings were at least partially linked to placebo effects induced by social interactions with competitors, and that athletes were able to explore untapped psychological potential. Indeed, in a more recent meta-analysis involving several different competitive cycling interventions, Davies, Clark et al. (2016) reported that the presence of an opponent increases athletes' performance, which is partially explained by higher motivation and changes in pacing especially at the start of the time trials. Given

that performance improvements were linked to alterations in psychological outputs, it is possible to assume that the presence of opponents is at least partially associated with placebo effects (Davis, Hettinga et al. 2020), although more evidence is warranted.

Recently, several experimental studies aimed to analyse how interactions with virtual opponents affect performance in a laboratory-controlled environment, to better understand the mechanisms behind this phenomenon (Table 1). From the current literature, most studies adopted deceptive interventions whereby participants competed against an on-screen avatar replicating their own performance achieved during individual time trials but informed it represented the performance of another cyclist of similar ability. For example, Corbett, Barwood et al. (2012) found performance improvements during 2-km cycling time trials when participants competed against an opponent replicating their best individual baseline performance, but were informed it represented the performance of another cyclist of similar ability. Similarly, Williams, Jones et al. (2015) found similar results and reported performance improvements of 2.8% during 16.1-km cycling time trials when participants competed against an opponent replicating their individual baseline performance, believing it to be an opponent of similar ability. They also reported reduced internal attentional focus during the competition trial and lower RPE, which resulted in increased fatigue tolerance. Moreover, Konings, Parkinson et al. (2018) showed that athletes improved 4-km cycling time trial performance when they competed against a virtual avatar representing their baseline performance, in comparison to riding alone. They also reported that improvements were accompanied by a greater decline in muscle force, although RPE was the same. To further elucidate the psychophysiological mechanisms behind improvements in performance during competition, Stone, Thomas et al. (2012) adopted a deceptive intervention including an augmented feedback condition, whereby participants surreptitiously competed against an avatar riding at 2% higher power outputs during a 4-km cycling time trial, but believed it represented the performance of another cyclist of similar ability. They found mean improvements in performance of 1.7% in comparison to a baseline individual time trial and attributed such improvements to a greater anaerobic energy contribution. Similarly, Ansdell (2018) found improvements during 4-km cycling time trial performance when athletes competed against an on-screen avatar surreptitiously riding at 2% higher power outputs than a baseline trial, although peripheral fatigue and RPE were the similar between conditions, attributing changes in performance to an altered pacing. Several other studies reported performance improvements using augmented feedback in comparison to individual time trials, reporting changes in psychological outputs, such as motivation, attentional focus and fatigue tolerance (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Davies, Clark et al. 2016).

Although the effects of opponents on performance are well-established during long-duration exercises, from the author's knowledge, only one study investigated the effects of opponents on short-duration exercise (< 2 min duration). More specifically, Wood, Bui et al. (2020) investigated the effects of head-to-head competitions during 1-km cycling time trials. In their study, participants competed against a virtual opponent replicating their individual time trial performance, thinking it was the performance of another cyclist of similar level. Contrasting the previous findings during long-duration time trials, they reported no differences in finishing times, mean power output, pacing and RPE. Their findings suggest that athlete-environment interactions may be affected by the duration of the exercise. However, the literature lacks more studies investigating the effects of opponents on performance and pacing during short-duration (< 2 min) exercises.

Several other studies reported similar results (Konings, Schoenmakers et al. 2016, Menting, Elferink-Gemser et al. 2019, Konings, Foulsham et al. 2020), and for a more comprehensive review please refer to Jones, Williams et al. (2013), Williams, Jones et al. (2014), Davies, Clark et al. (2016), Konings and Hettinga (2018) and Hettinga, Konings et al. (2017). Collectively, the results of these studies agree with the early findings of Triplett (1898) and show robust improvements in performance when athletes compete against a virtual opponent, irrespective of the intervention adopted (i.e., deceptive or accurate). The mechanisms behind such improvements are linked to alterations in psychophysiological factors, such as muscle force decline, greater anaerobic energy contribution, increased motivation, willingness to sustain fatigue and changes in pacing.

Table 1. Overview of the studies investigating cycling performance and competitions, using simulated avatars as opponents.

Study	Experimental design	Sample size and characteristics	Exercise protocol	Augmented feedback	Type of deceptive intervention		Performance Outcomes	Pacing outcomes
					Informed	Received		
(Corbett, Barwood et al. 2012)	Within-subjects	14 physically active men	2-km cycling time trials	No	Time trial against an opponent of similar ability	Time trial against an opponent representing their baseline performance	Riding against a virtual opponent increases time trial performance, mainly by an increased anaerobic energy yielded.	Higher power outputs in the second half of the time trial.
(Stone, Thomas et al. 2012)	Within-subjects	9 trained male cyclists	4-km cycling time trials	Yes	Time trial against an opponent of similar ability.	ACC: Time trial against an opponent representing their baseline performance DEC: Time trial against an opponent 2% faster than baseline performance	Participants completed ACC and DEC quicker than baseline; and DEC quicker than ACC. Performance improvements are associated with increased anaerobic energy contribution.	N/A
(Williams, Jones et al. 2015)	Within-subjects	15 competitive male cyclists	16.1-km cycling time trials	No	Time trial against an opponent of similar ability	Time trial against an opponent representing their baseline performance	Greater power output, heart rate, and speed during competition; unchanged RPE. Reduced internal attentional focus.	No differences in pacing (absolute power output).
(Williams, Massey et al. 2015)	Within-subjects	12 trained male cyclists	16.1-km cycling time trials	Yes	Time trial against opponents of similar ability.	Time trials against an opponent 2% higher speeds than fastest baseline; or opponent 5% higher speed than fastest baseline; or against both opponents (+2% and 5%).	Participants improved performance (time to completion) in all competitive trials: 1.4% during $TT_{102\%}$, 1.3% during $TT_{105\%}$, and 1.7% during $TT_{102,105\%}$.	No differences in pacing (relative speed)

(Jones, Williams et al. 2016)	Between-subjects	20 trained male cyclists CON: 10 DEC: 10	16.1-km cycling time trials	Yes	Time trial against a 'pacer' replicating fastest baseline performance	Time trial against a pacer 2% faster (DEC group) or replicating baseline performance (CON group);	Time trial performance increased (time to completion) to a similar extent in both groups. Negative perceptual responses during DEC (affect and self-efficacy). Higher RPE during competition for DEC group only.	N/A
(Jones, Williams et al. 2016)	Between-subjects	17 trained male cyclists CON: 9 DEC: 8	16.1-km cycling time trials	Yes	Time trial against an opponent 2% faster (CON) or replicating baseline performance (DEC)	Time trial against an opponent 2% faster	Time trial performance increased (time to completion) to a similar extent in both groups. Negative perceptual responses and higher RPE during DEC and CON (affect and self-efficacy)	N/A
(Shei, Thompson et al. 2016)	Within-subjects	14 male cyclists	4-km cycling time trials	Yes	Time trial against an opponent replicating the same power output of baseline (DEC); or against an opponent riding at 2% higher power outputs (ACC)	Time trial against an opponent riding at 2% higher power output	Time to completion and power output increased in both competitive trials in 10 participants. Motivation and RPE did not change.	No differences in pacing (absolute power output).
(Williams, Jones et al. 2016)	Within-subjects	10 trained male cyclists	16.1-km cycling time trials	Yes	Time trial following an opponent (no further information about opponent's performance)	Time trial following an opponent either at the same baseline speed; 5% faster; or 5% slower during the initial 4-km	Enforcing an initial speed 5% faster/slower than baseline does not affect time trial performance, although less physiological strain and positive psychological responses; a slow-start produced more positive perceptions and lower RPE.	N/A (manipulation of pacing during the initial 4-km)
(Stone, Thomas et al. 2017)	Within-subjects	10 trained male cyclists	4-km cycling time trials	Yes	Time trial against an opponent representing their baseline performance	Time trial against an opponent 2% faster; or 5% faster than baseline	Power output, speed and time to completion improved during 2% deceptive trial, but not during 5%; $\dot{V}O_2$, $\dot{V}CO_2$, RER, [La] and RPE unchanged between conditions.	Power output higher during both competitions at 2 km for 2% condition; and at 3.2 km for 5% condition.

(Ducrocq, Hureau et al. 2017)	Within-subjects	11 recreationally active individuals (3 women and 8 men)	5-km cycling time trials	Yes	Time trial against a "pacer", replicating baseline performance	Time trials against an opponent replicating baseline performance; or 2% faster; or 105% faster	Higher power output and lower time to completion in comparison to BSL only during 102%. In comparison to 100%, 102% yielded improved performance. $\dot{V}O_2$ and $\dot{V}CO_2$ higher during 102% in comparison to 100% but not from BSL. Lactate not different. Higher $\dot{V}E$ during 102% and 105% in comparison to 100%.	Higher initial power outputs during augmented feedback conditions (102% and 105%; but participants requested to follow the avatar).
(Konings, Parkinson et al. 2018)	Within-subjects	12 trained male cyclists	4-km cycling time trials	No	Time trial against an opponent of similar ability	Time trial against an opponent replicating baseline performance	Power output increased during competition in comparison to individual time trial; RPE unchanged, but higher heart rate throughout competition.	Higher initial and final power outputs during competition in comparison to individual time trial (absolute power output)
(Konings, Schoenmakers et al. 2016)	Within-subjects	12 physically active individuals	4-km cycling time trials	No	Time trial against an opponent of similar ability.	Time trials against an opponent who started slower and finished faster than baseline; or against a virtual opponent who started faster and finished slower than baseline.	Performance increased (time to completion and power output) during both opponent conditions.	Faster opponent evoked higher absolute initial power outputs in comparison to the slower opponent.
(Wood, Bui et al. 2020)	Within-subjects	12 physically active male individuals	1-km cycling time trials	No	Time trial against an opponent of similar ability	Time trial against a virtual opponent replicating baseline performance	Time to completion, power output and RPE were not different between all conditions.	No differences in pacing (absolute power output).

(Ansdell, Thomas et al. 2018)	Within-subjects	10 trained cyclists	4-km time trials	Yes	Time trial against an opponent representing their baseline performance	Time trial against a virtual opponent riding at the same power output of baseline (CON) or 2% higher (DEC).	Time to completion decreased during DEC in comparison to BSL, but not during ACC. However, mean power output was not significantly different; higher [La] during both only during DEC in comparison to BSL, but same RPE and neuromuscular fatigue levels between all conditions;	No differences in pacing (absolute power output).
(Crivoi do Carmo, Renfree et al. 2022)	Within-subjects	13 recreational male cyclists	10-km cycling time trials	Yes	Time trial against an opponent of similar ability	Time trial against a virtual opponent riding 6% faster or 3% slower than BSL.	Time to completion, power output, RPE and affect not different between time trials. Self-efficacy lower during fast opponent in comparison to BSL and slow opponent.	Lower power outputs during initial phases of the individual time trial in comparison to competitions; higher end spurt during individual time trials.

CON: control; BSL: baseline; DEC: deception condition; ACC: accurate condition.

Applied outcomes: sprinting and muscle strength performance. Previous studies investigated the placebo effects induced by different ergogenic aids on sprinting performance. Beedie, Coleman et al. (2007) analysed whether a placebo capsule described as either a substance that improves or decreases performance affected mean speed during 3x 30-m repeated sprints. The group that received the negative information (i.e., capsule detrimental to sprint performance), decreased performance by -1.7%, whereas no improvement was found in the positive information group. However, the authors suggested that the positive group were able to maintain a higher speed throughout the repeated sprints, indicative of a placebo effect. Their study was the first to evidence a nocebo effect—that is, a decrease in performance induced by negative beliefs resulting from a placebo intervention (Benedetti, Lanotte et al. 2007, Colloca and Barsky 2020, Hurst, Schipof-Godart et al. 2020). Using a similar design, Hurst, Foad et al. (2017) investigated the placebo and nocebo effects induced by an inert capsule described either as a powerful supplement that would improve or decrease sprinting performance. Compared to the control condition, speed was lower when participants received the capsule purported to decrease performance (-0.9%), although performance did not change for the participants that received the positive information. The results of both studies suggest that it might be challenging to induce placebo effects (or at least identify them) during very short exercise durations. It might be that short-duration exercises suffer less influence from external factors, such as environmental conditions and pacing (Abbiss and Laursen 2008, Foster, Hendrickson et al. 2009, Edwards and Polman 2013, Konings and Hettinga 2018) and are highly dependent on physical fitness rather than psychological outputs (e.g., motivation, decision-making…)—a key feature of placebo effects. In the study of Beedie, Coleman et al. (2007) it was further suggested that negative beliefs could be more powerful than positive beliefs in an intervention, although this is speculative. Perhaps even more importantly, in both studies, the authors used made-up substances which might impose a new challenge when trying to induce positive beliefs about a substance. The lack of robust specific scientific evidence showing the substance efficacy might have influenced the participants' beliefs.

In another study investigating the placebo effects on sprinting performance, Tolusso, Laurent et al. (2015) investigated whether a placebo drink (described as an ergogenic substance) affected performance during 3x "running-based anaerobic sprint tests" (RAST) completed on two consecutive days and found improved peak and mean power output when compared to the control condition. Similarly, de la Vega, Alberti et al. (2017) investigated whether a fictive and inert drink affected 200-m sprint performance. Their participants were split into three groups that only differed in the information received: 1) positive group: the drink improves performance; 2) partial positive: the drink may or may not improve performance; 3) neutral: the drink does not affect performance. They found

that the positive group improved performance by 2.41 s (6.2%) compared to the baseline trial, whereas partial positive and neutral groups ran 0.97 s and 0.72 s faster, although not significant. Both studies adopted longer short-duration exercises in comparison to the studies of Beedie, Coleman et al. (2007) and Hurst, Foad et al. (2017) aforementioned, which might explain the disparities. In the study by Tolusso, Laurent et al. (2015) the participants were required to complete a total of 18x 35m sprints on two consecutive days. It is possible to assume that this protocol might have induced considerable fatigue (confirmed by their results) and thus, psychological outputs such as motivation, and willingness to sustain exercise-induced pain, might have played an important role.

The first study to investigate whether placebo effects might influence muscle strength performance was published by Ariel and Saville (1972). For four weeks their participants received a placebo pill described as an anabolic steroid on a daily basis before a strength training session and after the intervention, force production improved by an average of 9.5%. Similarly, Maganaris, Collins et al. (2000) administered a placebo pill described as a powerful anabolic steroid and reported an improvement of 4.6% in the weight lifted. They also reported that when athletes were disclosed that they received a placebo, performance improvements were dissipated, enforcing the notion that expectancies about the pill affected their performance. The results of both studies suggest robust placebo effects induced by anabolic steroids on performance, which was also confirmed in a previous systematic review (Hurst, Schipof-Godart et al. 2020). Kalasountas, Reed et al. (2007) adopted a similar design to the studies aforementioned and informed their participants that they would receive a "strong combination of amino acids" and that the effects on strength performance would be immediate. They reported an average improvement of 11% in the weight lifted and when the true nature of the substance was disclosed, force production returned to control levels, a feature similar to the studies of Ariel and Saville (1972) and Maganaris, Collins et al. (2000). Although these studies did not investigate the mechanisms behind improvements in performance, they suggest that a positive attitude towards an ergogenic substance affects muscle strength performance through untapped psychological factors.

In another study, Pollo, Carlino et al. (2008) investigated the effects of a placebo drink, described as containing a high dose of caffeine, on leg extension performance. In the first part of the experiment, they found a significant increase in muscle work (11.8%) when participants received the placebo drink. Subsequently, they used a conditioning procedure (Benedetti, Mayberg et al. 2005, Colloca and Benedetti 2005), whereby the administration of the placebo drink was coupled with a surreptitious reduction in the amount of weight lifted, to enforce beliefs that the task was easier after taking the drink. They reported an even larger improvement of 22.1% in muscle work when the load was restored

to baseline. Similarly, Duncan, Lyons et al. (2009) investigated the effects of a placebo perceived as caffeine on leg extension performance. When participants perceived they ingested caffeine before the task, they completed more repetitions (at 60% of 1RM) and increased the total weight lifted with lower ratings of perceived exertion. Collectively, the results of the previous study suggest robust placebo effects induced by different placebo interventions on muscle performance. It seems that a conditioning protocol might induce even larger placebo effects, which is explored in more detail in the systematic review by Hurst, Schipof-Godart et al. (2020).

Collectively, it is clear that the literature on placebo effects during short-duration exercises is still scarce in comparison to endurance exercises and displayed contrasting results. There is a vast difference in protocols adopted, using different exercises, different ways of inducing placebo effects, and reporting different outcomes, which further complicates the application of results. However, from the results of the studies reported previously in this section, it seems like short-duration exercises are also susceptible to placebo effects, although more studies are needed to quantify its real effect on different exercise situations.

PLACEBO EFFECTS AND PACING

As mentioned in CHAPTER ONE, placebo effects might also affect how endurance athletes distribute their effort during a time trial—i.e., their pacing. However, only a few studies analysed changes in pacing resulting from placebo effects induced by ergogenic aids (Hulston and Jeukendrup 2009, Ross, Gray et al. 2015, Hurst, Schipof-Godart et al. 2019). More specifically, Ross, Gray et al. (2015) reported a faster start during 3-km time trials when participants self-administered a placebo injection purported to have similar effects as recombinant human erythropoietin. Similarly, Hurst, Schipof-Godart et al. (2019) reported higher initial running speeds when athletes ingested a placebo described as caffeine during 1000-m time trials. However, in the study of Hulston and Jeukendrup (2009) a placebo solution described as containing carbohydrates did not elicit changes in performance, nor pacing during a ~60 cycling min time trial. Collectively, the results of Ross, Gray et al. (2015) and Hurst, Schipof-Godart et al. (2019) suggest that the administration of a placebo may have increased their confidence in their ability to improve performance, which was also supported by qualitative data collected by Ross, Gray et al. (2015). However, there is a clear lack of studies investigating the placebo effects induced by ergogenic aids on pacing during endurance exercises, highlighting the need of controlling for such outcomes in future interventions.

Although research about placebo effects induced by ergogenic aids and pacing is still in its infancy, the effects of opponents on pacing have been reported in previous studies. For example, Corbett,

Barwood et al. (2012) showed that cyclists were able to keep higher power outputs during the second half of a 2-km cycling time trial during competition in comparison to an individual time trial. Konings, Schoenmakers et al. (2016) showed that a virtual opponent adopting a fast start, evoked substantial changes in cyclists' pacing during 4-km time trials in comparison to an opponent adopting a slow start, or in comparison to an individual time trial. Similarly, Williams, Jones et al. (2016) showed that the manipulation of an opponent's speed during the initial phases of a 16.1-km cycling time trial induced considerable changes in the cyclists' pacing throughout the time trial. Konings, Parkinson et al. (2018), found higher initial power outputs mainly during the start of a 4-km cycling time trial when participants competed against a virtual opponent in comparison to an individual time trial. Other experimental studies showed similar findings, highlighting that the behaviour of opponents affects cyclists' pacing (Stone, Thomas et al. 2012, Jones, Williams et al. 2013, Shei, Thompson et al. 2016) and a previous meta-analysis (Davies, Clark et al. 2016) showed that opponents induce changes in pacing mainly during the start or middle-parts of a cycling time trial. In the same study, the authors reported that several cycling studies were excluded from the analysis for not reporting power output and adopting speed as the main outcome of pacing analysis. This is an important limitation to consider, given that measurement errors of speed from different software or ergometers have not been extensively reported in the literature and might not reflect the athletes' effort accurately. It is imperative that future studies use robust parameters, such as power output, to analyse potential changes in performance and pacing and using virtual opponents that reflect dynamic changes in pacing found in typical racing situations.

VIRTUAL-REALITY SOFTWARE AND SPORTS SCIENCES

Virtual-reality cycling software, such as Zwift, has recently emerged as a popular training alternative among cyclists, driven mainly by the ongoing COVID-19 pandemic (McIlroy, Passfield et al. 2021, Washif, Farooq et al. 2021). In such environments, cyclists interact with each other in a virtual world and can compete against each other. Reflecting the rising interest in July 2020, the first Virtual Tour de France was held on Zwift, including both men's and women's races, featuring professional riders (Westmattelmann, Stoffers et al. 2022), and in December 2020, the *Union Cycliste Internationale* (UCI) hosted the "UCI Cycling Esports World Championships".

Zwift is currently one of the most popular cycling platforms, with more than 2.5 million registered users in 2021, located in more than 190 countries (McIlroy, Passfield et al. 2021). Within Zwift, cycling power output is measured from a smart trainer, which is then converted into an on-screen avatar representing the cyclist's performance. The avatar's speed and distance covered depend on several different factors, such as slipstream/drafting effects, course profiles (i.e., uphill vs downhill

sections), virtual equipment (i.e., lighter bikes or aerodynamic wheels) and the cyclist's height and body mass. The adaptable nature of Zwift allows cyclists to prepare for different kinds of competitions in a time-efficient manner and reducing costs, lessening the need for athletes and coaches/staff to travel, as new courses are continuously being developed, and cyclists can ride in a variety of different worlds, simulating real-world conditions. Zwift has currently over 70 racing courses available simulating official UCI courses, allowing for a greater training specificity from traditional indoor cycling. For example, famous climbs such as the Alpe d'Huez and Mount Ventoux, or famous sprints such as the Champs-Élyssés, can be simulated on Zwift and allow athletes to train or even compete, in the comfort of their homes, close to their families and in a safer way. A recent prospective study (McIlroy, Passfield et al. 2021) described the strengths and weaknesses associated with virtual-reality cycling. Among the strengths, they reported 1) increased affordance, suiting a wide range of budgets; 2) allows for innovative team management strategies; 3) provides realistic simulations of different environments; 4) increases rider safety compared to road cycling; and 5) increased used engagement through gamification. However, the weaknesses may involve 1) variability in the accuracy across platforms and connected devices (e.g. power meters); 2) "cyber-doping" has been previously reported (e.g., manipulation of body mass to increase the power output/body mass ratio, which improves avatar's speed); 3) problems with hardware and different software (e.g., loss of signal or connectivity); 4) technical cycling skills can be reduced.

A recent study involving 12,526 athletes in 142 countries, analysed athletes' training practices during the COVID-19 pandemic and reported that most of them adopted a home-based training strategy as a solution for the unfeasibility of outdoor training (Washif, Farooq et al. 2021). Therefore, remote-based practices, such as the use of Zwift, emerged as an effective technology to assist their training. It is certain that applications like Zwift play a role in helping people maintain their fitness, and potentially in preventing the spread of future pandemics. By providing an additional digital opportunity for exercising, these types of applications can help people stay active and healthy even when they are unable to participate in traditional sports and exercise activities. In addition, the ability to virtually mediate interactions with other users can provide a sense of social connection and support, which can be important for mental health (Wilke, Mohr et al. 2022). Given the increasing popularity of virtual-reality exercise software, it can be a valuable tool for sports scientists as it allows athletes to train and compete virtually, while social distancing.

Although experimental studies assessing performance outcomes in virtual-reality software are still in its infancy, Westmattelmann, Grotenhermen et al. (2021) investigated whether it is possible for virtual sports to have objectively measurable performance parameters that are similar to those of traditional

real-world sports. They found that performance in virtual-reality races does not match the performance of real-world races, as traditional outdoor racing involves longer-race durations. However, when races of similar durations were matched in virtual-reality vs real-world, it is evident that physiological demands are similar. In the same study, they also investigated professional cyclists' perceptions of similarities and differences between real-world and virtual-reality sports. From cyclists' perspective, the organisational aspects of virtual racing are facilitated, and travelling and hotel stays are reduced, which consequently, decreases the overall costs associated with real-world races. It is also evident that interactions with team and staff are reduced, which is particularly important at these times when the risk of COVID-19 infection must be contained. More recently, (Bjärehed and Bjärehed 2022) investigated the dynamics of virtual cycling racing, assessing users' performance over a range of different races and durations and reporting levels of agreement between primary and secondary power meters. Their findings agree with the study mentioned previously in this paragraph (Westmattelmann, Grotenhermen et al. 2021), suggesting that physiological demands of virtual racing might be similar to traditional competitive races as long as the duration is standardised. Moreover, they showed that cyclists' equipment/setup, produces similar power outputs with good agreement between different power meters for the same time points (e.g., 5 s, 15 s, 1 min, 5 min, 20 min). Although the previous studies assessed competitive performance and support the notion that virtual racing might be similar to traditional racing, there is a need for studies assessing the reproducibility of cycling time trials performed on a virtual-reality software (such as Zwift). Analysing the reproducibility of performance during virtual-reality time trials would thus provide important insights for coaches and athletes preparing for races of different durations, and also support researchers aiming to adopt remote interventions to analyse sports performance.

Virtual-reality cycling software, therefore, provides an important, new field of research. Researchers are now able to assess performance outcomes while social distancing, allowing athletes to engage in a virtual world, with the added bonus of decreasing costs associated with traditional laboratory-based studies. The increasing popularity of virtual-reality platforms in recent years has provided a unique opportunity for sports scientists to conduct research on cycling performance in a more efficient and convenient way. It may be argued that developing studies using virtual-reality cycling platforms can provide a more ecologically valid environment for research, as participants would be familiar with the environment and equipment in comparison to laboratory-based studies. This could lead to increased relevance and generalisability of the research findings, as participants will be responding to stimuli that closely mimic real-world cycling conditions. Additionally, the use of virtual-reality platforms can provide a more immersive and engaging experience for participants, which may lead to

improved reliability and applicability of findings. Finally, such platforms offer the opportunity to recruit larger sample sizes, which is often a challenge in sports sciences, allowing researchers to collect relevant data from a diverse range of participants, from any part of the world, and to do so quickly and at a lower cost, improving studies feasibility.

CONCLUSION

The findings reported in this chapter evidence that a competitive edge can be obtained through augmenting beliefs in oneself or the efficacy of performance-enhancing treatments. Placebos have been demonstrated as a means of augmenting performance under certain circumstances and if those situations are applied and timed appropriately then it seems likely that this could lead to performance change. In elite sports, the difference between first and last place can be extremely minor and so any competitive edge is meaningful to potential medallists. However, it is important to note that studies specifically investigating the efficacy of placebo effects typically have utilised small sample sizes and might have failed to find any significant differences because of low statistical power. Most studies were also conducted in highly controlled laboratory environments, which makes the extrapolation of the results to real-world settings difficult. To cover such limitations, an interesting alternative is to develop remote research designs, using virtual-reality software (e.g., such as Zwift), which allows researchers to reach a geographically broad sample, potentially increasing the generalisability of findings.

Placebo effects are, thus, a psychophysiological phenomenon, with the potential of improving performance in a range of different disciplines. It is plausible to suggest, therefore, that most interventions adopted in sports sciences, whether through nutritional or mechanical ergogenic aids, equipment manipulation, or the presence of competitors, might have at least some placebo effects components. It is important that future studies, consider the effects of participants' beliefs on different interventions, attempting to control for changes in performance induced by placebo effects. Whether adopting placebo-effect interventions by coaches is ethically or morally right is another matter that warrants further exploration.

CHAPTER THREE

Reproducibility of cycling performance on Zwift

TRANSITION

The previous chapter provided an overview of the various ways in which placebo effects can be induced and how virtual-reality software may serve as an innovative alternative to traditional laboratory-based studies. However, given that virtual-reality software is still relatively new, it is crucial for researchers to first evaluate how performance and pacing are affected during exercise situations that utilise this technology. Investigating the reproducibility of cycling performance and pacing is a straightforward process of repeating a time trial over a number of times, with a reasonable number of individuals, which provides information about the random error of the outcome measure (e.g., power output). This provides important insights into the random error of the measure and helps researchers to understand the natural variation in performance and pacing. For example, when a group of cyclists performs 2 or more time trials on different days, there will always be a change in the mean power output generated between time trials, even when the conditions are standardised (e.g., same bike, same course, same time of the day, and following the same diet). These natural changes in performance are an important consideration when participants perform a series of time trials as part of an experimental intervention. For example, if a dietary intervention yield changes in performance that are larger than the random error of the performance test being used, coaches can determine whether the intervention was effective. This is crucial for researchers/coaches/athletes/practitioners to be able to accurately evaluate the effectiveness of interventions and make informed decisions about training protocols. That said, the aim of this chapter is to investigate the reproducibility of performance and pacing during cycling time trials performed on the virtual-reality software Zwift. The information presented in this chapter will be essential for understanding the random error of performance and pacing, which will inform the subsequent experimental chapters.

INTRODUCTION

In early- to mid-2020, to prevent the spread of COVID-19, sport and exercise science laboratories worldwide ceased all activity, and social distancing measures were put into force to prevent transmission of the virus (de Boer, Hoekstra et al. 2021). While the pandemic recedes, restrictive measures still exist, and it seems likely the world may not ever fully return to the pre-COVID environment. Nevertheless, it is important for research to continue and thus cycling research is presented with an ethical and practical challenge of examining outcome measures in laboratories (Souza, Bernardes et al. 2022), while at the same time ensuring the health and safety of both researchers and participants. A need, therefore, exists in identifying innovative means to gain meaningful outcome measures that can be conducted in an environment that do not increase the risk of COVID-19 infection. One potential solution is developing remote exercise study designs where possible and appropriate with the use of online cycling platforms that allow for social distancing, yet still provide opportunities for insightful information about cyclists' performance. However, despite the obvious attractiveness of being able to conduct meaningful research in remote settings, outcomes must be robust and reproducible.

As mentioned in CHAPTER TWO, among several online cycling platforms, Zwift (McIlroy, Passfield et al. 2021) is one of the most popular with over 3 million users registered (Reed 2021) in more than 190 countries (McIlroy, Passfield et al. 2021). It consists of a virtual-reality game/software that allows cyclists to ride their bikes on a stationary trainer, in any location, replicating training/competitive environments, while presenting an opportunity for remote social interaction, competition, training and intervention studies. To the author's knowledge, no research has examined the reproducibility of cycling performance on such virtual platforms. Given the recent pandemic restrictions, such research is timely, while also presenting an opportunity to investigate a methodological approach that could have considerable appeal for researchers due to the potential for a larger and wider field of participants than is usual for laboratory experiments due to the nature of remote exercise. Therefore, well-constructed remote exercise trials using a virtual-reality platform might provide important information for cyclists, sports scientists and coaches aiming to examine performance outcomes in a remote-based environment.

Reproducibility is a measure that informs the consistency of performance tests in repeated trials for the same athlete (Hopkins, Schabort et al. 2001). Nimmerichter, Williams et al. (2010) and MacInnis, Thomas et al. (2018) found high reproducibility of mean power output during 20-min field- and laboratory-based time trials, reporting intraclass coefficient correlations (ICC) of 0.98 (95%CL of 0.95—0.99) and 0.99 (95%CL of 0.95—1.0), respectively. In a review of exercise performance

measures, Currell and Jeukendrup (2008) reported that coefficients of variation (CV) are usually lower than 5% for cycling time trials in the field and the laboratory. However, Hopkins, Schabort et al. (2001) suggested that reproducibility is affected by athletes' performance level and sex. However, only a few studies have analysed how performance level affects the reproducibility of mean power output (Laursen, Shing et al. 2003, Zavorsky, Murias et al. 2007). The results from previous studies reported lower typical errors (TE) and CVs for top-ranked cyclists during 40- (Laursen, Shing et al. 2003) and 20-km (Zavorsky, Murias et al. 2007) laboratory-based time trials, which was explained by higher cycling experience. The differences between women and men, on the other hand, have received little attention. In an early study, Bishop (1997) analysed the reproducibility of 60-min cycling time trials in women and reported a mean ICC of 0.97, but they did not compare this against men. Although the reproducibility of laboratory- and field-based cycling time trials is well established, it is yet to be determined how it is affected by performance groups and sex in a virtual-reality environment.

The reproducibility of performance tests might also be affected by how cyclists distribute the work rate—*i.e.,* pacing (Hopkins, Schabort et al. 2001, Abbiss and Laursen 2008, Foster, Hendrickson et al. 2009, Edwards and Polman 2013). However, only a few studies have examined the reproducibility of pacing across multiple cycling time trials (Stone, Thomas et al. 2011, Thomas, Stone et al. 2012). Both Thomas, Stone et al. (2012) and Stone, Thomas et al. (2011), showed that although macro-level pacing (Edwards and Noakes 2009) was similar during 20- and 4-km laboratory-based time trials, there was a higher variability—evidenced by higher TE—within-participants at the start and end of the time trials. Sex and performance level have also been shown to influence pacing during cycling races (Abbiss, Ross et al. 2013, Bossi, O'Grady et al. 2018, Sandbakk, Solli et al. 2018, Moss, Francis et al. 2019), with faster athletes and women usually adopting a more even pacing approach to time trials (Hopkins and Hewson 2001, Sandbakk, Solli et al. 2018). However, there is a need to examine the reproducibility of pacing across repeated time trials, noting that pacing is situation-specific, develops with experience (Foster, Hendrickson et al. 2009) and thus is a self-regulated output (Edwards and Polman 2013, Elferink-Gemser and Hettinga 2017). How a virtual-reality environment influences pacing is therefore of considerable interest to cyclists, coaches and sports scientists.

The first aim of this chapter is to examine the reproducibility (i.e., intra-subject reproducibility where there is consistency between time trials for the same cyclist) of mean power output during 20-min time trials on a virtual-reality cycling platform. Second, to examine whether reproducibility is similar between different performance levels and sex. Finally, we sought to determine the pacing between athletes of different performance levels and sex, and further assess the overall reproducibility.

METHODS

Participants (n = 44). After advertisements on social media (e.g., Facebook, Twitter), 44 recreational cyclists (11 women, 33 men; 37 ± 8 years old, 180 ± 8 cm, 80.1 ± 13.2 kg) volunteered to participate. Eligibility criteria stipulated participants were between 18 and 55 years old, free of injury, had used Zwift for more than 4 months and had not experienced COVID-19 symptoms (i.e., high temperature, a new, continuous cough and a loss or change to a sense of smell or taste) in the 2 months preceding participation. The lead author's institutional human research ethics committee approved the study in compliance with the Declaration of Helsinki (ref.: ETH2021-0133) and all participants provided digital informed consent prior to participation (Appendix 1).

Study design. A within-participant, repeated measures, remote-research design was adopted, whereby participants performed 3 x 20-min time trials on a virtual cycling platform (i.e., Zwift) interspersed by 5-7 days each at the same time of the day (± 2 h). The 20-min time trial was chosen as it is a standard performance measure among cyclists (MacInnis, Thomas et al. 2018).

20-min cycling time trials and procedures. All time trials were performed on participants' own cycle setup, on which they coupled their exercise equipment with the virtual-reality platform and then navigated their on-screen avatar through the virtual road that simulated outdoor conditions. Each time trial was performed at the "Tempus Fugit" course, which is available to all Zwift users and was designed as an out-and-back flat course, containing 17.3 km and 16 m of elevation gain. The time trial protocol (see below) was developed by the research team, which was exported as a workout file (.zwo) and sent to participants' e-mail, who then imported the file to their accounts. Participants were provided with detailed instructions, containing a step-by-step guide about how to import and export files (Appendix 2).

Before each 20-min time trial, participants performed a 10-min warm-up at their habitual self-selected intensity (*i.e.*, defined during the first time trial and replicated throughout), followed by 5-min rest. They were instructed to standardise their diet, fluid intake, equipment (*i.e.*, bike and/or trainer) and environment (*i.e.*, the position of a fan, place and starting time) during each time trial, whereas also avoiding high-intensity and long-duration exercises 48-h beforehand. Participants performed all time trials individually and used their time trial virtual bike—which removes the drafting effect feature, caused by overtaking other riders. The day before the start of each time trial, participants were e-mailed instructions described previously and requested to calibrate their equipment according to the manufacturer's instructions.

After exercise completion, participants exported the time trial file in a Flexible and Interoperable Data Transfer (FIT) format and sent it to the main investigator's e-mail. Given that there might be differences in the performance data generated by distinct power meters devices attached to participants' bikes and the virtual platform, they were requested to export the FIT file generated from the folder in their device (e.g., laptop or tablet) instead of the file from other potential sources. The participants also indicated which type of trainer they used. The detailed description of the trainers used by the participants can be found in Table 2**Error! Not a valid bookmark self-reference.**, along with corresponding studies that investigated the reproducibility of those available (Hopker, Myers et al. 2010, Zadow, Kitic et al. 2016, Wainwright, Cooke et al. 2017, Zadow, Kitic et al. 2018).

Table 2. Description of trainers used by the participants (n = 44) in this study.

n	Manufacturer	Country	Models (n)	Type
7	Elite	Italy	Direto (6); Suito (1)	Direct-drive
16	Tacx	Netherlands	Neo 2T (5); Neo (4); Flux S Smart (3); Flux 2 (2); Satori (1); Vortex (1)	Direct-drive, wheel-on
5	Wattbike[a,b]	United Kingdom	Atom (3); Pro (2)	Indoor bike
14	Wahoo[c,d]	United States	Kickr Core (8); Kickr (5), Snap (1)	Direct-drive, wheel-on
1	Saris	United States	H3 (1)	Direct-drive
1	Bkool	Spain	Pro 2 (1)	Wheel-on

[a] Previous studies reported high reproducibility of Wattbike Ergometers (Hopker, Myers et al. 2010, Wainwright, Cooke et al. 2017); [b] Previous studies reported high reproducibility of Wahoo Ergometers (Zadow, Kitic et al. 2016, Zadow, Kitic et al. 2018).

Statistical analysis. Descriptive data are reported as mean ± standard deviation unless otherwise stated. The mean power output, cadence, and heart rate achieved in each time trial were extracted from the FIT file generated by the virtual platform using a training-analysis software (TrainingPeaks WKO+ v3.0, PeaksWare, Lafayette, Colorado, USA). Within-participant differences in mean power output, cadence and heart rate between time trials were analysed using two-way repeated-measures ANOVAs with Bonferroni pairwise comparisons.

The overall reproducibility of mean power output across the time trials was reported by calculating ICC, CV and TE between each time trial and as percentages derived from log-transformed data

(Hopkins 2017). To examine whether reproducibility was similar between athletes from different performance levels, participants were ranked into 4 performance groups (*i.e.*, 25% quartiles; Q1, Q2, Q3, Q4; each group n = 11) based on the mean relative power output (W/kg) produced during their best time trial. They were also split between women and men to analyse whether reproducibility was similar between sex. To analyse the reproducibility of pacing, the mean power output in 2-min intervals was normalised to the mean power output achieved during each time trial. The TE and changes in the mean normalised power outputs [90% confidence limits] between trials 1-2 and 2-3 were calculated for each 2-min time-interval; two-way repeated-measures ANOVAs were then used to analyse differences between each 2-min time-interval. To analyse the effects of both performance level and sex on reproducibility and pacing, participants were ranked into 4 performance groups (*i.e.*, 25% quartiles; Q1, Q2, Q3, Q4; each group n = 11) based on the mean relative power output (W/kg) produced during their best time trial and split by sex (n = 11 women and 33 men).

Data analyses were performed using SPSS (26.0, IBM, Armonk, USA) and an online published spreadsheet (Hopkins 2017) (Microsoft Office 365, Excel, Microsoft, Redmond, USA). Statistical significance was set at $P \leq .05$ and effect sizes were calculated as partial eta-squared (η_p^2), of which η_p^2 = 0.01, 0.06 and 0.14 indicates a small, medium and large effect, respectively (Cohen 1988).

RESULTS

Overall results. Individual values for power output, heart rate and cadence in each time trial are shown in Figure 2. There were no differences in mean power output (256 ± 52, 254 ± 51 and 255 ± 52 W; $F = .95$, $P = .391$, $\eta_p^2 = .02$), and heart rate (161 ± 13, 160 ± 13 and 161 ± 13 beats·min^{-1}; $F = 1.57$, $P = .215$, $\eta_p^2 = .04$) between time trials 1 to 3 respectively. However, there was an interaction effect for cadence (87 ± 9, 86 ± 9 and 86 ± 8 rev·min^{-1} for time trials 1 to 3, respectively; $F = 5.81$, $P = .007$, $\eta_p^2 = .81$), and pairwise comparisons showed a difference between time trials 1-3 ($P = .006$), but not between trials 2-3 ($P = .230$). During their best time trial, women and men achieved 2.92 ± 0.47 vs 3.47 ± 0.74 W/kg, respectively; performance groups Q1 to Q4 achieved 4.17 ± 0.45, 3.60 ± 0.18, 3.11 ± 0.17, 2.44 ± 0.40 W/kg, respectively.

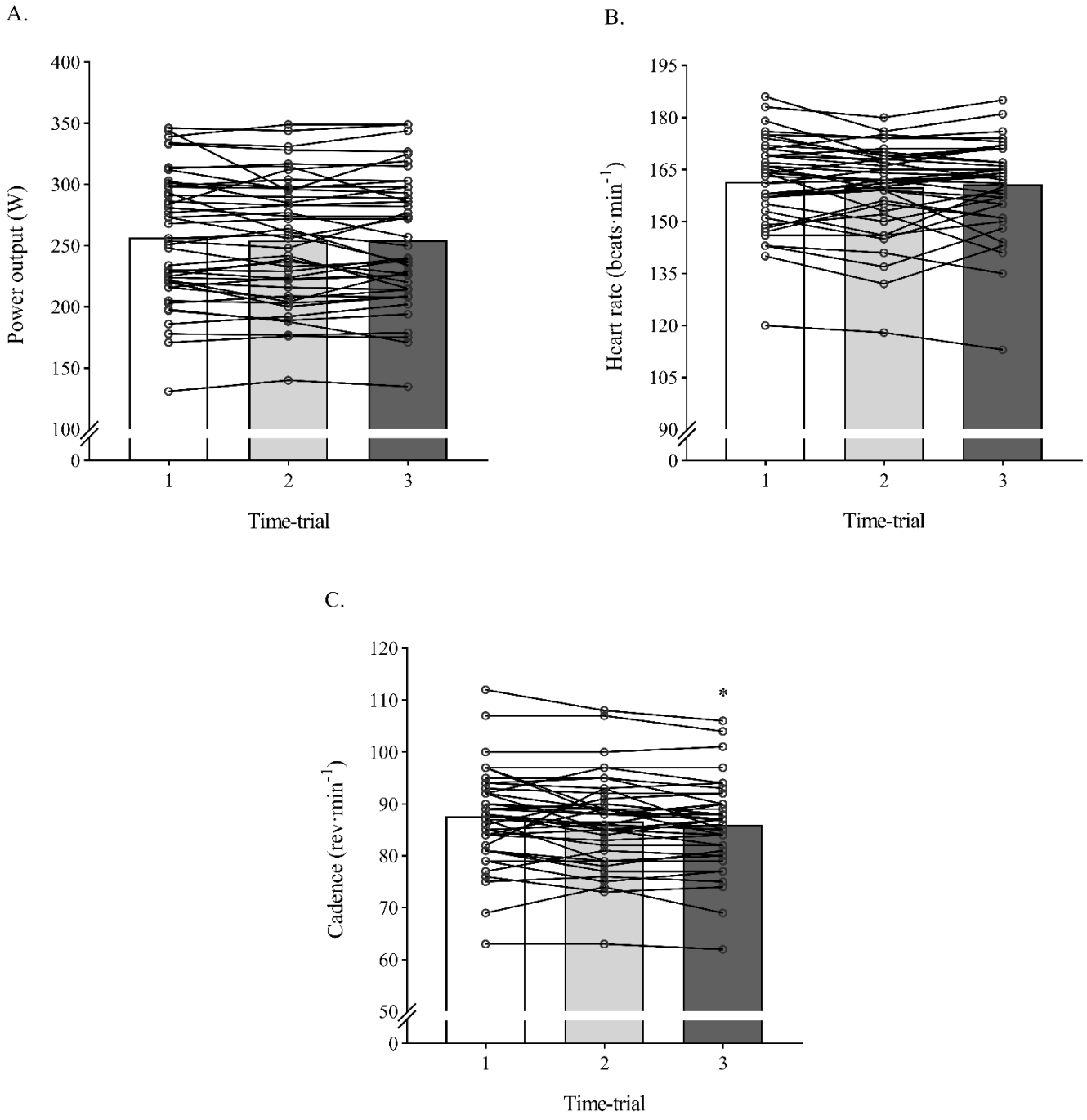


Figure 2. Individual values for mean power output, heart rate and cadence for each athlete during the time trials. Each bar represents the mean values for each time trial. * Denotes difference from time trial 1 (P = .006).

Reproducibility analysis. The ICC, TE and CV of mean power output along with 95%CL between trials 2-1 and 3-2 for the overall sample and split by performance groups and sex are presented in Table 3. Women and men had similar outcomes, although Q1 showed a lower CV (2.6% [1.9—4.1%]) in comparison to the overall sample (3.7% [3.2—4.5%]). When the reproducibility for the participants who have been using the virtual platform for more than 24 months was analysed, there was higher reproducibility for the more experienced riders with a mean ICC, TE and CV of 0.99 [0.98—1.00], 6.7 W [5.29—9.82 W] and 2.6% [2.0—3.8%] against 0.96 [0.93—0.97], 10.17 W [8.76—12.29 W] and 4.0% [3.4—4.9%] for those using for less than 24 months, respectively.

Table 3. Mean power output (W) within-subject intraclass correlation coefficients, absolute typical errors (W) and typical errors as coefficients of variation (%) between time trials for the overall sample, and split by performance groups and sex. Data are presented as mean [CL95%].

		Performance groups				Sex	
	Overall (n = 44)	**Q1 (n = 11)**	**Q2 (n = 11)**	**Q3 (n = 11)**	**Q4 (n = 11)**	**Women (n = 11)**	**Men (n = 33)**
ICC$^{(TT2-TT1)}$	0.97 [0.95—0.99]	0.96 [0.86—0.99]	0.85 [0.54—0.96]	0.99 [0.95—1.00]	0.97 [0.89—0.99]	0.97 [0.91—0.99]	0.96 [0.92—0.98]
ICC$^{(TT3-TT2)}$	0.97 [0.94—0.98]	0.96 [0.85—0.99]	0.86 [0.57—0.96]	0.97 [0.91—0.99]	0.95 [0.84—0.99]	0.95 [0.82—0.99]	0.96 [0.91—0.98]
ICC$^{(mean)}$	**0.97 [0.95—0.98]**	**0.96 [0.88—0.99]**	**0.87 [0.66—0.96]**	**0.98 [0.94—0.99]**	**0.96 [0.89—0.99]**	**0.96 [0.89—0.99]**	**0.96 [0.92—0.98]**
TE$^{(TT2-TT1)}$	9.11 [7.53—11.55]	7.66 [5.35—13.44]	13.35 [9.33—23.44]	7.22 [5.04—12.67]	6.16 [4.30—10.81]	6.56 [4.59—11.52]	9.77 [7.85—12.92]
TE$^{(TT3-TT2)}$	9.61 [7.94—12.17]	7.29 [5.10—12.80]	12.38 [8.65—21.72]	9.52 [6.65—16.71]	7.91 [5.52—13.87]	9.73 [6.80—17.08]	9.68 [7.78—12.80]
TE$^{(mean)}$	**9.36 [8.02—11.28]**	**7.48 [5.63—11.80]**	**12.88 [9.70—20.32]**	**8.45 [6.37—13.34]**	**7.09 [5.34—11.18]**	**8.30 [6.25—13.10]**	**9.72 [8.20—12.23]**
CV$^{(TT2-TT1)}$	3.5 [2.9—4.5]	2.6 [1.8—4.5]	4.7 [3.2—8.3]	3.1 [2.2—5.6]	3.2 [2.2—5.7]	3.3 [2.3—5.8]	3.5 [2.8—4.7]
CV$^{(TT3-TT2)}$	4.0 [3.3—5.0]	2.5 [1.8—4.5]	4.7 [3.3—8.4]	4.1 [2.9—7.3]	3.9 [2.7—6.9]	4.4 [3.0—7.8]	3.9 [3.1—5.1]
CV$^{(mean)}$	**3.7 [3.2—4.5]**	**2.6 [1.9—4.1]**	**4.7 [3.5—7.5]**	**3.7 [2.7—5.8]**	**3.6 [2.7—5.7]**	**3.8 [2.9—6.1]**	**3.7 [3.1—4.7]**

ICC - intraclass correlation coefficient; TE - typical error; CV - coefficient of variation; TT - time trial; Q1-4 - performance groups split by quartiles.

Pacing and TE [CL90%] of normalised mean power output are shown in Figure 3. There was higher variability of normalised power output at the start and end of each time trial (TE = 5.06% and 4.36% for intervals 0-2 min and 18-20 min, respectively), in comparison to the remaining time intervals.

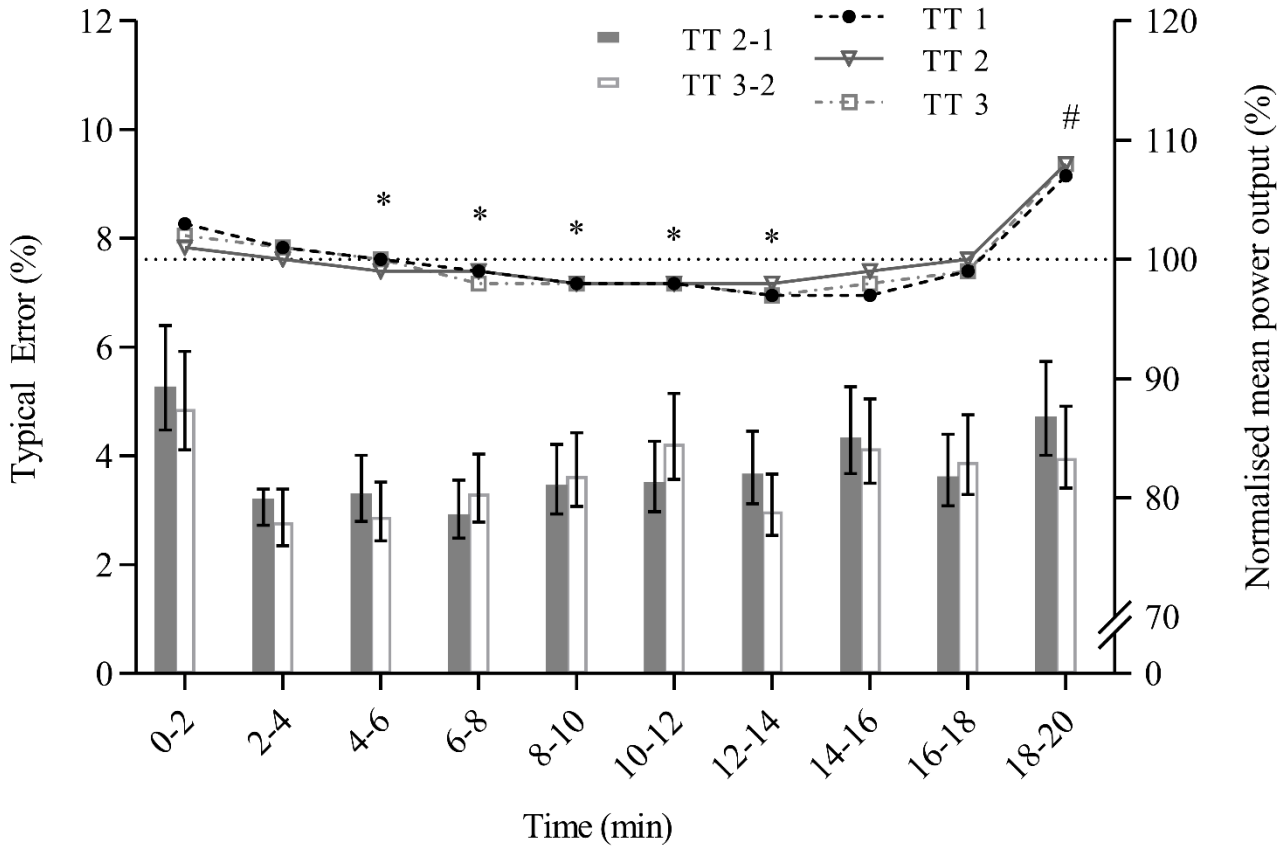


Figure 3. Pacing adopted in each time trial (right Y-axis) and Typical Error [90%CL] between time trials 2-1 and 3-2 (left Y-axis) for each 2-min time-interval. The dotted line corresponds to 100% of normalised mean power output. * Denotes a main effect of time in comparison to time-interval 2-4 min (all $P < .047$). # Denotes a main effect of time in comparison to all previous time-intervals (all $P < .001$), except 0-2 min ($P = .359$).

There was a main effect of time ($F = 18.32$, $P < .001$, $\eta_p^2 = .31$) and pairwise comparisons showed that mean normalised power output decreased from time-interval 2-4 min to 12-14 min (all $P < .047$) and increased during time-interval 18-20 min in comparison to all previous time-intervals (all $P < 0.001$), except from 0-2 min ($P = .359$) (Figure 3). However, pacing was not different between time trials ($F = 1.31$, $P = .249$, $\eta_p^2 = .03$; Figure 3), sex ($F = 1.45$, $P = .240$, $\eta_p^2 = .03$; Figure 4A) and performance groups ($F = 1.33$, $P = .251$, $\eta_p^2 = .09$; Figure 4B).

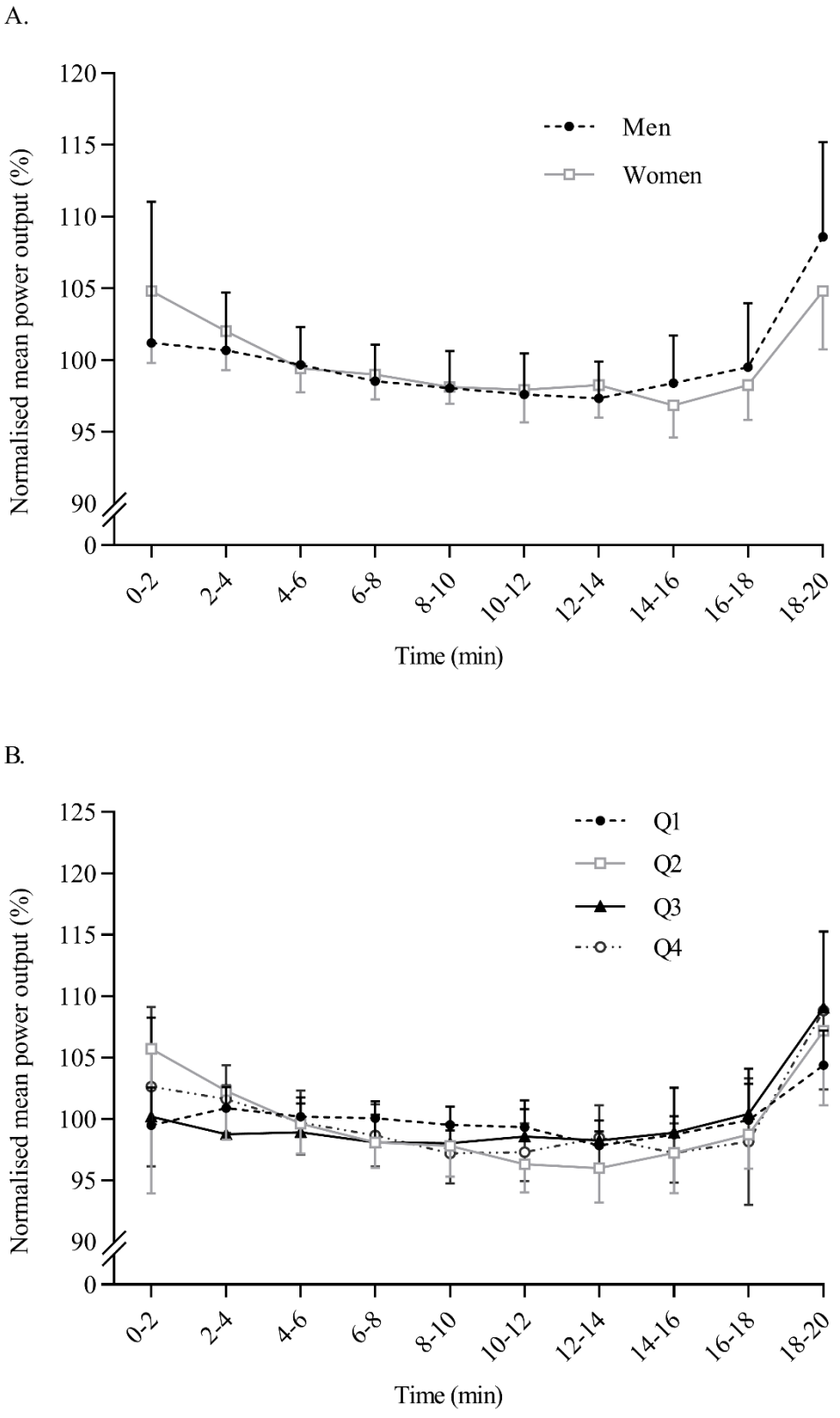


Figure 4. Pacing adopted by sex (A) and performance groups (B).

DISCUSSION

This is the first study to show that cycling performance and pacing during 20-min time trials performed on a virtual-reality platform are reproducible at an intra-individual level and comparable to laboratory-based studies. The CV for mean power output between time trials was lowest for top-ranked participants (i.e., top 25%). Although the number of women participants was lower in comparison to men, the results do not support the notion that sex affects reproducibility. Pacing was also similar between time trials, sex and performance groups, and was further characterised by higher variability of power outputs at the start and finish of the time trial (first and last 2-min, respectively). The findings of this study are likely to assist sports scientists, coaches and athletes aiming to measure cycling performance during online virtual software. Virtual-reality software, therefore, offers an interesting alternative to laboratory-based studies, providing an accessible tool that could potentially widen the pool of study participants to a worldwide community, with the bonus of offering an applied setting.

Mean power output and heart rate were not different between time trials, although cadence was lower in the third time trial compared to the first (87 ± 9 vs. 86 ± 8 rev·min^{-1}, respectively) but not to the second (86 ± 9). However, a difference of 1 rev·min^{-1} is unlikely to represent a real effect nor influenced the participants' performance. In fact, Stone et al. (2011), analysed the reproducibility of cadence during 4-km time trials and found a larger variability in comparison to mean power output, which may explain the differences found between the third and first time trial. Arguably, the differences in cadence between time trials 1 and 3 might suggest that a familiarisation trial is recommended in experimental designs using such virtual environment.

The ICC values found in this study (0.97 [CL95% 0.95—0.98]), are similar to the results of Nimmerichter et al. (2010), who reported high reproducibility of mean power output during field-based 20- and 4-min time trials (0.98 [CL95% 0.95—0.99] and 0.98 [CL95% 0.92—0.99] respectively). It also agrees with MacInnis (2018), who found ICC values of 0.99 [CL95% 0.95—1.00] and 0.98 [CL95% 0.91—1.00] during laboratory-based 20- and 4-min time trials, respectively. While MacInnis, Thomas et al. (2018) reported a mean CV of 1.4% during the 20-min time trials, which was lower than the CV of 3.7% found in this study. However, this is most likely explained due to the homogenous population of elite athletes used in their study (MacInnis, Thomas et al. 2018). The frequent exposure to high-intensity exercise they are exposed to can reduce variability in performance (Hopkins, Schabort et al. 2001), which is also supported by the findings of this study showing that the top-ranked participants had the lowest CV. The ICC values suggest that cycling

performance during 20-min time trials on a virtual platform is reproducible and similar to laboratory- and field-based cycling time trials. It is possible to suggest that the use of exercise in a home-based setting via virtual platforms can be useful for engaging with others in a community while remote, enhancing motivation and providing a stable environment for recording outcomes that are not unduly affected by day-to-day variation. These do not replace laboratory reproducibility studies on standardised equipment but do provide a means for gaining meaningful data for athletes, coaches and researchers where the reproducibility of an individual's performance on their own setup is of value.

The top-ranked participants in this study had a lower CV (2.6%) than the overall sample (3.7%) for mean power output between time trials. This finding is consistent with the results of Zavorsky, Murias et al. (2007) who analysed the reproducibility of 20-km cycling time trials and their top-ranked participants demonstrated a mean CV of 2.5%, against 3.7% reported for the overall sample. As suggested by Hopkins et al. (2001), trained athletes might have more competitive and training experience, which might explain why the top-ranked participants' displayed lower variation in performance. Indeed, Laursen, Shing et al. (2003), found higher reproducibility of performance during 40-km time trials for their top-ranked participants and found that they had significantly more cycling experience than the slower ones. It is noteworthy that the TE between Q1, Q3 and Q4 was similar, although the CV was lower for Q1. This might be explained by considering that higher values of power output achieved by Q1 might have yielded higher TEs (Hopkins 2000), although performance varied to a lesser extent. Surprisingly, Q2 showed a higher variation in performance evidenced by the CV and TE. Although reasonable explanations cannot be provided due to the lack of sufficient data, it might be assumed that cycling experience played a role (Laursen, Shing et al. 2003).

The reproducibility analysis between women and men in this study yielded similar results. In contrast, Hopkins and Hewson (2001) analysed the results of official running races, including cross-country, road, half-marathon and marathon races and found that female runners display lower variability in performance in comparison to males. In another study (Hopkins, Schabort et al. 2001), the authors reviewed the literature and identified the factors that might affect reproducibility. They suggested that variability in performance might be higher in non-athletic women than in non-athletic men, and deduced that women might be less active and that the menstrual cycle might also play a role. However, the results of this study do not support those assumptions and suggest that the reproducibility of performance during 20-min time trials between women and men is similar. These results agree with Bishop (1997) who reported a mean ICC of 0.97 for women during 60-minute cycling time trials, which is similar to our study and the ICC found in previous studies with male cyclists (Jeukendrup, Saris et al. 1996, Currell and Jeukendrup 2008, Nimmerichter, Williams et al. 2010). However, there

is a clear sex bias in the sports sciences research, in which women are underrepresented (Cowley, Olenick et al. 2021). Although women and men were recruited in this study, the differences in the sample size must be considered.

The pacing the participants adopted was similar across the time trials, although TE was higher mainly at the start and end (*i.e.*, first and last 2 min). Such results corroborate with those of Thomas, Stone et al. (2012) and Stone, Thomas et al. (2011), who found that pacing is consistent between time trials of 20 and 4 km, respectively, although TE might be higher at the start and end (first and last 10% of the time trial distance). In contrast, the pacing the participants adopted in this study differed from that reported in the study of Stone, Thomas et al. (2011), who found a reverse J-shaped strategy, whereas the pacing displayed in this study was characterised by a fast start, followed by a progressive decrease in power output (*i.e.*, from 2-4 to 12-14 min), and an end-spurt of a similar intensity of the start (Abbiss and Laursen 2008, Lima-Silva, Correia-Oliveira et al. 2013, Roelands, de Koning et al. 2013, Smits, Polman et al. 2016). Whereas in this study the participants were not blinded to any kind of feedback, in the study by Stone, Thomas et al. (2011) the participants received feedback only about the distance covered every 400 m, which might in part explain the discrepancy. Indeed, Smits, Polman et al. (2016), compared how the absence of feedback affects performance and pacing, and showed that although performance was the same as when athletes received full continuous feedback, pacing differed, suggesting that the source of information available affects pacing. Abbiss, Thompson et al. (2016) showed that cyclists adopt higher power outputs at the start of distance-based time trials in comparison to time-based time trials, which might also reflect the differences in pacing between this study and the study of Stone, Thomas et al. (2011).

There were no differences in pacing between performance groups or sex. This is somewhat surprising, given that previous studies have shown that pacing differs between cyclists of different performance levels and sex (Abbiss, Ross et al. 2013, Bossi, O'Grady et al. 2018). More specifically, Abbiss, Ross et al. (2013) showed that faster mountain bike cyclists adopt a more even pacing when compared to slower ones. Bossi, O'Grady et al. (2018) analysed 5 editions of the UCI cyclo-cross World Championships and showed that women adopt different pacing from men, especially during the last lap of the race. However, the differences in the profile, nature, duration and specific demands of the cycling tasks between this study and the others might explain the disparities. The previous studies also analysed head-to-head competitions, in which pacing is influenced by other competitors (Hettinga, Konings et al. 2017) on varying gradients and terrain (Cangley, Passfield et al. 2011) of longer duration. Although pacing is context-driven and other competitors might have had an impact

on participants' performance, the findings of this study indicate pacing is consistent during 20-min cycling time trials performed on Zwift.

The results found in this study are particularly important in times when face-to-face activities might be impacted due to restrictions caused by future pandemics and sports scientists, coaches and athletes might necessarily incorporate virtual training into their routine. This also has implications for experimental designs where participants may reside in remote, rural communities and be unable to attend training or laboratory sessions. Therefore, having a reproducible and remote system (Bird, Karageorghis et al. 2021) is beneficial for those aiming to understand performance measures in a more applied setting and closely related to athletes' training practices. This study confirms that technology could be useful for a variety of experimental studies examining cycling performance using remote designs. Studies that are performed in the athletes' own environment are important for researchers and athlete support personnel (e.g., coaches) aiming to monitor and evaluate sport performance outcomes. The originality of this work identifies the potential application of remote exercise and doing so in a reproducible way that is of ecological importance. Therefore, the use of remote designs using virtual-reality software has the potential to reach a wider, larger pool of participants, and may be the bridge between laboratory studies and real-world settings.

Limitations. This study has reported novel findings, but these should be interpreted considering some limitations. First, it is important to note that on most virtual platforms, cyclists usually share the virtual road with other users which may have influenced the participants' performance (Hettinga, Konings et al. 2017). While they were instructed to not compete against and avoid others in the virtual platform, performance may have been affected by the presence of other cyclists. Second, although the reproducibility of mean power output was high, the accuracy and the validity of power outputs generated by the participants' trainer could not be analysed, rather than how consistently they were reproduced by the individual riders. Given the potential differences in the types of trainers used, discrepancies across models/devices might be expected (Passfield, Hopker et al. 2017, Bouillod, Soto-Romero et al. 2022). However, as suggested by Atkinson and Nevill (1998), the reproducibility of any new measurement tool should be tested before its validity, as it is unlikely that it will be valid if not adequately consistent. Future research should therefore examine the validity of home-based training setups.

CONCLUSION

In summary, the results of this study suggest that mean power output during 20-min cycling time trials performed on a virtual platform is reproducible and similar for both women and men. Top-ranked and

experienced cyclists might display higher reproducibility of performance between time trials. The results of this study provide sports scientists, coaches and athletes, with benchmark values for future interventions in a virtual-reality environment.

CHAPTER FOUR

Placebo effects induced by beetroot juice during virtual-reality cycling performance

TRANSITION

The previous chapter demonstrated that 20-minute cycling time trial performances using the Zwift virtual reality platform are reproducible and well comparable to laboratory-based studies. This knowledge is crucial as underpinning information with which to ascertain whether or not further experimental studies using such virtual reality systems can provide meaningful results. As reproducibility was high using Zwift, it gives the confidence to design and explore further experiments of exercise in remote settings such as those involving either simple or perhaps complex interventions. This opens up great possibilities for experimental design, access to wide pools of participants and exploration of novel designs to test concepts such as placebo effects in a non-laboratory setting, which is a concept not yet tested. Therefore, the results of the experiment in CHAPTER THREE provided valuable insights into performance and pacing in such remote designs and served as a foundation to inform the assumptions made in the following chapters of this thesis. In CHAPTER FOUR, the focus is to apply the knowledge of reproducibility gained in CHAPTER THREE to a first intervention study delivered remotely. Therefore, CHAPTER FOUR explores the efficacy of placebo effects in response to remote exercise using a balanced placebo design, comparing outcomes from a commonly used nutritional supplement (beetroot juice) and a matched/disguised placebo. This involved the analysis of the effects induced by the ingestion of nitrate-rich beetroot juice or a placebo before a cycling time trial. As previously discussed in the early chapters of this thesis, placebo effects research involving nutritional ergogenic aids have received growing attention in the last years and studies focused on the supplementation of substances such as caffeine and carbohydrate. While beetroot juice has been suggested as an ergogenic aid for endurance athletes due to its high concentration of nitrate, performance benefits seen in laboratory-based studies with small sample sizes have yet to be confirmed in real-world scenarios or evaluated for placebo effects. The aim of this study is, therefore, to investigate the placebo and ergogenic effects of beetroot juice on cycling time trial performance, using a remote-study design and recruiting a large sample size. The results of this study will provide valuable information on the effectiveness of nitrate-rich beetroot juice as an ergogenic aid in real-world cycling performance and whether any observed effects are due to a placebo effect.

INTRODUCTION

In CHAPTER TWO, placebo effects were described as a positive psychobiological outcome, which is often the result of a person's expected and/or learned response to a purported beneficial intervention (Beedie, Benedetti et al. 2018, Hurst, Schipof-Godart et al. 2020). A large body of evidence has shown that placebo effects can improve sport performance when participants believe they ingest a nutritional ergogenic aid, such as caffeine (Beedie, Stuart et al. 2006, Hurst, Schipof-Godart et al. 2019), sodium bicarbonate (McClung and Collins 2007) and carbohydrate (Clark, Hopkins et al. 2000). Indeed, a systematic review (Hurst, Schipof-Godart et al. 2020) indicated that placebo effects induced by nutritional ergogenic aids can have small to medium effects on sport performance (effect size: 0.35, 95% CI = 0.20 to 0.51). Although placebo effects of nutritional ergogenic aids have been extensively studied, no study has empirically examined potential placebo effects induced by beetroot juice ingestion.

Beetroot juice is a popular nutritional ergogenic aid amongst athletes and a natural, rich source of nitrate (Jones 2014, Shannon, Allen et al. 2022). In the past decade, a plethora of research has investigated its influence on sport performance (Jones, Vanhatalo et al. 2020, Senefeld, Wiggins et al. 2020, Shannon, Allen et al. 2022), of which benefits are associated with vasodilation, increased blood flow to working muscles and a reduction in the oxygen cost of exercise (Jones 2014, Jones, Vanhatalo et al. 2020). However, a recent meta-analysis (Senefeld, Wiggins et al. 2020) found that most studies reported no changes in performance, suggesting that the effects of nitrate may be task-specific and associated with the supplementation strategy, population and exercise demands. For example, Wilkerson, Hayward et al. (2012), found that an acute dose of 6.2 mmol nitrate did not affect 50-mile cycling time trial performance or pacing in well-trained participants, suggesting that the athletes' high training status affected the results. A recent expert consensus (Shannon, Allen et al. 2022) further highlighted key limitations in the scientific literature on nitrate and performance, indicating that studies tend to be underpowered and lack translation to real-world settings, thereby complicating the analyses of its effects. The equivocal nature of results in response to nitrate supplementation indicates that performance effects could also be attributable to other non-specific factors, such as placebo effects (Benedetti, Mayberg et al. 2005, Beedie and Foad 2009, Hurst, Schipof-Godart et al. 2020, Brietzke, Cesario et al. 2022) or pacing (Edwards and Polman 2013), and it is unknown whether benefits are a result of the belief it has been received, the pharmacological effects or a combination of both.

To understand the interaction of physiological responses and placebo effects, researchers have advocated for the use of the four-treatment, balanced placebo design (Beedie, Benedetti et al. 2018), in which both the treatment administered (e.g., beetroot juice vs. placebo) and information about the treatment (e.g., told beetroot juice vs. told placebo) are manipulated in a 2 × 2 factorial design. Using this design, a previous study (Hurst, Schipof-Godart et al. 2019) reported that when participants received a placebo but were told it was caffeine, their time to complete 1000-m improved to the same magnitude as when they received caffeine and were told it was caffeine. Performance improvements were also associated with higher running speeds during the initial phases of the time trials, stressing the importance of accounting for changes in pacing in placebo effects research. These findings were similar for other ergogenic aids using a similar design, such as sodium bicarbonate (McClung and Collins 2007) and carbohydrate (Clark, Hopkins et al. 2000) and highlight the significant impact placebo effects can have on the efficacy of nutritional ergogenic aids. However, to the author's knowledge, no studies have examined the placebo effects induced by beetroot juice using an appropriately powered balanced-placebo design and in a real-world setting.

In most beetroot juice or placebo effects research, outcomes are often assessed within laboratory environments (Shannon, Allen et al. 2022), in which a researcher administers the intervention to participants in person. However, during the COVID-19 pandemic, such type of research has become impractical given the social distance restrictions imposed. As mentioned earlier in this thesis, remote-based, virtual-reality software, such as Zwift (McIlroy, Passfield et al. 2021), became increasingly popular, whereby cyclists would ride on a stationary trainer at their own homes. Such virtual-reality platforms have received considerable scientific attention (Souza, Bernardes et al. 2022) and in the previous chapter, it was shown that performance during 20-min cycling time trials on Zwift is reproducible. A unique opportunity, therefore, exists for researchers to harness this technology and examine the effects of experimental interventions in socially distant environments. That said, this study aimed to use a balanced placebo design to examine both placebo and ergogenic effects of beetroot juice during 20-min cycling, virtual reality cycling time trials.

METHODS

The methods section of the present study was reported according to the Consolidated Standards of Reporting Trials (CONSORT) guidelines (Schulz, Altman et al. 2010). The lead author's institutional human research ethics committee approved the study in compliance with the Declaration of Helsinki (ref.: ETH2021-0238) and all participants provided digital informed consent prior to participation (Appendix 4).

Trial design and randomisation. A quasi-randomised, repeated-measures, between-subject, balanced-placebo design was adopted, to investigate the ergogenic and expectancy effects induced by beetroot juice on cycling time trial performance. Participants performed 3x 20-min cycling time trials on a virtual-reality software (i.e., Zwift) interspersed by 5-7 days each at the same time of the day (± 2 h). The first time trial was composed of familiarisation, the second and third time trials were randomised into baseline and experimental, to control for potential learning effects. After completing the familiarisation, participants were randomly assigned to one of four experimental groups:

1. Informed beetroot juice/given beetroot juice (BRJ/BRJ; n = 17; 2 women, 15 men) – participants were informed they received beetroot juice and were given beetroot juice;
2. Informed beetroot juice/given placebo (BRJ/PLA; n = 17; 2 women, 15 men) – participants were informed they received beetroot juice but given a placebo;
3. Informed placebo/given beetroot juice (PLA/BRJ; n = 17; 4 women, 13 men) – participants were informed they received a placebo but were given beetroot juice;
4. Informed placebo/given placebo (PLA/PLA; n = 16; 4 women, 12 men) – participants were informed they received a placebo and were given a placebo.

The lead researcher was responsible for enrolling and randomising participants to each group but was blinded to participants' allocation of beetroot juice or placebo until all statistical analyses had been completed. Participants were randomly assigned sequentially numbered codes using computer-generated software (www.randomization.com) in a 1:1:1:1 ratio. No other members of the research team were aware of randomised allocations, and one researcher not involved with data collection, labelled beetroot juice and placebos for random assignment (i.e., W, X, Y, Z). Participants were unaware of the existence of other groups until the completion of the final trial.

Participants (n = 67). Sample size was estimated *a priori* by statistical power analysis (G*Power, 3.9.1.7), assuming a statistical power of 0.80, α error of 0.05 and effect size of 0.35. The estimation was based on the results of a previous meta-analysis analysing the placebo effects on sports performance (Hurst, 2019), and power analysis reported 64 participants would be required. After advertisement on social media (i.e., Facebook, Twitter), 102 cyclists initially volunteered to participate (22 women and 80 men; 44 ± 11 years old, 177 ± 9 cm, 75.8 ± 11.8 kg) and eligibility criteria stipulated participants were 1) UK-based cyclists; 2) between 18 and 60 years old; 3) non-smokers; 4) free of injury; 5) had used Zwift for more than 4 months; and 5) had not experienced any COVID-19 symptoms (i.e., defined as high temperature, new, continuous cough and loss or change to a sense of

smell/taste) in the 2 months preceding participation. A flow diagram displaying the progress of the participants and the reasons for exclusion can be found in Figure 5.

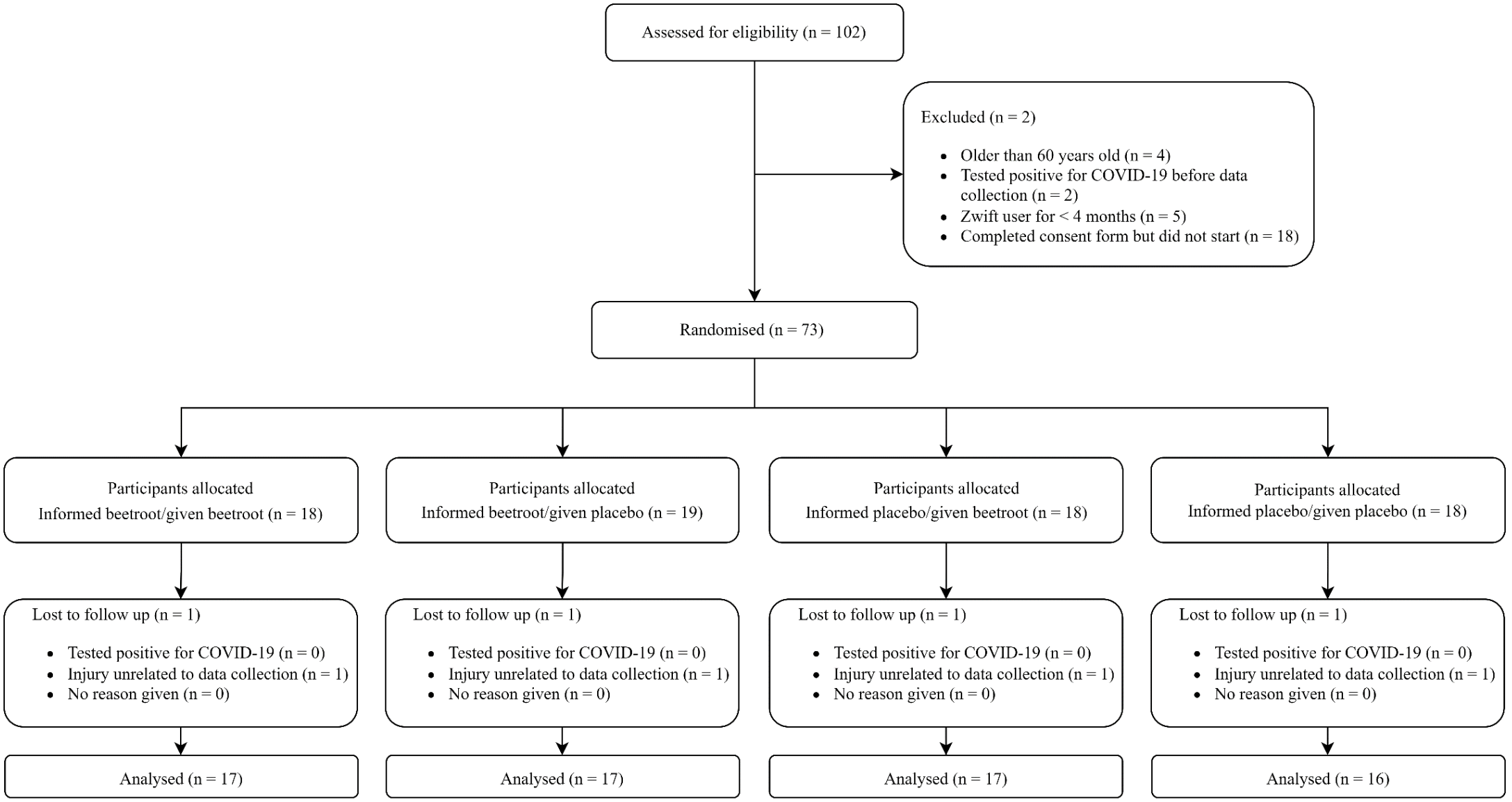


Figure 5. CONSORT flowchart displaying the progress of participant recruitment, randomisation, and reasons for exclusion.

Interventions. Before the start of the experimental time trial, participants self-administered either 70 mL of nitrate-rich beetroot juice (containing ~552 mg of nitrate; Beet It Sport; James White Drinks Ltd.®, Ipswich, United Kingdom, UK) or a placebo containing 70 mL of nitrate-depleted beetroot juice (containing ~0.2 mg mmol of nitrate; Beet It Sport; James White Drinks Ltd., Ipswich, United Kingdom, UK). To manufacture the placebo drinks, the beetroot juice is passed through a column containing Purolite A520E ion-exchange re-sign, before pasteurisation, which selectively removes nitrate ions. Both drinks were indistinguishable in taste and smell, and the bottles were identical. Participants were asked to self-administer the substance 2 h before the start of the time trial and to fast during the time between the supplementation and the start of the warm-up. They were also requested to complete a food diary 24 h before the start of each time trial, to ensure the diet was consistent between time trials and that they administered the drink 2 h before the start.

In line with current recommendations for reporting fine details of participant contact and communication (Beedie, Benedetti et al. 2018), participants were emailed leaflets containing detailed information about the benefits of beetroot juice on cycling performance (Appendix 5**)**. They included key studies reporting the ergogenic benefits of beetroot juice supplementation (Lansley, Winyard et al. 2011, Senefeld, Wiggins et al. 2020) and an infographic developed by the Australian Institute of Sport (Appendix 6). Twenty-four hours before their experimental session, participants were informed whether they were sent a placebo drink–described as an inert substance that would not induce any ergogenic effects–or the beetroot juice drink–described as an active substance that could induce ergogenic effects based on extensive previous research. Given that placebo effects are a social phenomenon, the information provided was standardised among the participants in each group, minimising potential differences in how it was presented (Beedie, Benedetti et al. 2018, Davis, Hettinga et al. 2020). After participants completed all time trials, they were debriefed about the true nature of the study in line with APA guidelines.

Outcome measures. Main outcomes during each 20-min time-trial were mean power output (relative [W] and absolute [W/kg]) and power output in 2-min intervals, speed ($km \cdot h^{-1}$), distance covered (km), heart rate ($beats \cdot min^{-1}$) and cadence ($rev \cdot min^{-1}$). Additionally, before data collection started, participants were asked to rate how much they agreed that “supplements improve my performance”, on a Likert scale ranging from 1 (strongly disagree) to 6 (strongly agree), to assess their beliefs about the efficacy of ergogenic aids.

Independent analysis of nitrate content. As encouraged by an expert consensus Delphi study for studies examining beetroot juice on sport performance (Shannon, Allen et al. 2022), we independently verified the nitrate content of the beetroot juice and placebo drinks.

The analysis of both drinks was performed using ion-pair high-performing liquid chromatography (HPLC). A 2 mL sample was taken from 10 freshly opened sample bottles (n = 5 for beetroot juice and n = 5 for placebo) and centrifuged for 15 min at 4200 g at 4 ºC. The supernatant was passed using a 0.45 μm filter and diluted with mobile phase running buffer (1:20 ratio) before being injected into the HPLC. The mobile phase was prepared using 4 mM tetrabutylammonium chloride, 2 mM KH_2PO_4 and 20% MeOH (pH 3.9) and a C_{18} analytical column (4.5 x 250 mm, X-bridge). All samples were run at 20 ºC with a sample injection volume of 10 μl and a flow rate of 0.5 mL/min was used for chromatographic analysis. The detection wavelength for nitrate was set at 210 nm and peaks were assigned based on retention times of external standards. An external calibration curve was used for the quantification of nitrate with standard solutions (0.99 mg/L – 500 mg/L) prepared from an initial stock (1000 mg/L) using serial dilution in HPLC-grade water.

A good separation of nitrate was identified with retention times of 11.86 min. A range of concentrations was used to generate calibration curves, which showed good linearity (R^2 = 0.9999). The calibration curves were used to determine the limit of detection and limit of quantification for nitrate and were found to be 0.0124 mg/L and 0.038 mg/L, respectively. The mean nitrate concentration in the beetroot juice and placebo drinks was 552 ± 13 mg and 0.2 ± 0.1 mg per 70 mL, respectively.

Procedures. Two days before each time trial, participants were instructed to maintain their normal diet, be consistent in their intake of nitrate-rich foods (Lansley, Winyard et al. 2011, Boorsma, Whitfield et al. 2014), avoid high-intensity, long-duration exercise and the use of mouthwash, and produce the highest possible power output during each 20-min time trial. The day before the start, participants were e-mailed standardised instructions and requested to calibrate their equipment according to the manufacturer's guidelines. All time trials were performed on participants' setup and Zwift account, of which they navigated their on-screen avatar through the virtual road that simulated outdoor conditions. The time trial protocol was developed by the research team through the lead researcher's Zwift account, which was exported as a workout file (.zwo) and sent to participants' e-mail, who then imported the file to their accounts. Participants were provided with detailed instructions, containing a step-by-step guide about how to import the workout file to their accounts (Appendix 2).

Participants performed all time trials individually and used their virtual time trial bike—available to everyone on Zwift—which removes the drafting effect feature, caused by overtaking other riders. They first performed a 10-min warm-up at their habitual self-selected intensity (i.e., defined during familiarisation and replicated throughout), followed by 5-min rest, and completed the 20-min trial at the virtual "Tempus Fugit" course, which is designed as an out and back flat course, available to all users, containing 17.3 km and 16 m of elevation gain. The 20-min time trial was chosen as it is a standard performance measure among cyclists (MacInnis, Thomas et al. 2018), familiar to Zwift users and has high reproducibility (Matta, Edwards et al. 2022).

After each time trial, participants exported their data file in a Flexible and Interoperable Data Transfer (FIT) format and emailed it to the lead researcher. Given that there might be differences in the performance data generated by Zwift and external power meters devices (e.g., Garmin or SRM), participants were requested to export the file from their Zwift account folder instead of the file generated by other sources. Between each time trial, participants were instructed to keep their diet, fluid intake, equipment (i.e., bike and/or trainer) and environment (i.e., the position of a fan, place and start time) the same as the previous trial.

Statistical analysis. Descriptive data are reported as mean ± standard deviation along with 95% confidence intervals (95%CI). One-way ANCOVAs were used to assess the differences in power output (in absolute and relative values), speed, distance, heart rate and cadence during the experimental trials between the 4 experimental groups, controlling for their respective values achieved during baseline. To investigate the effect of condition on pacing, the average power output from each 2-min segment was initially percentage normalised to the average power output of the entire 20-min for each participant, hereafter referred to as normalised power output. This procedure enables the characterisation of pacing per se (Thomas, Stone et al. 2012, Davis, Hettinga et al. 2020), in contrast with the distribution of absolute power output that is performance dependent. Then, two-way repeated-measures ANOVAs were used to assess differences in pacing between trials, and changes were assessed by interaction effects only. A Spearman's rho correlation was performed to assess the relationship between changes in mean power output between baseline and experimental trials (in relative values), and participants' beliefs about the efficacy of ergogenic aids. Data analyses were performed using SPSS (27.0, IBM, Armonk, USA) with statistical significance set at $P \leq .05$.

RESULTS

As shown in Figure 5, 102 participants expressed interest in the study and were assessed for eligibility. A total of 29 were excluded, leaving 73 who were randomised to one of the four groups. Five

participants dropped out, leaving a final sample size of 67 (12 women, 55 men; 44 ± 9 years old, 177 ± 8 cm, 73.9 ± 9.3 kg) who completed all trials and were included in the analysis.

Descriptive data for baseline and experimental trials for all variables between each group are presented in Table 4. There were no differences in mean absolute ($F = .72$, $P = .544$, $\eta_p^2 = .03$) and relative power output ($F = .55$, $P = .652$, $\eta_p^2 = .03$), speed ($F = .95$, $P = .420$, $\eta_p^2 = .04$), distance ($F = 1.59$, $P = .202$, $\eta_p^2 = .07$), heart rate ($F = .08$, $P = .970$, $\eta_p^2 = 0.04$) and cadence ($F = .16$, $P = .921$, $\eta_p^2 = 0.01$) between baseline and experimental time trials for all groups.

Table 4. Mean SD, along with [95%CI] for each variable in each group, between baseline and experimental trials.

	Experimental group							
	BRJ/BRJ (n = 17)		BRJ/PLA (n = 17)		PLA/BRJ (n = 17)		PLA/PLA (n = 16)	
	BSL	EXP	BSL	EXP	BSL	EXP	BSL	EXP
Power output (W)	253 ± 53 [226–281]	255 ± 54 [228–283]	286 ± 49 [261–311]	290 ± 46 [267–314]	257 ± 53 [229–284]	256 ± 52 [230–283]	251 ± 57 [220–281]	254 ± 55 [224–283]
Power output (W/kg)	3.45 ± 0.59 [3.14—3.75]	3.47 ± 0.61 [3.16—3.79]	3.79 ± 0.69 [3.43–4.15]	3.84 ± 0.64 [3.51–4.17]	3.51 ± 0.65 [3.18–3.85]	3.52 ± 0.66 [3.18–3.85]	3.49 ± 0.78 [3.07–3.91]	3.52 ± 0.74 [3.13–3.92]
Speed (km/h)	39.82 ± 2.69 [38.43–41.20]	39.85 ± 2.81 [38.40–41.29]	41.38 ± 2.66 [40.02–42.75]	41.58 ± 2.44 [40.33–42.84]	40.01 ± 3.09 [38.42–41.60]	39.99 ± 2.98 [38.46–41.53]	39.54 ± 3.72 [37.56–41.52]	39.79 ± 3.08 [38.15–41.43]
Distance (km)	13.28 ± 0.90 [12.81–13.73]	13.29 ± 0.94 [12.80–13.77]	13.82 ± 0.84 [13.39–14.25]	13.92 ± 0.82 [13.49–14.34]	13.34 ± 1.02 [12.81–13.87]	13.28 ± 0.97 [12.78–13.78]	13.18 ± 1.24 [12.52–13.84]	13.29 ± 1.01 [12.75–13.82]
Heart rate (beats·min^{-1})	163 ± 7 [160–167]	164 ± 7 [161–168]	160 ± 11 [157–162]	161 ± 11 [158–163]	160 ± 12 [154–166]	161 ± 11 [156–167]	159 ± 10 [154–165]	160 ± 9 [155–165]
Cadence (rev·min^{-1})	89 ± 7 [86–93]	89 ± 8 [85–93]	88 ± 8 [83–92]	88 ± 7 [84–91]	88 ± 4 [86–90]	88 ± 4 [86–90]	88 ± 9 [83–92]	88 ± 8 [84–92]

BRJ: beetroot juice; PLA: placebo

BSL: baseline trial; EXP: experimental trial

Two-way repeated measures ANOVA revealed that pacing was not different between baseline and experimental trials for BRJ/BRJ (F = .81; P = .605; η_p^2 = .05; Figure 6A), BRJ/PLA (F = 1.67; P = .103; η_p^2 = .09; Figure 6B) PLA/BRJ (F = 1.37; P = .206; η_p^2 = .08; Figure 6C) and PLA/PLA (F = .22; P = .991; η_p^2 = .01; Figure 6D).

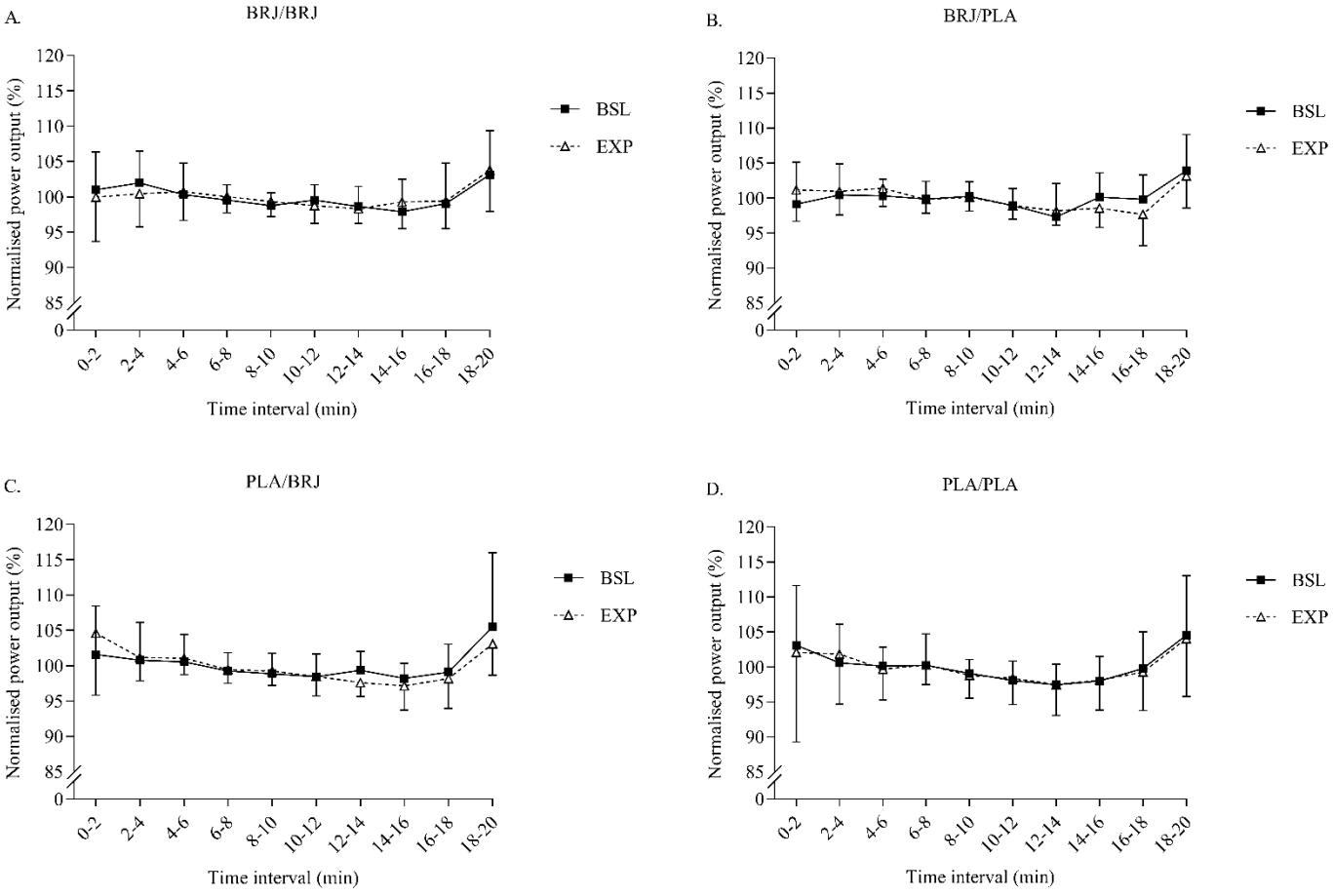


Figure 6. Pacing adopted between baseline (BSL) and experimental (EXP) trials for each group: A) Informed beetroot juice/given beetroot juice; B) informed beetroot juice/given placebo; C) informed placebo/given beetroot juice; and D) informed placebo/given placebo.

Finally, there were no significant correlations between athletes' belief in supplements efficacy and changes in performance for BRJ/BRJ (*r* = -.07, *P* = .766), BRJ/PLA (*r* = -.30, *P* = .242), PLA/BRJ (*r* = -.33, *P* = .201) and PLA/PLA (*r* = .12, *P* = .655).

DISCUSSION

The main finding of this remote (at home) supplement delivery study was that an acute dose of beetroot juice does not influence performance or pacing during virtual-reality, 20-min cycling time trials, nor induce placebo effects. This is both interesting and surprising as laboratory-based studies of beetroot juice have often shown a positive performance outcome (Clark, Hopkins et al. 2000, McClung and Collins 2007, Beedie and Foad 2009, Hurst, Schipof-Godart et al. 2019) although it is unclear whether this may in part be due to placebo effects. The balanced placebo design adopted allowed the investigation of whether previous findings were a result of the pharmacological effects of beetroot juice, the belief it has been received or a combination of both. Nonetheless, while the aim was to induce positive beliefs about the ergogenic effects of beetroot juice, there were no differences in performance or pacing. An intriguing and novel possible explanation for such findings also exists insofar as a remote delivery methodology removes the experimenter from the physical experiment and may, therefore, also mitigate the social aspects of laboratory-based interventions—a key aspect of placebo effects.

Previous studies have shown positive effects of nutritional ergogenic aids on performance (Maughan, Burke et al. 2018), and placebo conditions in which participants are induced to believe its efficacy might have similar effects to the actual ergogenic aid (Benedetti, Mayberg et al. 2005, Beedie, Benedetti et al. 2018, Hurst, Schipof-Godart et al. 2020). Indeed, a previous systematic review (Hurst, Schipof-Godart et al. 2020) reported small to moderate placebo effects induced by the hidden administration of ergogenic aids, such as caffeine, carbohydrates and sodium bicarbonate. Hurst, Schipof-Godart et al. (2019) showed that the belief of ingesting caffeine, when in fact, athletes received a placebo, improved 1,000-m running performance, and Clark, Hopkins et al. (2000) reported improvements of 4.3% in cycling performance when athletes ingested a placebo described as carbohydrate. However, that was not the case in this study. Placebos can take various forms such as an inert pharmaceutical pill, a sham technology, or the presence of a researcher, of which the latter could be considered a social placebo (Davis, Hettinga et al. 2020). For placebos to be effective (i.e., induce placebo effects) there must be an information-exchange encounter between two or more people (researchers and participants) (Benedetti, Mayberg et al. 2005, Beedie, Benedetti et al. 2018). Although speculative, the remote nature of this study may have at least partially removed a potential "experimenter effect," whereby the presence of a researcher in a laboratory setting could have influenced the participants' behaviour (Rosenthal 1976). These findings support previous suggestions that placebo effects can be highly social in nature (Davis, Hettinga et al. 2020), and induced by social interactions between researchers and participants. Thus, by conducting this study remotely and

limiting direct contact between researchers and participants, the impact of such experimenter effects on the results may have been reduced.

There were no changes in performance from the open (BRJ/BRJ group) administration of beetroot juice between baseline versus experimental trials. This is consistent with some previous studies showing no ergogenic effects (Cermak, Stinkens et al. 2012, Callahan, Parr et al. 2017, Hurst, Saunders et al. 2020), although earlier studies contain some variability of outcome, likely due to differences in sample sizes, experimental designs and population. More specifically, Cermak, Stinkens et al. (2012) investigated whether beetroot juice affected ~60-min time trial performance (acute dose of 8.7 mmol nitrate) and although plasma nitrite concentration was higher in comparison to placebo, performance was not different. Exploring a slightly different supplementation strategy, Callahan, Parr et al. (2017) investigated whether beetroot crystals ingested in capsules (5 mmol nitrate over 3 days) affected 4-km cycling performance in trained athletes and did not find any differences in comparison to placebo. Using a competitive setting, Hurst, Saunders et al. (2020) investigated the effects of an acute dose of beetroot juice (~6.2 mmol nitrate) on 5-km running performance, and while times decreased when participants ingested beetroot juice, it was not different from placebo. While a meta-analysis (Senefeld, Wiggins et al. 2020) reported mean performance improvements of ~3% after nitrate supplementation, effect sizes are small (d = 0.17) indicating that performance changes in response to nitrate supplementation are highly susceptible to variability. By removing the experimenter during the administration of the intervention and the time trials, it could be speculated that such variability may in part, be introduced by the presence of the researcher and their expectations.

Dynamic data from this study indicated that the pacing (Figure 6) over the 20-min time trials did not differentiate between baseline and experimental conditions in any of the groups, partially contrasting previous findings (Ross, Gray et al. 2015, Hurst, Schipof-Godart et al. 2019). For example, Hurst, Schipof-Godart et al. (2019) investigated the placebo effects induced by caffeine ingestion on 1,000 m running performance and reported faster speeds at the start of the trial. Ross, Gray et al. (2015) reported a faster start during 3 km time trials when participants self-administered a placebo injection purported to have similar effects as recombinant human erythropoietin. In this study, it is likely that participants may not have had strong positive beliefs in the ergogenic effects of beetroot juice, which is supported by the lack of significant associations between athletes' belief in supplements' efficacy and changes in performance. However, the lack of differences in pacing during the overt administration of beetroot juice (BRJ/BRJ group), partially agrees with previous findings showing no effects of nitrate on pacing during 40-min (Bescos, Ferrer-Roca et al. 2012), 60-min (Cermak, Stinkens

et al. 2012) and 50-mile (Wilkerson, Hayward et al. 2012) cycling time trials. It is important to note that those studies reported no changes in performance after nitrate supplementation in comparison to a placebo, which might explain why pacing was not different. The findings of this study could be also explained as a consequence of the reduced "experimenter effect" mentioned previously in this section, whereby the social aspect between the researcher and participants was removed.

Limitations. Some aspects of this study must be interpreted considering the following limitations. First, while the effects of an acute dose of beetroot juice on cycling performance were investigated, there is evidence suggesting chronic doses over a longer period may be more efficacious (Wylie, Kelly et al. 2013, Shannon, Allen et al. 2022). However, the amount of nitrate chosen in this study was selected as it is more convenient to athletes, and in accordance with a previous study showing improved cycling performance with a similar amount (Lansley, Winyard et al. 2011). Second, as the aim of this study was to adopt a design replicating participants' day-to-day reality and increase the ecological validity of the findings, the amount of nitrate in their daily diet was not controlled. It has been suggested that athletes with a nitrate-rich diet, may display lower responsiveness to nitrate supplementation(Jones 2014). Finally, although software with reported high reproducibility and comparable to laboratory-based studies was used (Matta, Edwards et al. 2022), outcomes within the laboratory were not directly compared. Future studies should adopt similar designs in a hybrid format, involving a mix of field- and laboratory-based time trials to better elucidate the direct impact of nitrate supplementation, the mechanisms behind potential changes and whether the physical presence of an experimenter and their expectations influence participants' performance.

CONCLUSIONS

The results of this study indicate that ingesting an acute dose of beetroot juice does not improve virtual-reality 20-min cycling time trial performance irrespective of whether the athlete was informed they received beetroot juice or a placebo. This suggests that the purported benefits of an acute dose of beetroot juice may be limited in enhancing cycling performance within virtual reality environments, such as Zwift. This finding was similar to when participants received a placebo and informed it was beetroot juice and highlights that placebo effects may be less likely to occur when the researcher delivering the intervention is absent. These results have important implications for future research delivering nutritional and placebo effect interventions and the need to further elucidate the influence of the presence of researchers in the magnitude of effects reported.

CHAPTER FIVE

Social placebo effects induced by cycling competitions in the laboratory

TRANSITION

The previous chapter demonstrated a null, yet novel effect in response to a nutritional supplement (beetroot juice) and a placebo administered remotely. Positive change in physical performance has routinely been shown in laboratory studies after the administration of many nutritional supplements and also in the administration of placebos. However, as this effect was not shown in CHAPTER FOUR, it questions whether other factors may influence performance such as the 'Experimenter Effect' whereby participants perhaps seek to please the experimental tester, who is physically present in the laboratory as a form of social facilitation. The virtual reality platform protocol was shown in CHAPTER THREE to be reproducible and so it seems possible that the virtual reality platform is revealing some important new insights into motivations, beliefs and performances conducted in the presence of others who are physically or virtually present. While carrying out remote data collection is an interesting alternative to laboratory-based studies, sports scientists may not be able to collect physiological data in such settings and elucidate mechanisms behind performance and pacing. It is, therefore, important to evaluate laboratory and virtual responses to more complex situations such as competition. Therefore, the subsequent two chapters are dedicated to exploring and comparing responses which examine the effects of opponents in laboratory and remote, virtual reality experiments. In the current chapter, a more complex design in a laboratory setting was adopted, to investigate the psychophysiological responses to different competitive situations on cycling performance. This study sought to investigate the effects of simulated head-to-head competition (in the form of an opponent representing the participants' baseline performance) and augmented feedback (in the form of an opponent riding at higher power outputs than participants' baseline trial) on cycling performance and pacing, and the associated ventilatory responses.

INTRODUCTION

As mentioned in CHAPTER TWO, the effects of competition on performance have attracted the interest of sports scientists for over 100 years and the seminal work of Triplett (1898) demonstrated that head-to-head cycling competition facilitates improved performance in comparison to exercising alone. Following the study of Triplett (1898), Wilmore (1968) was the first to report similar ventilatory responses such as $\dot{V}O_2$, $\dot{V}_E$ and heart rate during multiple person competition in comparison to an individual time to exhaustion test, highlighting the importance of social and psychological inputs to performance. The performance improvements observed in their studies were accounted for as a result of constructs such as motivation (McCormick, Meijen et al. 2015, Hettinga, Konings et al. 2017) and/or dynamic changes in pacing (Abbiss and Laursen 2008, Foster, Hendrickson et al. 2009, Renfree, West et al. 2012, Edwards and Polman 2013, Roelands, de Koning et al. 2013).

To this day, recent studies have explored how the athlete—environment interactions affect cyclists' performance and pacing (for reference, see Table 1), finding similar results to the early studies of Triplett (1898) and (Wilmore 1968). To further investigate the interactions between opponents and their effects on performance, recent research has adopted laboratory-based interventions manipulating participants' expectations about virtual opponents through deceptive augmented feedback (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Davies, Clark et al. 2016). For example, Ansdell, Thomas et al. (2018) investigated whether 4-km cycling performance was improved when participants competed against a virtual opponent riding at 2% higher power outputs than their previous baseline individual time trial, although they had deceptively been informed the opponent would exactly replicate their baseline performance. They found mean performance improvements of ~1.7% during the deceptive trial, which was accompanied by increased blood lactate concentration ([La]), despite no changes in RPE. Similarly, Ducrocq, Hureau et al. (2017) investigated changes in performance during 5-km cycling time trials and found improved performance when cyclists were instructed to follow a virtual opponent riding 2% faster than baseline, although again, deceptively informed it represented the performance of their baseline individual time trial. Improvements in performance in their study were also associated with higher $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}_E$. Other studies mentioned earlier in this thesis found similar results (Stone, Thomas et al. 2012, Williams, Massey et al. 2015, Jones, Williams et al. 2016, Williams, Jones et al. 2016), and collectively support the notion that deceptive augmented feedback improves performance. It is important to highlight, however, that those previous studies used virtual avatars as opponents, replicating the performance of participants' baseline individual time trial (e.g., 2% higher power outputs than baseline). Although informative, such

strategy may equivocally lead to performance changes induced purely by social facilitation induced by the opponent (Edwards, Dutton-Challis et al. 2018), and not as a cause of the deceptive intervention *per se*. That said, establishing a baseline performance improvement between an individual and a competitive time trial, and further manipulating the opponent's performance in relation to a competitive trial would provide further evidence about the effects of augmented feedback on performance.

An athlete's perception of their opponents' abilities during head-to-head competitions also plays a crucial role in exercise regulation, whereby individuals constantly evaluate their performance in comparison to direct competitors (Strauss 2002, Hibbert, Billaut et al. 2018, Parton and Neumann 2019). In such contexts, the challenge imposed by different opponents yields different performance outcomes (Hibbert, Billaut et al. 2018, Parton and Neumann 2019). For example, some studies have suggested competing against an opponent who is perceived to have superior performance has been suggested to impair performance and reduce motivation (Parton and Neumann 2019), although presumably, this may have a differential effect on different individuals and their motivations. Nevertheless, a previous study showed a lack of performance improvements when cyclists competed against a superior opponent riding at 5% faster speeds than a baseline individual time trial (Ducrocq, Hureau et al. 2017). This suggests that competing against an opponent perceived as having an advantage, could impair competitive performance improvements observed during races between athletes of similar ability, meaning there is probably a range within which an opponent is considered competitive and perhaps not competitive if they are too different in terms of performance level. However, it is also currently unknown whether competing against an opponent who is perceived to have an advantage by the means of performance enhancing substances also affects cycling performance. Such a question is particularly relevant given the widespread use of ergogenic aids in sports (De Hon, Kuipers et al. 2015) and could provide valuable insights into the dynamics of head-to-head competition and motivation.

The first aim of this study was to investigate whether simulated head-to-head competition affects cycling performance and pacing in comparison to an individual baseline time trial and to establish a baseline competitive performance. The second aim of this study was to assess whether cycling performance and pacing are further affected after the provision of both augmented deceptive and also accurate feedback in the form of a virtual competitor, riding at 2% higher power outputs than the previous competitive time trial. Within the second aim, a deceptive design was adopted where athletes were led to believe they would compete against an opponent who had an advantage over them and compare it against an accurate condition, whereby they were correctly informed about the opponent's

performance. This study also aimed to investigate the bioenergetic responses between baseline and the subsequent competitive time trials (i.e., $\dot{V}O_2$; $\dot{V}CO_2$, $\dot{V}_E$, RER).

METHODS

Participants (n = 12). The sample size was estimated *a priori* by statistical power analysis (G*Power, 3.1.9.7) based on the results of a previous study that adopted a similar design (Ducrocq, 2017), and showed that 10 participants would be needed to achieve 85% statistical power. Fourteen participants were initially recruited to account for dropouts, and 2 withdrew due to injury unrelated to the study protocol. Therefore, 12 trained male cyclists participated in the study and their characteristics are described in Table 5**Error! Not a valid bookmark self-reference.**. Eligibility criteria stipulated participants were 18-55 years old, performing > 6 hours of cycling per week, familiar with time trials, free of any neuromuscular injury and had not experienced COVID-19 symptoms (i.e., high temperature; a new, continuous cough; and loss or change of sense of smell or taste) in the 2-months preceding participation. The lead author's institutional human research committee approved the study in compliance with the declaration of Helsinki (ref.: ETH2021-0364) and all participants provided written informed consent to participation (Appendix 8).

Table 5. Participants' characteristics (n = 12) and preliminary test results; mean ± SD.

Age (years)	38 ± 8
Height (cm)	182 ± 7
Body mass (kg)	74.9 ± 10.3
$\dot{V}O_2max$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	58.6 ± 7.2
$\dot{V}O_2max$ ($L \cdot min^{-1}$)	4.43 ± 0.41
$\dot{V}E_{peak}$($L \cdot min^{-1}$)	179 ± 14
RER_{peak}	1.22 ± 0.06
$\dot{W}_{max}$ (W)	400 ± 41
$\dot{W}_{max}$ ($W \cdot kg^{-1}$)	5.40 ± 0.63
Maximal heart rate ($beats \cdot min^{-1}$)	180 ± 14

$\dot{V}O_2max$, maximal oxygen uptake; $\dot{V}E_{peak}$, peak minute ventilation RER_{peak}, peak respiratory exchange ratio; $\dot{W}_{max}$, maximal work rate during incremental test.

Experimental design. A within-subject, repeated-measures experimental design was adopted, and participants visited the laboratory on 6 occasions, at the same time of the day (± 2 hours) separated by at least 72 hours (see schematic design below, Figure 7). During the first visit, participants performed a maximal incremental test and were familiarised with the time trial protocol used in the subsequent sessions. Each session involved a 15-min warm-up based on Borg's 6-20 RPE scale (see below, and a schematic design can be found in Appendix 10), followed by a 20-min time trial, that differed in the information given. Visit 2 was comprised of an individual baseline time trial (baseline), whereas in visits 3 to 6, they competed against an on-screen avatar. A deceptive intervention was adopted, in which participants were informed the aim of the study was to investigate the effects of exogenous ketone on competitive cycling performance and that on one occasion they would compete against another participant of the study that received either a ketone drink or a placebo before the time trial.

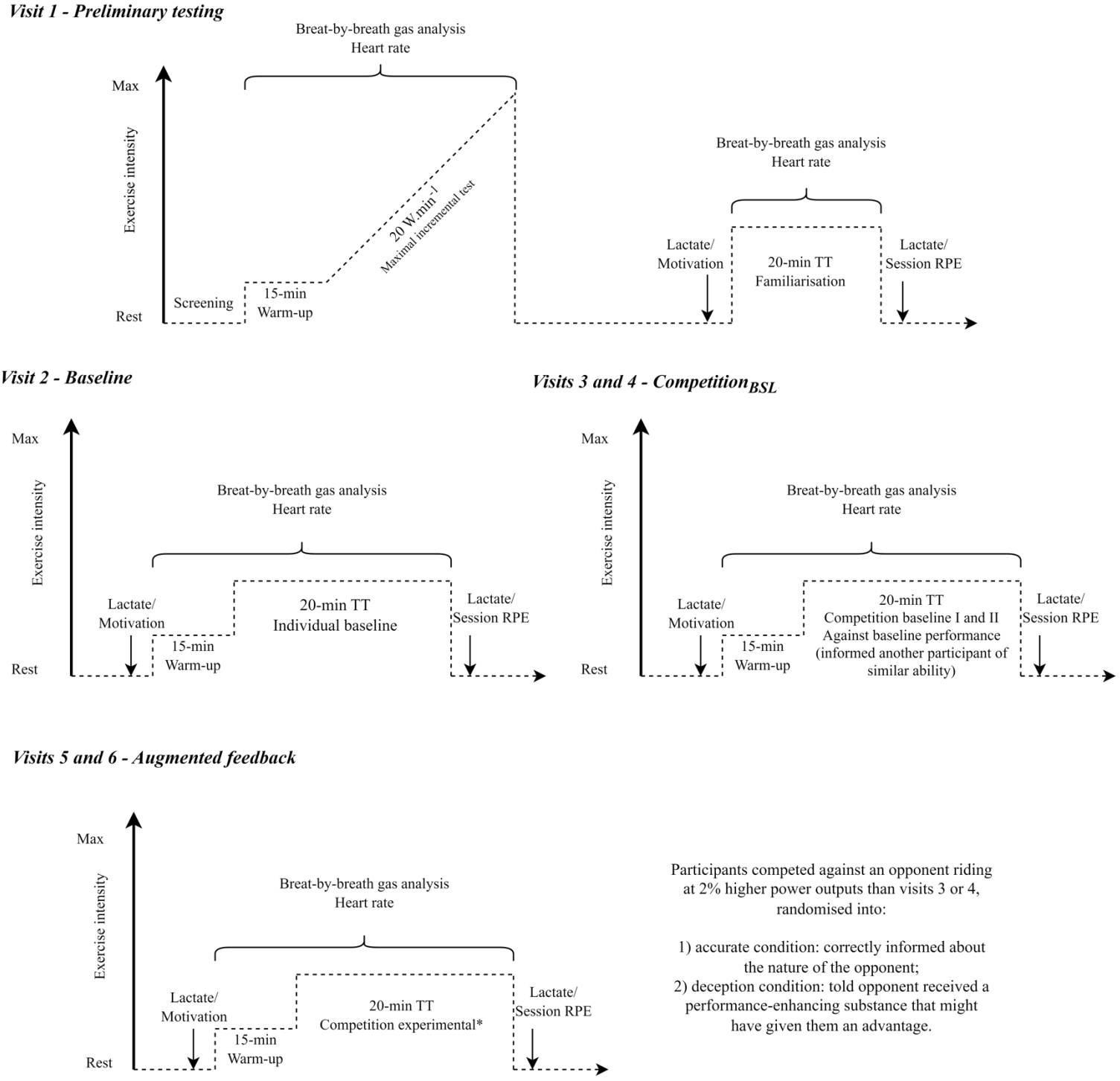


Figure 7. Schematic design.

Preliminary testing. In the first visit, participants' height and weight were measured. Subsequently, they performed a maximal incremental test on an electromagnetically braked cycle ergometer (Velotron, RacerMate, Seattle, USA). Participants adjusted the bike dimensions before the start of the test (replicated throughout the subsequent visits) and warmed up for 5 min at 80 W. The test started at 100 W followed by increases of 25 W every minute until voluntary exhaustion or inability to maintain a cadence above 60 rev·min^{-1} despite verbal encouragement. Participants were instructed to adopt a self-selected cadence but to avoid abrupt changes throughout the test. Gaseous exchange was collected continuously using a breath-by-breath metabolic analyser (Vyntus CPX, Jaeger-CareFusion, Höchberg, Germany) and $\dot{V}O_2max$ was defined as the highest 30-s mean. Prior to the test, the gas analyser was calibrated as per the manufacturer's instructions, using standard gases of known concentrations. Power output and heart rate data were recorded throughout the test, and the maximal power output ($\dot{W}_{max}$) was defined as the mean of the last 5 s.

Following 30-min of recovery, participants were familiarised with the 20-min time trial protocol (including the warm-up protocol, described below), of which they were instructed to achieve the highest possible power output, but were blinded to all information, apart from time elapsed.

Experimental trials. In the subsequent sessions, participants completed 5x 20-min time trials (i.e., visits 2 to 6; one baseline and 4 experimental). Before the start of each time trial, they completed a 15-min warm-up based on the 6-20 RPE scale, according to Bossi, Mesquida et al. (2020). It consisted of 5 min at RPE intensity corresponding to 11 (light), followed by three 1-min high-intensity intervals at 16 (between hard and very hard), interspersed by recovery periods of 2-min and a final 3-min at 9 (very light) (Appendix 10). Participants were allowed to adjust the gear ratio and/or cadence to match the required RPE.

Visit 2 was composed of an individual 20-min baseline time trial, of which participants were requested to achieve the highest power output possible. During sessions 3 and 4 (competition$_{BSL}$), they competed against an on-screen avatar representing their baseline performance, which also replicated the distribution of power output (i.e., pacing) adopted by each participant. However, participants were informed they would compete against another participant of the study who achieved similar performance. The last two sessions were composed of augmented feedback time trials and randomised into 1) accurate and 2) deception, in which they competed against another on-screen avatar, that represented their best performance achieved during competition trials 3 or 4. However, the avatars' mean power output was increased by 2%, replicating the relative pacing adopted by each participant. During accurate, participants were informed that they would compete against their best performance

increased by 2% and that if they were able to closely follow the avatar, they would improve performance. During deception, participants were informed that they would compete against another participant of the study who might have received an exogenous ketone drink or a placebo, which could have improved their performance. This design was adopted in a way that participants would not suspect about the true nature of the study and to induce a sense of competition between them. The exogenous ketone was chosen as it has recently become a popular ergogenic aid among cyclists (Evans, McClure et al. 2022). As its potential performance benefits have not been extensively explored, it was assumed participants would not be induced by strong beliefs about its effectiveness before the start of the time trial but still believe that it could give an advantage to their opponent. The 2% increase in power output was chosen according to previous studies that used similar designs (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Davies, Clark et al. 2016), which represents the smallest worthwhile change in performance (Hopkins, Hawley et al. 1999) and consequently, provide the least chance of being detected by the participants. During all sessions, a flat, virtual course was projected on a screen by the ergometer software, which depicted the participants' performance as a graphical avatar.

Participants were instructed to maintain their regular training but to refrain from intense exercise 24 hours before each visit, and to prepare as they would for competition. They were also asked to refrain from caffeine in the 3 hours prior to each session and to replicate their diets as much as they could in the 24 hours before each visit. Every session was performed in a laboratory-controlled environment (18-19°C, 40% humidity) and a cooling fan was positioned behind the participants.

Outcome measures. Before the start of each time trial, participants completed a motivation questionnaire (Matthews, Campbell et al. 2001). In summary, the questionnaire is composed of 14 statements scored on a 5-point Likert scale (0 = not at all to 4 = extremely) that assess intrinsic and success motivation (see Appendix 11).

During all time trials, power output, cadence, and heart rate were measured continuously by the ergometer, but all feedback was hidden from the participants, apart from time elapsed. Each time trial file was extracted from the Velotron 3D (2008) software in a Flexible and Interoperable Data Transfer (FIT) format and subsequently analysed using a training-analysis software (TrainingPeaks WKO+ v.3.0, PeaksWare, Colorado, USA). Heart rate (Polar H7, Polar Electro, Kempele, Finland), pulmonary ventilation and gas exchange (Vyntus CPX, Jaeger-CareFusion, Höchberg, Germany) were measured continuously during both the warm-up and time trial. Respiratory data were smoothed into 10-s intervals, and the mean $\dot{V}O_2$; $\dot{V}CO_2$, $\dot{V}_E$ and RER were recorded. Athletes were allowed a

2-3 min period between the warm-up and the start of the time trial to remove the facemask and drink water if requested.

Before and after each time trial (< 2 min), blood lactate concentration ([La]; 3 μL) was collected from a fingertip of the participants' right hand and immediately analysed with a test strip by electrochemical method (LactatePro 2 Lactate Meter, Arkray Inc, Kyoto, Japan). Around 20 min after the end of each time trial, the session RPE (sRPE) was recorded, on a 0 (rest) to 10 (maximal) scale.

Data analysis. All data are reported as mean ± standard deviation. One-way repeated-measures analyses of variance were performed to assess the differences between mean absolute power output (W), relative power output (W/kg), heart rate, cadence, [La], $\dot{V}O_2$; $\dot{V}CO_2$, $\dot{V}_E$, RER, sRPE, intrinsic motivation and success motivation between each time trial. To analyse within-participant differences in the pacing, the mean power output in 2-min intervals was normalised to the mean power output of each trial. Two-way repeated-measures analyses of variance were used to assess differences in pacing. Changes were assessed by interaction effects only. Following the analyses of variance, LSD post-hoc pairwise comparisons were used to identify where significant differences existed within the data and partial eta squared (η_p^2) were computed as effect sizes estimate. All data analyses were performed using SPSS (27.0, IBM, Armonk, USA) with statistical significance set at $P \leq .05$.

RESULTS

All descriptive data corresponding to each time trial is reported in Physiological outcomes**.** There were no main effects for mean heart rate (F = 7.90, *P* = .508, ηp2 = .67), pre [La] (F = .58, *P* = .510, ηp2 = .05), post [La] (F = 1.58, *P* = .213, ηp2 = .13), V̇E (F = 2.19, *P* = .108, ηp2 = .17), V̇O2 (F = 2.51, *P* = .076, ηp2 = .19), RER (F = 2.01, *P* = .132, ηp2 = .15). However, there were main effects between time trials for mean V̇CO2 (F = 4.49, *P* = .010, ηp2 = .29), and in comparison to baseline, mean V̇CO2 was higher during competitionBSL (*P* = .003), DEC (*P* = .025), and accurate (*P* = .003).

Psychological outcomes. There were no main effects between time trials for sRPE (F = 3.38, *P* = .065, ηp2 = .26), intrinsic motivation (F = 0.97, *P* = .420, ηp2 = .08) and success motivation (F = 1.13, *P* = .352, ηp2 = .09) between any of the time trials.

Pacing. There were interaction effects between time trials and 2-min time-intervals (F = 2.36, *P* < .001, ηp2 = .18), and pairwise comparisons are reported in Figure 8.

Table 6.

Performance outcomes. There were main effects for mean absolute power output (F = 3.24, *P* = .034, η_p^2 = .23), and pairwise comparisons showed that power output during competition$_{BSL}$ and accurate was higher in comparison to baseline (*P* < .001 and *P* = .036, respectively), but not during deception (*P* = .152).

Physiological outcomes. There were no main effects for mean heart rate (F = 7.90, *P* = .508, η_p^2 = .67), pre [La] (F = .58, *P* = .510, η_p^2 = .05), post [La] (F = 1.58, *P* = .213, η_p^2 = .13), $\dot{V}E$ (F = 2.19, *P* = .108, η_p^2 = .17), $\dot{V}O2$ (F = 2.51, *P* = .076, η_p^2 = .19), RER (F = 2.01, *P* = .132, η_p^2 = .15). However, there were main effects between time trials for mean $\dot{V}CO_2$ (F = 4.49, *P* = .010, η_p^2 = .29), and in comparison to baseline, mean $\dot{V}CO_2$ was higher during competition$_{BSL}$ (*P* = .003), DEC (*P* = .025), and accurate (*P* = .003).

Psychological outcomes. There were no main effects between time trials for sRPE (F = 3.38, *P* = .065, η_p^2 = .26), intrinsic motivation (F = 0.97, *P* = .420, η_p^2 = .08) and success motivation (F = 1.13, *P* = .352, η_p^2 = .09) between any of the time trials.

Pacing. There were interaction effects between time trials and 2-min time-intervals (F = 2.36, *P* < .001, η_p^2 = .18), and pairwise comparisons are reported in Figure 8.

Table 6. Mean values ± SD corresponding to each time trial.

	Baseline	Competition$_{BSL}$	Deception	Accurate
Absolute power output (W)	276 ± 38	283 ± 38*	280 ± 36	284 ± 40*
Cadence (rev·min^{-1})	97 ± 8	98 ± 7	100 ± 8	98 ± 7
Heart rate (beats·min^{-1})	169 ± 12	170 ± 13	169 ± 13	168 ± 12
Pre [La] (mmol·L^{-1})	1.72 ± 0.50	1.85 ± 0.40	1.98 ± 0.48	1.82 ± 0.89
Post [La] (mmol·L^{-1})	12.00 ± 3.66	13.10 ± 4.13	11.75 ± 4.07	12.37 ± 5.08
$\dot{V}E$ (L·min^{-1})	128 ± 24	132 ± 20	133 ± 18	133 ± 22
$\dot{V}O_2$ (L·min^{-1})	3.73 ± 0.40	3.83 ± 0.37	3.82 ± 0.33	3.81 ± 0.42
$\dot{V}CO_2$ (L·min^{-1})	3.73 ± 0.35	3.85 ± 0.34*	3.88 ± 0.29*	3.89 ± 0.40*
RER (A.U)	1.00 ± 0.02	1.01 ± 0.03	1.01 ± 0.03	1.02 ± 0.03
sRPE (A.U)	8.3 ± 1.3	8.6 ± 0.9	8.7 ± 0.9	9.2 ± 0.6
Intrinsic motivation (A.U)	23.8 ± 3.6	24.5 ± 3.6	24.4 ± 3.9	23.8 ± 3.9
Success motivation (A.U)	20.9 ± 3.0	20.8 ± 3.7	21.8 ± 3.9	21.6 ± 3.6

*: different from baseline;

[La], blood lactate concentration; $\dot{V}E$, minute ventilation; $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide production; RER, respiratory exchange ratio;

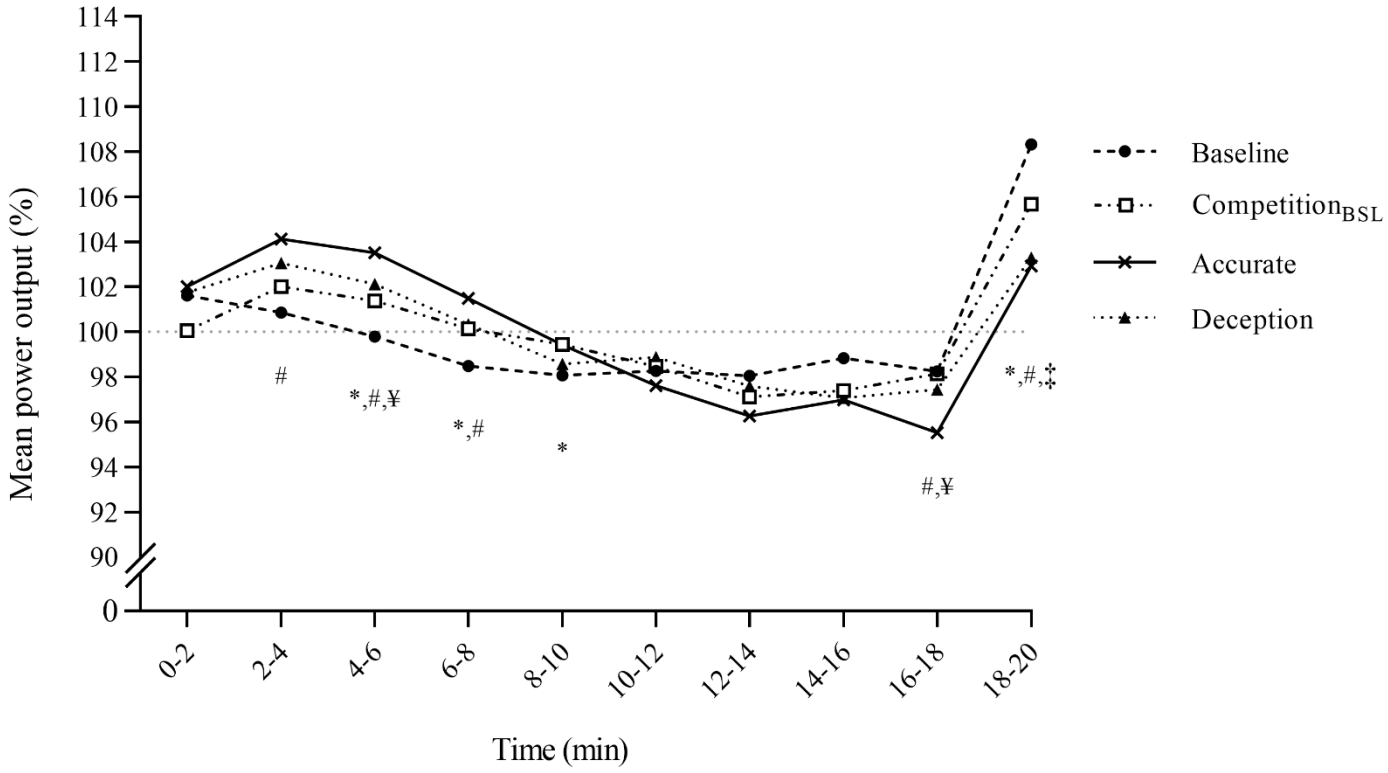


Figure 8. Overall pacing adopted during each 20-min time trial. * difference between baseline and competition$_{BSL}$ (all $P < .041$); # difference between baseline and accurate (all $P < 0.40$); ¥ difference between competition$_{BSL}$ and accurate (all $P < .038$); ‡ difference baseline and deception ($P = .007$).

DISCUSSION

The main findings of this study confirm early observations that head-to-head cycling competition leads to improved performance, vs. individual time-trial performance. However, this does not appear to be the case when participants are led to believe the opponent has a potential advantage through the use of a performance-enhancing substance. It is possible this might have led to task disengagement and thus a lack of change from baseline in that condition. Similarly to previous studies, mean $\dot{V}CO_2$ was higher during all competitive trials (competition$_{BSL}$, accurate and deception) in comparison to baseline, which may suggest a higher anaerobic metabolism contribution (although RER and Post [La] were not different). As motivation and sRPE were scored similarly across all trials, the findings suggest that there may be a level of subconscious decision-making being undertaken by athletes when determining how much effort to apply in an exercise situation vs an opponent. This has potentially wide implications across sports where prejudice and perception of opponents' physical capabilities determine whether or not people engage or disengage with competitive sport.

Competition$_{BSL}$ vs Baseline. The work of Triplett (1898), was the first to show that the presence of opponents positively affects performance, attributing such changes to the social facilitation aspect of competition. Following his work, several more recent studies investigated the effects of competition on performance, reporting reproducible findings that agree with Tripplet's early results (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Hettinga, Konings et al. 2017, Konings and Hettinga 2018). The findings of this study agree with those observations, showing that cycling performance improved when participants competed against a virtual opponent replicating their baseline performance, but when also informed it represented the performance of another individual of similar ability. This suggests there may be a 'sweet spot' where opponents may or may not be considered competitive and when their performance level is too different to be considered a true competitor. For example, Corbett, Barwood et al. (2012), Williams, Jones et al. (2015) and Konings, Schoenmakers et al. (2016) reported performance improvements during 2-, 16.1-, and 4-km cycling time trials, respectively, when participants unknowingly competed against an opponent replicating their individual baseline performance. Interestingly, changes in performance in this study were accompanied by increased $\dot{V}CO_2$ during competition$_{BSL}$ in comparison to baseline, suggesting higher anaerobic energy contribution. Such findings agree with Corbett, Barwood et al. (2012) who also found increased $\dot{V}CO_2$ during 4-km cycling time trials when participants competed against an avatar replicating their baseline performance. However, such findings must be interpreted with care, as RER and Post [La] were not different. Although there is not enough data to provide an evidence-based explanation, it can be assumed that head-to-head competition allows athletes to explore untapped anaerobic capacity, increasing their willingness to sustain higher exercise intensities even at a sub-aware level (Edwards and Polman 2013).

Intriguingly, sRPE, motivation (i.e., intrinsic and success), post [La], $\dot{V}E$ and heart rate were all similar between competition$_{BSL}$ and baseline which is consistent with previous findings. More specifically, Konings, Schoenmakers et al. (2016) and Williams, Jones et al. (2016), showed that although performance was improved during competitive cycling time trials, RPE was rated similarly. Ducrocq, Hureau et al. (2017) reported no differences in post [La], $\dot{V}E$ and heart rate when participants competed against an avatar replicating their performance during baseline. Although it has been previously proposed that performance changes during competitions are associated with higher motivation levels (Jones, Williams et al. 2013, Williams, Jones et al. 2014), this was not the case in this study. Consistent with the results reported in this chapter, Shei, Thompson et al. (2016) found that self-motivation was not correlated with improvements in cycling performance during competition. This suggests that any performance gain was probably supported by motivation

enhancement at a sub-aware level (Edwards and Polman 2013), merely being in the company of opponents, or at least when they were considered competitive and not on a performance enhancing substance. While the influence of other psychological factors is not ruled out (i.e., such as self-efficacy or goal setting), this study's results and of Shei, Thompson et al. (2016) do not support previous suggestions that changes in performance during competition are associated with increased conscious motivation.

Pacing data in this study showed that improvements in performance during competition$_{BSL}$ in comparison to baseline were accompanied by higher power outputs during the first half of the time trial. However, power output was decreased during the last 2 min in comparison to baseline. It is likely that the higher intensities during the first half of the time trial led to increased fatigue (Ducrocq, Hureau et al. 2017), which in turn could have affected the participants' capacity to generate high power outputs towards the end of the time trial. It is also likely that in situations where participants had a significant lead over the opponent towards the last 2 minutes of the race, they might have chosen to consciously decrease exercise intensity and effort, to avoid severe fatigue and homeostatic disruption. The pacing results hereby presented, partially agree with Konings, Schoenmakers et al. (2016) who found increased initial power output during 4-km cycling competitions in comparison to baseline, but contrary to the findings of this study, also found increased power output at the end of the time trial. Contrasting to the results of this study, Corbett, Barwood et al. (2012) found increased power output during the second half of 2-km competitive time trials. Moreover, other previous studies showed no differences in pacing between competitive time trials and individual time trials (Williams, Jones et al. 2014, Wood, Bui et al. 2020). The contrasting findings suggest that pacing is situation-specific and that the environment, time trial distance and behaviour of opponents might affect pacing differently (Abbiss and Laursen 2008).

Augmented feedback: accurate and deception conditions. Providing deceptive or accurate augmented feedback in the form of an opponent riding at higher power outputs than what cyclists' are led to believe, has been shown to improve performance (Stone, Thomas et al. 2012, Williams, Massey et al. 2015, Jones, Williams et al. 2016, Williams, Jones et al. 2016, Ducrocq, Hureau et al. 2017). However, previous studies manipulated opponents' performance based on an individual time trial–i.e., the opponent replicated the augmented performance in relation to a baseline individual time trial. Although such designs have provided important insights into the dynamics of head-to-head competitions, changes in performance during competition may not accurately represent a true change to baseline, as the mere presence of an opponent might affect performance due to social facilitation

(Triplett 1898, Edwards, Dutton-Challis et al. 2018). Different from previous studies, during both augmented feedback conditions in this study (i.e., accurate and deception), the opponents' performance was representative of competitive performance, rather than of an individual baseline time trial (i.e., 2% higher power outputs than competition$_{BSL}$). Interestingly, although the opponent's performance was the same during accurate and deception conditions, participants were able to improve performance only during the accurate feedback condition in comparison to baseline. It might be possible that when athletes competed against an opponent who they believed could have had an unassailable advantage over them, this led to task disengagement (Rhoden, West et al. 2015), in which participants perceived the goal of winning the race to be unrealistic. It is important to note, however, that the information provided to participants about their opponent was different in each condition, which might have affected how they approached the competitions. Somewhat similar to Ducrocq, Hureau et al. (2017), the participants during accurate were informed that if they were able to follow the opponent as closely as possible, they would improve their own best performance. However, during the deception condition, they were asked to win the race and informed that the opponent might have received a performance-enhancing substance, giving them a potential advantage. It has been previously shown that goal orientation affects performance (Rhoden, West et al. 2015, Hibbert, Billaut et al. 2018, Crivoi do Carmo, Renfree et al. 2022), and it is plausible that the goal of winning (deception condition) in comparison to the goal of improving their own best performance (accurate condition), affected how participants approached each time trial.

sRPE, motivation (i.e., intrinsic and success), pre and post [La], $\dot{V}E$, $\dot{V}O_2$, RER and heart rate were all similar between both augmented feedback conditions (deception and accurate) in comparison to baseline, which partially agree with previous research. For example, several studies reported no changes in RPE during augmented feedback conditions (Williams, Jones et al. 2014, Shei, Thompson et al. 2016, Stone, Thomas et al. 2017, Ansdell, Thomas et al. 2018, Crivoi do Carmo, Renfree et al. 2022). Stone, Thomas et al. (2017) also reported similar $\dot{V}O_2$, RER and heart rate between augmented feedback conditions and baseline. In this study, $\dot{V}CO_2$ was higher during both deception and accurate in comparison to baseline, contrasting the results of Stone, Thomas et al. (2017), but agreeing with Ducrocq, Hureau et al. (2017). The differences between study designs, participants' characteristics, time trial protocol and information provided to participants, most likely explain the disparities and make it challenging to compare the results. However, again, motivation was not different during the augmented feedback conditions, which contrasts previous suggestions that performance improvements previously observed are associated with increased motivation (Jones, Williams et al. 2013, Williams, Jones et al. 2014).

The pacing data showed interesting results when the augmented feedback conditions were compared against the others. During accurate, power output was higher in comparison to baseline from time-points 2-4 min to 6-8 min. This is most likely evidence that participants tried to match the opponents' performance until about halfway through the time trial, but were unable to do so towards the end, as power output was lower during the last two time points (16-18 and 18-20 min). The higher intensities during the start might again have led to accumulated fatigue (Ducrocq, Hureau et al. 2017), leading to a less pronounced end-spurt in comparison to baseline. The lower power output towards the end of the time trial might also be evidence of goal disengagement, whereby participants perceived the aim of keeping up with the opponent to be unrealistic. Such findings are supported by previous research showing increased power output during the early phases of cycling time trials (Davies, Clark et al. 2016) and Crivoi do Carmo, Renfree et al. (2022) also showed a less pronounced end spurt during competition in comparison to baseline. Interestingly, during deception, whereby participants were led to believe they were competing against an opponent who might have had an advantage, they displayed similar pacing to baseline. Power output was only lower during the last time-point during deception, which is further evidence of goal disengagement. Interestingly, there were no differences in pacing between deception and accurate conditions, therefore it seems the approach was similar but with less pronounced minute-to-minute power outputs in the deception trial due to a level of task disengagement.

Limitations. The novel findings reported in this study should be interpreted cautiously considering some limitations. First, the effects of different competitive settings were investigated in a laboratory-controlled environment, which could not accurately represent the dynamics of typical outdoor racing situations. For example, during competition$_{BSL}$, the pacing adopted by the virtual opponent replicated the participants' pacing during baseline. In real-world scenarios, it is likely that the pacing adopted by opponents will dramatically change and deviate from athletes' pacing, and be influenced by different racing scenarios (e.g., course gradient, environmental conditions, behaviour of other opponents). This study also adopted a study design in which participants competed against only one opponent in a head-to-head competition, which is not the case in most mass-start cycling races. Future studies should adopt study designs investigating the effects of multiple opponents with distinct pacing profiles and different performance levels, on real-world cycling performance.

CONCLUSION

In conclusion, the findings of this study confirm early reports that competition stimulates performance with concomitant alterations in pacing, and that such changes are independent of sRPE and conscious

motivation. However, the belief that an opponent may have an unfair advantage appears to negate performance effects and as a consequence, task disengagement appears to occur. Such findings could be of value to athletes, coaches and policy setters to ensure fairness across categories of competition, as this could impact both performances of those competing or even whether people compete at all. It is clearly of importance to ensure athletes believe their opponents are not of unassailable quality and that at least some, if not all the competitive field are genuine opponents who could be beaten. This requires realistic goal setting and race planning.

CHAPTER SIX

Social placebo effects induced remotely in competition cycling trials using a virtual-reality software

TRANSITION

In the previous chapter, it was found that simulated competitions undertaken in a laboratory setting, with an experimenter attending the testing session induced some positive changes to cycling performance and pacing. However, it is yet to be investigated whether the presence of opponents affects performance remotely using virtual-reality software, which has higher ecological validity and may deliver outcomes independent of any experimenter effect. Moreover, although previous laboratory-based studies investigated the effects of different virtual opponents on performance compared to an individual time trial, only a few studies used real opponents in an applied setting. More specifically, previous studies developed virtual opponents who either knowingly or unknowingly replicated the participants' own performance (as in the previous chapter), limiting the extrapolation of results to real-world scenarios. This chapter aimed to address such gaps in the literature by inducing real competitions between participants who achieved similar performance during an individual baseline time trial, using virtual-reality software to connect competitors remotely, thus making use of such modern technology to widen the pool of participants and utilise a different methodological design to more traditional laboratory-based exercise studies. The potential changes in performance and pacing during the virtual races were investigated, to provide valuable insights into how athletes perform and adapt in competitive scenarios across both laboratory and remote experimental designs.

INTRODUCTION

As mentioned previously in this thesis, Triplett (1898) and Wilmore (1968) historical studies showed that cyclists perform better when they race against an opponent rather than riding alone, which is supported by several more recent studies (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Davies, Clark et al. 2016, Hettinga, Konings et al. 2017, Konings and Hettinga 2018). Working physically harder in supposedly maximal exercise trials ought not to be possible, yet it has been shown on numerous occasions, largely explained by the concept of 'exercising with reserve' and the central governor principle of regulatory control (e.g., Noakes et al. 1996) whereby the circumstances of the exercise might elicit greater than usual motivation and thus tap into a reserve capacity of energy/power. Therefore, the mechanisms behind such improvements have been attributed to many factors such as psychophysiological factors, such as a crowd effect, intrinsic or extrinsic motivation and so on, all contributing to increased cardiovascular responses (i.e., greater muscle recruitment/activation leading to increased anaerobic metabolism contribution) (Corbett, Barwood et al. 2012, Stone, Thomas et al. 2012). These factors that result in previously untapped exercise reserves whereby someone performs better than usual could therefore be more attributable to the circumstances of the exercise and the social/environmental factors that affect it; this is the concept of social facilitation (Edwards, Dutton-Challis et al. 2018).

Most previous competition studies have been performed in laboratory-based environments, using simulated avatars as competitive opponents, usually replicating the participants' own performance. From the author's knowledge, only a few studies have used 'real' opponents to investigate the effects of competition on cycling performance in a controlled laboratory environment (Hibbert, Billaut et al. 2018, Venhorst, Micklewright et al. 2018). For example Venhorst, Micklewright et al. (2018) aimed to investigate the psychophysiological responses that influence performance and pacing during 70-km cycling time trials performed individually or against a performance-matched opponent. They found that when compared to the individual time trials, the winners of the 70-km cycling races were able to increase performance by 2.24%, whereas losers decreased performance by 1.69%. In contrast, Hibbert, Billaut et al. (2018) showed that performance during a 5-km cycling time trial is not affected when participants competed against an opponent of similar ability or against a group of 4 cyclists of similar abilities. Given the contrasting results and the lack of studies investigating performance outcomes during competition using real-opponents and in a real-world scenario, more studies are warranted.

As mentioned in the previous chapter, an important aspect of competition that has not been explored extensively is regarding athletes' expectations of their opponents' strengths and abilities (Strauss

2002, Parton and Neumann 2019). For example, if an athlete perceives their opponent to have superior performance (and consequently, an advantage), they may feel discouraged and disengage from the competition, leading to suboptimal performance, particularly if they believe their opponent is unassailable. Indeed, in the previous chapter, it was found that only the deception time trial did not result in improved performance compared to baseline testing. All other competitive scenarios resulted in performance gain and so it appeared that a level of disengagement occurred in the deception (i.e. where they were told the opponent was taking a performance-enhancing drug) condition, probably due to participants believing that the opponent was unassailable. However, it is important to note that simulated avatars were used as opponents, which might not accurately reflect a real-world scenario. Thus, to further elucidate the understanding of the impact of opponents' expectations on performance, it is vital that studies use real opponents in real-world settings (i.e., such as using 'real people' during virtual-reality exercise environments, connected remotely through the software) to better replicate the dynamic competitive scenarios faced by athletes.

Similar to the previous chapter, the aim of this study is to adopt a deceptive intervention to investigate the effects of different competitive environments on cycling performance and pacing, using a virtual-reality software, Zwift; but delivered remotely, connecting real opponents exercising from different locations around the world. Based on the previous findings, it is hypothesised that participants would improve performance only during the accurate condition, but during deception, performance would be similar to baseline, indicating disengagement; and that participants would adopt higher initial speeds in the first half of the competitions in comparison to baseline, most likely influenced by being positively engaged and seeking to match or better the opponent's performance & behaviour.

METHODS

Participants (n = 14). After advertisements on social media (e.g., Facebook, Twitter), 30 cyclists (2 women, 28 men; 43 ± 7 years old, 180 ± 7 cm, 77.2 ± 9.3 kg) volunteered to participate. Given that participants were matched based on the performance achieved during individual baseline time trials (see below), 14 male participants were able to complete at least one experimental trial and therefore, were included in the analysis (46 ± 8 years old, 181 ± 6 cm, 78.3 ± 9.7 kg). Eligibility criteria stipulated participants 1) were between 18 and 55 years old; 2) free of injury; 3) had used Zwift for more than 4 months; 4) using a "direct-driver" trainer; 5) had not experienced COVID-19 symptoms (i.e., high temperature, a new, continuous cough and a loss or change to a sense of smell or taste) in the 2 months preceding participation; 6) were able to produce ~255 W or 3.5 W/kg during a 20 min time trial (which represents the average performance of participants reported in CHAPTER THREE). The lead author's institutional human research ethics committee approved the study in compliance

with the Declaration of Helsinki (ref.: ETH2021-0380) and all participants provided digital informed consent prior to participation (Appendix 12).

Study design. A within-participant, quasi-randomised repeated measures, remote-research design was adopted, whereby participants performed 4 x 20-min time trials on a virtual cycling platform (i.e., Zwift) interspersed by 5-7 days each at the same time of the day (± 2 h). The first 2 sessions were composed of baseline individual time trials, whereas the last 2 were composed of randomised experimental trials: accurate and deception. During the experimental time trials, participants competed against different opponents of similar performance (see below) but differed in the information they received. The 20-min time trial was chosen as it is a standard performance measure among cyclists (MacInnis, Thomas et al. 2018) and most performance tests on Zwift involve this time trial duration.

20-min cycling time trials and procedures. All time trials were performed on participants' own setup, of which they navigated their on-screen avatar through the virtual road that simulated outdoor conditions. Each time trial was performed at the "Tempus Fugit" course, which is available to all Zwift users and was designed as an out-and-back flat course, containing 17.3 km and 16 m of elevation gain. The time trial protocol (see below) was developed by the research team, which was exported as a workout file (.zwo) and sent to participants' e-mail, who then imported the file to their accounts. Participants were provided with detailed instructions, containing a step-by-step guide about how to import and export files.

During the first two sessions, participants completed individual 20-min time trials, and were requested to produce the highest possible mean power output during the time trials. After session 2, their best performance of the two time trials was used to match participants who achieved a similar performance (± 3.7% difference) for the subsequent experimental trials. During sessions 3 and 4, participants competed head-to-head against a different opponent (1 vs 1) in each time trial, which also differed in the information they received. During the accurate session, they were correctly informed they would compete against another participant of the study who achieved similar performance during the individual time trials. In the deceptive trial, however, participants were informed they would compete with another participant in the study of similar performance, but were given a medical exemption by the research team to receive a prohibited performance-enhancing substance that could give them an advantage. To avoid the effects of potential beliefs from the participants regarding the efficacy of different performance-enhancing substances, they were not informed which substance their opponent had received. Although before data collection, it was stipulated the differences between opponents

should be no more than the mean CV of 3.7% reported in the reproducibility study (CHAPTER THREE), participants always competed against an opponent that achieved a performance within ± 2% difference. The competition trials were performed using the "Meet up" option on Zwift, which allow users to ride in the course without the interference of others.

Before each 20-min time trial, participants performed a 10-min warm-up at their habitual self-selected intensity (*i.e.*, defined during the first time trial and replicated throughout), followed by 5-min rest. They were instructed to standardise their diet, fluid intake, equipment (*i.e.*, bike and/or trainer) and environment (*i.e.*, the position of a fan, place and starting time) during each time trial, whereas also avoiding high-intensity and long-duration exercises 48-h beforehand. Participants performed all time trials individually and used their virtual time trial bike—which removes the drafting effect feature, caused by overtaking other riders and does not allow them to use Power Ups (features within the game which could give the riders short boosts in speed, such as instantly reducing their weight by 10% for 15 seconds). The day before the start of each time trial, participants were e-mailed instructions described previously and requested to calibrate their equipment according to the manufacturer's instructions.

Outcome measures. Participants exported each time trial data file in a Flexible and Interoperable Data Transfer (FIT) format and sent it to the main investigator's e-mail. Given that there might be differences in the data (i.e., average power output, cadence and heart rate) generated by distinct power meters devices (such as Garmin or SRM) and Zwift, participants were requested to export the file from their Zwift account folder instead of the file generated by other external sources. The mean power output, power output in 2-min intervals, speed, distance, cadence and heart rate achieved during each time trial were extracted from the FIT file using a training analysis software (TrainingPeaks, WKO+ v3.0, PeaksWare, Lafayatte, Colorado, USA) and treated as the outcome measures.

Before and after each time trial, participants were asked to rate the *expected* and the *experienced* pain intensity and pain unpleasantness, respectively, during each time trial (Gagnon-Dolbec, Fortier et al. 2021). They were provided with standardised instructions to distinguish intensity and unpleasantness, of which intensity was described as the sensory dimension of the pain, which translates into the quantity of the pain expected/experienced; and unpleasantness was described as the emotional dimension of the pain, or the extent to which the pain is considered uncomfortable or bothering. Validated numerical scales ranging from 1 to 10 were used to assess pain intensity (0 = no pain at all to 10 = most intense pain imaginable) and unpleasantness (0 = not unpleasant at all to 10 = most unpleasant pain imaginable), according to Gagnon-Dolbec, Fortier et al. (2021).

Statistical analysis. All results are presented as mean ± SD, unless stated otherwise. To investigate the effect of condition (i.e. baseline 1, baseline 2, accurate, and deception) on participants' average power output, average speed, completed distance, average cadence, average heart rate, expected and experienced pain intensity, and expected and experienced pain unpleasantness, while accounting for individual variability, a linear mixed-effects model was built with the participant as a random effect. The marginal means for each condition were estimated, and pairwise comparisons were conducted with Tukey's adjustment for multiple comparisons to explore differences between conditions.

To investigate the effect of condition on pacing, the average power output from each 2-min segment was initially percentage normalised to the average power output of the entire 20-min for each participant. This procedure enables the characterisation of pacing per se (Thomas, Stone et al. 2012, Davies, Clark et al. 2016), in contrast with the distribution of absolute power output that is performance dependent. Then, several linear regression and mixed-effects models with increasing complexity were fitted to the data to examine the relationship between normalised power output and the 2-min segments. Starting from an intercept only (model 0), a model was built with segment as a predictor (model 1), which was followed by the incorporation of its quadratic (model 2) and cubic (model 3) terms. To account for potential differences across conditions, an interaction between predictors condition and segment was added to models 2 (model 4) and 3 (model 5). Next, a random intercept and slope for segment were added to model 2 to account for individual variability (model 6). This was followed by model 6's incorporation of a cubic term for segment (model 7). Lastly, an interaction between predictors condition and segment was added to models 6 (model 8) and 7 (model 9). Given that the average of normalised power outputs of each performance is always 100%, models with random intercepts only are not justifiable as they would not improve the fit of the pooled models. The marginal means for the intercept of each condition were estimated for the selected model, and pairwise comparisons were conducted with Tukey's adjustment for multiple comparisons to explore differences between conditions. The optimal model was selected based on both the Akaike information criterion and likelihood ratio tests. Data modelling was performed using R 4.2.1 (R Foundation for Statistical Computing, Vienna, Austria). Significance level was set at $P \leq 0.05$.

RESULTS

The summary data associated with baseline 1, baseline 2, accurate, and deception conditions are presented in Table 7. Individual and modelled responses (except for cadence) are presented in Figure 8. Except for expected pain unpleasantness, in which baseline 1 differed from all other conditions (all $P \leq 0.048$), there were no other condition effects (all $P \geq 0.134$).

Table 7. Central tendency, dispersion, and number of samples for each condition (mean ± SD).

Condition	Baseline 1 (n = 14)	Baseline 2 (n = 14)	Accurate (n = 12)	Deception (n = 11)
Power Output (W)	296 ± 39	292 ± 38	309 ± 38	299 ± 47
Speed ($km \cdot h^{-1}$)	41.6 ± 1.5	41.5 ± 1.5	42.0 ± 2.0	41.8 ± 1.8
Distance (km)	13.9 ± 0.5	13.8 ± 0.5	14.0 ± 0.6	13.9 ± 0.6
Cadence ($rev \cdot min^{-1}$)	84 ± 12	84 ± 11	84 ± 10	85 ± 10
Heart rate ($beats \cdot min^{-1}$)	161 ± 10	158 ± 12	160 ± 11	161 ± 12
Expected Pain Intensity (A.U.)	7 ± 2	8 ± 1	8 ± 2	8 ± 2
Experienced Pain Intensity (A.U.)	7 ± 1	8 ± 1	7 ± 1	8 ± 2
Expected Pain Unpleasantness (A.U.)	6 ± 3*	8 ± 1	8 ± 2	8 ± 2
Experienced Pain Unpleasantness (A.U.)	7 ± 1	7 ± 1	7 ± 2	8 ± 2

* denotes statistical difference from all other conditions (all $P \leq 0.048$); A.U: arbitrary units (scale ranging from 0-10).

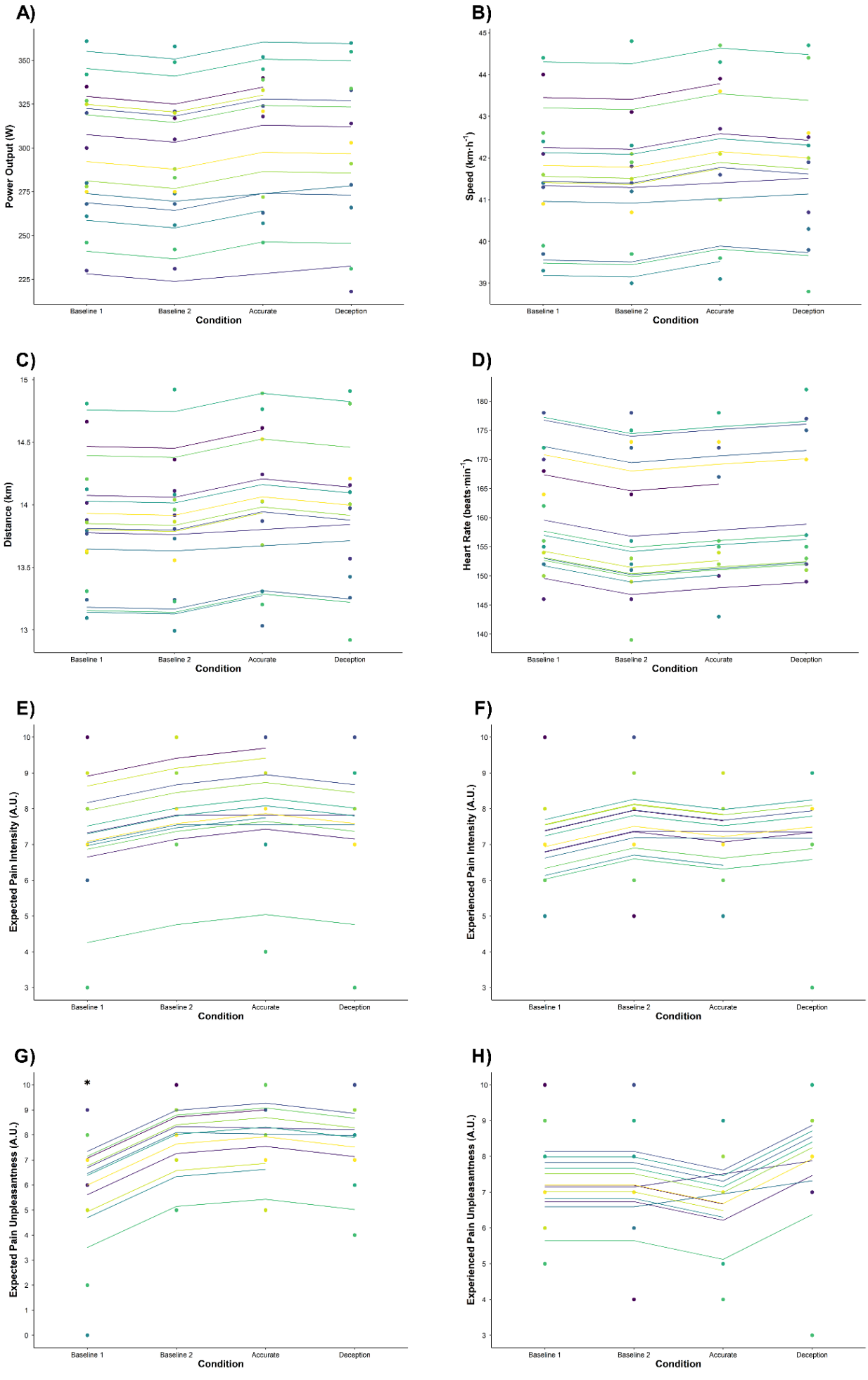

A)
Power Output (W)
350
325
300
275
250
225
Baseline 1
Baseline 2
Accurate
Deception
Condition
B)
Speed (km·h⁻¹)
45
44
43
42
41
40
39
Baseline 1
Baseline 2
Accurate
Deception
Condition
C)
Distance (km)
15
14.5
14
13.5
13
Baseline 1
Baseline 2
Accurate
Deception
Condition
D)
Heart Rate (beats·min⁻¹)
180
175
170
165
160
155
150
145
140
Baseline 1
Baseline 2
Accurate
Deception
Condition
E)
Expected Pain Intensity (A.U.)
10
9
8
7
6
5
4
3
Baseline 1
Baseline 2
Accurate
Deception
Condition
F)
Experienced Pain Intensity (A.U.)
10
9
8
7
6
5
4
3
Baseline 1
Baseline 2
Accurate
Deception
Condition
G)
*
Expected Pain Unpleasantness (A.U.)
10
9
8
7
6
5
4
3
2
1
0
Baseline 1
Baseline 2
Accurate
Deception
Condition
H)
Experienced Pain Unpleasantness (A.U.)
10
9
8
7
6
5
4
3
Baseline 1
Baseline 2
Accurate
Deception
Condition

Figure 9. Power output (panel A), speed (panel B), distance (panel C), heart rate (panel D), expected pain intensity (panel E), experienced pain intensity (panel F), expected pain unpleasantness (panel G), and experienced pain unpleasantness (panel H) of each time trial condition. Dots represent individual records; lines represent the modelled responses. Each colour represents an individual participant. * denotes statistical difference in Expected Pain Unpleasantness from all other conditions (all $P \leq 0.048$).

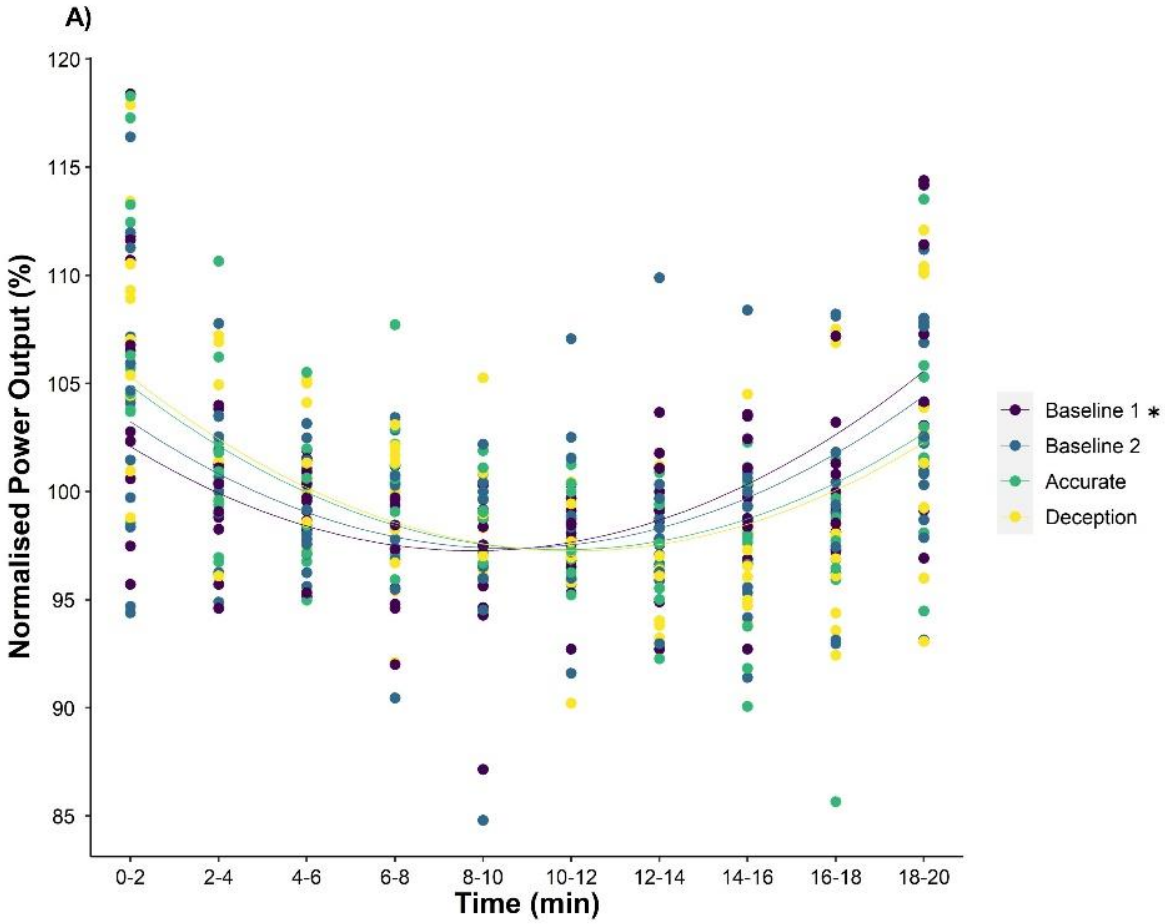
The pacing adopted by participants was best described by model 8 (Table 8), representing a quadratic polynomial function that varied by condition (Figure 9). Pairwise comparisons revealed that participants started their time trials at a lower normalised power for baseline 1 (106.5%) compared with accurate (109.9% – $P = 0.004$) and deception (110.4% – $P = 0.001$) conditions. Except for the cubic polynomial models 3 ($P = 0.714$), 5 ($P = 0.709$), 7 ($P = 0.695$), and 9 ($P = 0.687$), all increasingly complex models showed progressively better fit to the data, as indicated by decreasing Akaike information criterion values and significant likelihood ratio tests (all $P \leq 0.001$).

Table 8. Model 8 estimates for pacing.

Dependent Variable	Best Model	Random Effects (SD)		
		Intercept	2-min Segment	Residual
Normalised Power Output (%)	2-min segment (quadratic), by-individual random intercepts and slopes	2.7	0.5	3.7
Baseline 1*	Normalised Power Output = 106.47822 – (3.40706 · Segment) + (0.31821 · Segment^2)			
Baseline 2	Normalised Power Output = 107.88194 – (3.66094 · Segment) + (0.31821 · Segment^2)			
Accurate	Normalised Power Output = 109.92599 – (4.03856 · Segment) + (0.31821 · Segment^2)			
Deception	Normalised Power Output = 110.43087 – (4.13210 · Segment) + (0.31821 · Segment^2)			

For segment, consider 1: 0–2 min, 2: 2–4 min, 3: 4–6 min… 10: 18–20 min.

* denotes statistical difference from accurate ($P = 0.004$) and deception ($P = 0.001$) conditions.


A)
Normalised Power Output (%)
120
115
110
105
100
95
90
85
0-2
2-4
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
Time (min)
Baseline 1 *
Baseline 2
Accurate
Deception

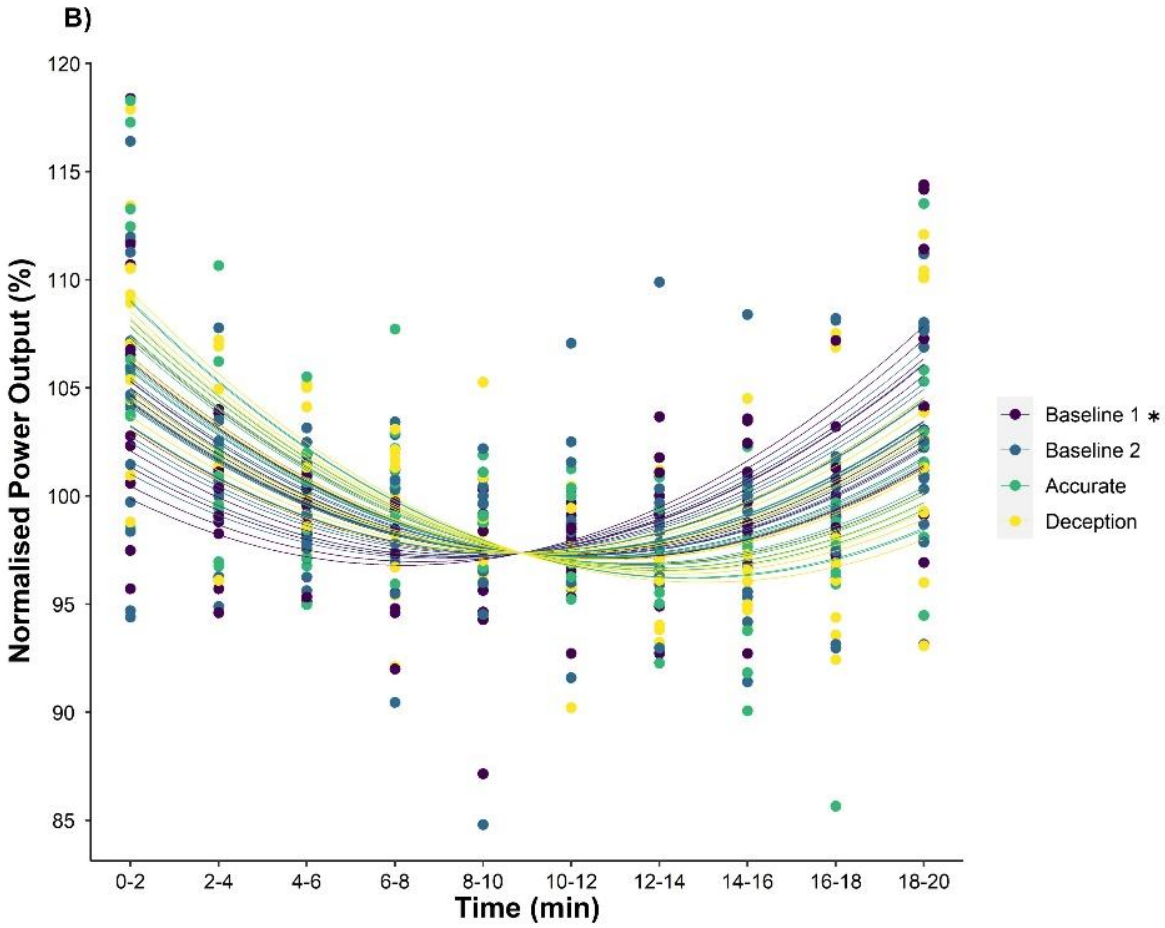

B)
Normalised Power Output (%)
120
115
110
105
100
95
90
85
0-2
2-4
4-6
6-8
8-10
10-12
12-14
14-16
16-18
18-20
Time (min)
Baseline 1 *
Baseline 2
Accurate
Deception

Figure 10. Relationship between normalised power output and the 2-min segments of 20-min time trials. Dots represent single normalised power output records. Lines represent the modelled pacing profile of each condition (panel A) or each participant's performance (panel B). * denotes statistical difference from accurate (P = 0.004) and deception (P = 0.001) conditions.

DISCUSSION

The main findings of this study showed that performance during individual time trials and head-to-head competitions are similar (irrespective of whether participants are led to believe their opponents have an advantage over them or correctly informed about the opponent's ability), contrasting previous findings. The normalised power output during the first 2 min was lower during baseline 1 in comparison to accurate and deception, suggesting a potential learning effect. Similarly, expected pain unpleasantness was lower during baseline 1 in comparison to the other conditions, which may also indicate a learning response to sensations of pain that was corrected after the initial baseline time trial.

The findings of this study contrast several previous laboratory-based observations, showing that simulated competitions induce improvements in performance. As mentioned elsewhere in this thesis, several previous reviews (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Davies, Clark et al. 2016, Konings and Hettinga 2018) showed that the presence of opponents riding at 100% or 102% power outputs than participants' baseline performance induced improvements in mean power output during cycling time trials. In this study, the manipulation of competitive settings involved real opponents riding within a ± 2% difference of participants' baseline power output, in an attempt to induce fair competition between them and to resemble an applied scenario. This substantially differs from previous studies that utilised simulated avatars. However, using real opponents, Hibbert, Billaut et al. (2018) showed that performance during a 5-km cycling time trial is not affected when participants competed against one or multiple opponents. Our results and of Hibbert, Billaut et al. (2018), may suggest that positive findings observed during studies using simulated avatars, might not be as evident when real opponents are used. A possible explanation for this is that real racing is extremely dynamic, whereby the behaviour of an opponent may affect the athlete's performance (Hettinga, Konings et al. 2017) and although speculative, it is possible that each race will induce different demands, depending on the opponent's performance and goal orientation (Rhoden, West et al. 2015, Hibbert, Billaut et al. 2018).

While convenient for certain types of research, simulated avatars may not provide the same level of applicability and complexity that real opponents do; by using real opponents, therefore, it was possible to capture the nuances of cyclists' behaviour in competitive, applied settings. It is worth noting that

the ± 2% differences in performance between participants during accurate and deception trials may have prompted them to adopt strategic racing approaches with the aim of winning the race, rather than merely aiming to improve their performance (Foster, de Koning et al. 2023). For example, participants who were slightly ahead of their opponents might have decided to maintain a given effort, adopting a more conservative racing strategy, and keeping the lead under control. Conversely, those who were slightly behind may have felt more pressure to take risks and adopt a more aggressive approach, which might have eventually induced higher levels of fatigue (Ducrocq, Hureau et al. 2017, Ansdell, Thomas et al. 2018) or led to goal disengagement (Rhoden, West et al. 2015, Crivoi do Carmo, Renfree et al. 2022). Taken together, in competitive settings where the goal of winning the race is more important than setting a personal best, performance improvements previously seen during laboratory-based interventions are less clear.

Similar to CHAPTER THREE and CHAPTER FOUR, this study adopted a remote-research design, in which no researchers were directly supervising the time trials, which may explain our results. Unlike traditional laboratory-based trials in which researchers supervise the participants in person, this study had no direct supervision, and thus, the results were less likely to be influenced by researcher expectations. Although speculative, it is possible that removing social interactions between participants and researchers may reduce the influence of placebo effects on performance induced by opponents. Such finding is somewhat unsurprising, given that the placebo effects induced by different interventions (e.g., such as ergogenic aids or the presence of opponents) are highly social phenomena, and dependent on information exchanges between participants and researchers (Davis, Hettinga et al. 2020). This is particularly relevant to single-blinded research designs where the researcher is fully aware to the different interventions in each trial. In the studies published to date that compared cycling performance during individual time trials against competition (Jones, Williams et al. 2013, Williams, Jones et al. 2014, Davies, Clark et al. 2016), the researchers were not blinded to which condition (accurate or deception) the participants were assigned to in each time trial. This may underscore the notion that researchers' expectations might influence participants' behaviour during different time trial conditions. Although challenging, future studies investigating different competitive environments should aim to adopt double-blinded research designs in which neither the participants nor the researcher responsible for the data collection is aware of the specific interventions in each trial.

Interestingly, the expected pain unpleasantness was lower during baseline 1 in comparison to the other conditions. Such finding confirms previous evidence that pain perception is influenced by factors such as previous exposure and experiences with pain (Mauger 2014, Stevens, Mauger et al. 2018). It

is possible that during the initial baseline time trial, participants were not yet familiar with unpleasant sensations of pain induced by 20-min time trials. After the exposure to the exercise-induced pain, they may have developed a learning response that resulted in an increased expected pain unpleasantness in the subsequent time trials. Our results highlight the importance of including familiarisation time trials in cycling studies, to expose the participants to the exercise-induced pain experienced during cycling time trials. Moreover, the lack of changes in performance between conditions might have contributed to the similar pain intensity ratings, heart rate and cadence across time trials.

Although there were no differences in performance between baselines and any of the competitive time trials, there were differences in pacing. More specifically, normalised power output during baseline 1 was lower during the first 2-min of the time trial in comparison to accurate and deception. Such findings suggest a potential learning effect, whereby participants adapted the initial exercise intensity after the first time trial. Indeed, Noreen, Yamamoto et al. (2010) analysed the reproducibility of uphill cycling time trials when participants were paced by a virtual avatar representing their own previous performance, and showed slower starts during the first time trial. Again, those results highlight the importance of familiarisation trials during cycling studies, to improve the reproducibility of the data and control for potential changes in pacing between repeated time trials.

Limitations. Some aspects of this study should be interpreted considering some limitations. As the aim was to increase the ecological validity of the study and use real opponents, it is possible to speculate whether the changes in opponents' performance between accurate and deception might have induced higher variability in participants' performance and explain the lack of significant differences. By using different opponents in each experimental condition, potential changes in their pacing may have affected participants' performance. Moreover, given the remote nature of the study, it was not possible to collect any other relevant mechanistic data to better understand changes in athletes' physiological status during each condition. Although there were no changes in performance, the cardiorespiratory responses (as evidenced in the previous chapter) may have been different. Perhaps the sample size used in this study was not large enough to detect significant changes. Although we initially aimed to recruit a large sample, differences in time-zones and differences in performance of more than 3.7% between them, presented substantial challenges to include more participants.

CONCLUSION

In conclusion, this study indicates that the typical improvements in performance between individual time trials and competitions observed in laboratory-based time trials may not translate to applied settings where actual opponents are present, and participants are unsupervised. Interestingly, the

virtual-reality platform may have eliminated the laboratory effect of enhanced performance resulting from social facilitation induced by the presence of an experimenter. The findings of this study have important implications for future research designs, which should aim to adopt double-blinded designs to investigate competitive cycling performance.

CHAPTER SEVEN

Overall summary, discussion and future directions

OVERALL SUMMARY

With virtual-reality cycling becoming popular over recent years (McIlroy, Passfield et al. 2021, Souza, Bernardes et al. 2022), the first aim of this study evaluated the reproducibility of cycling performance and pacing during time trials performed on Zwift. Subsequently, three virtual-reality and one laboratory-based experimental study were conducted. More specifically, the placebo and ergogenic effects induced by beetroot juice on virtual cycling performance were investigated in CHAPTER FOUR. In CHAPTER FIVE, the placebo effects on cycling performance were investigated from a social perspective, whereby different competitive scenarios were induced in the laboratory. Participants were asked to compete against an avatar replicating their individual baseline performance or riding at 2% higher power outputs (deceptive or accurate augmented feedback). Finally, in CHAPTER SIX a similar design to Chapter Five was adopted to investigate the effects of real opponents on performance, on Zwift.

The main findings of the four studies were as follows:

1) Performance and pacing during 20-min cycling time trials performed on Zwift are reproducible and comparable to laboratory-based time trials, offering a novel method for sport scientists to use in conducting cycling research;
2) The ingestion of beetroot juice or a placebo described as beetroot juice does not induce ergogenic or placebo effects during 20-min time trials on Zwift and does not affect pacing; perhaps because of the limited social contact between researchers and participants;
3) Compared to an individual baseline time trial, head-to-head simulated competition improves cycling performance in the laboratory, when athletes compete against an avatar replicating a previous individual best performance;
4) Cycling performance during a laboratory time trial is similar to baseline when athletes compete against an opponent whom they think has an advantage over them by the means of a performance-enhancing substance (deception);
5) When athletes are correctly informed about the true nature of the avatar (accurate) during a laboratory time trial, performance improvements are evident in comparison to an individual baseline time trial;
6) While improvements during laboratory-based cycling competitions were shown, this was not evident on virtual-reality software (i.e., Zwift), which might again, suggest that limited social contact between researchers and participants might influence how they approach the experimental time trials.

GENERAL DISCUSSION

The global outbreak of the COVID-19 pandemic led to unprecedented closures of sport and exercise laboratories worldwide, presenting significant challenges for sport scientists reliant on laboratory-based testing (Lourenco and Tasimi 2020, Stenson, Fleming et al. 2022, Edwards and Hettinga 2023). Although face-to-face research activities were heavily impacted (Souza, Bernardes et al. 2022), it presented exciting opportunities to adopt innovative designs to investigate performance outcomes in applied settings, such as in virtual reality. This thesis was not an exception, as most of this research was conducted during lockdown (2020-2022). Overall, the main findings of this research may suggest that positive effects of ergogenic aids or simulated competition observed in laboratory-based studies are not as evident as during remote designs. More specifically, although it was reported that cycling performance is reproducible over consecutive time trials (CHAPTER THREE), remote experimental interventions, such as the ingestion of beetroot juice (CHAPTER FOUR) or simulated competitions (CHAPTER SIX), did not induce changes in performance when conducted on Zwift.

Unlike CHAPTER FIVE, in which a laboratory-based study was conducted with the physical presence of the researcher and participant, CHAPTER FOUR and CHAPTER SIX involved the removal of direct supervision. The absence of the physical presence of the researcher led to the suggestion that placebo effects may not be induced when social interactions between the participant and researcher are limited. While this finding is novel in sport sciences research, it is not surprising, given that placebo effects resulting from different experimental interventions rely heavily on social contact and information exchange between participants and researchers (Davis, Hettinga et al. 2020). In such contexts, the presence of others (i.e., in this case, a researcher) may be a source of arousal that induce dominant responses of the participant/athlete (Zajonc 1965, Markus 1978), altering their natural behaviour. Those findings highlight the importance of considering the role of social contact and information exchange between researchers and participants, during placebo effects research.

Virtual-reality research designs and the potential for novel innovative projects. CHAPTER THREE reported that the reproducibility of cycling performance on a virtual-reality platform is reproducible, presenting opportunities for innovative designs in sports contexts across several different areas (Le Noury, Polman et al. 2022). One major advantage of using this approach as a training tool is its ability to re-create environments that are difficult to simulate using traditional methods. For example, Tour de France cyclists might use virtual-reality software (e.g., Zwift) to train for specific demanding mountain stages, such as the Alpe d'Huez, from their homes. This also has the potential to provide a safer alternative with reduced risk of injury (e.g., crashes) and damage to equipment (Le Noury, Polman et al. 2022).

Although this research found null results using remote designs and virtual reality, those designs offer a wide range of opportunities to develop novel, innovative and applied interventions to investigate sports performance. For example, CHAPTER THREE included a geographically diverse sample, including athletes from 5 different continents, including developing countries such as South Africa and Brazil. Although CHAPTER FOUR included only UK-based participants (because of potential customs issues), there were participants from different areas of England, Scotland, Wales and Northern Ireland. Adopting remote designs, therefore, allow researchers to reach a broader and more diverse population of athletes across different geographical locations, offering greater application of findings. This approach can eliminate potential logistical barriers associated with travelling and/or scheduling conflicts, making participant recruitment easier and cost-effective (Buhrmester, Talaifar et al. 2018). Considering that laboratory-based data collection often involves high costs associated with expensive equipment, which are not promptly available in developing countries, remote-research designs offer an interesting, novel and relatively cheap alternative to laboratory-based studies. Although speculative, remote study designs might also enhance the ecological validity of studies by capturing athletes' behaviours in a familiar and applied environment, rather than in controlled laboratory settings.

The successful implementation of the remote interventions reported in this thesis, although non-significant, suggests that certain experimental interventions do not necessarily require direct face-to-face contact between researchers and participants, which could expand the possibilities around remote interventions (Souza, Bernardes et al. 2022). For example, a previous study provided guidelines for orthopaedic surgeons to optimise the quality of telemedicine involving assessments such as range of motion, hypertension and joint rotation (Tanaka, Oh et al. 2020). Mani, Sharma et al. (2017) verified the validity and reliability of a remote physical therapy evaluation for musculoskeletal conditions, demonstrating good concurrent validity and reliability for assessing pain, swelling, range of motion, muscle strength, balance, gait, and functional capacity. A previous review (Dijkstra, Ergen et al. 2020) offered an interesting overview of guiding principles on how to plan and perform sport and exercise medicine assessments remotely. They showed that patients may be able to perform self-assessment tests of parameters such as blood pressure and glucose, heart rate, and step count, which should be further discussed with their clinician to identify potential diagnoses. In terms of sports performance, a previous multi-centre study involving 142 countries and 12,526 countries showed that 83% of athletes aimed to maintain or develop general fitness during the COVID-19 lockdown, adopting at-home exercise interventions (Washif, Farooq et al. 2021). In such settings, self-assessment tests can be implemented with relative ease, provided standardised instructions are followed. For example,

cycling-based time trials and critical power testing (Jones, Vanhatalo et al. 2010) can be performed at home (e.g., on Zwift or another software) or even outdoors, with the help of smart trainers or power meters. Similarly, running-based time trials and critical speed testing (Galbraith, Hopker et al. 2014) can be completed on a treadmill or an athletics track, simply using a stopwatch. Given that this thesis showed a high reproducibility of 20-min time trials on cycling performance, and successfully delivered different experimental interventions, this offers a starting point to stimulate remote-based cycling research, and assist coaches and athletes in their training monitoring and prescription.

Within sport sciences, the prevalence of multicentric studies is scarce (Impellizzeri 2017). That said, the potential of using virtual-reality software and remote interventions to facilitate multi-centre collaborations between research groups is noteworthy. It has been previously proposed that there is an underrepresentation of researchers affiliated with low- and middle-income countries on the editorial boards of top-ranked sports sciences journals (Memon, Ahmed et al. 2022). Therefore, virtual-reality software might be a prominent tool to stimulate the inclusion of those who are not often involved in scientific research. Virtual-reality software and remote study designs may allow researchers from geographically distinct locations to collaborate, engage in discussions and collect data following methodological standards. Implementing such projects, offer advantages particularly in terms of expanding the diversity of the research project, promoting inclusion and multi-centre collaborations. Nevertheless, to ensure the success of such collaborations, researchers must adhere to consistent guidelines and procedures, and ensure that testing protocols are standardised.

Laboratory-based interventions. Positive changes to physical performance have routinely been shown in laboratory studies after the administration of many nutritional supplements (Maughan, Burke et al. 2018) and also the administration of different forms of placebos (Hurst, Schipof-Godart et al. 2020). Indeed, CHAPTER FIVE (laboratory intervention) explored the effects of different competitive environments on cycling performance. Results showed improved power output when participants competed against their own augmented performance (+2% power outputs) and correctly informed so, but not when they were informed their opponent represented a participant who might have had an advantage by the means of a performance enhancing substance. The results reported in that chapter, contrasted the findings reported in CHAPTER SIX (remote intervention).

An important methodological aspect to consider is the role of the experimenter and how they may affect participants' performance. It has been previously shown that the presence of an experimenter in a testing setting may influence participants' performance (Rosenthal 1976), and more recently, that the provision of verbal encouragement improves exercise performance (Edwards, Dutton-Challis et

al. 2018). For example, Markus (1978) and Sheridan, Marchant et al. (2019) showed improvements in performance during a motor task test and during bench press exercise, respectively, when being spotted by an individual in comparison to performing the tests alone. Similarly, Edwards, Dutton-Challis et al. (2018) showed that external verbal encouragement improves sprint and endurance performance in comparison to a condition with no encouragement. Altogether, the results of those studies suggest that the presence/behaviour of experimenters most likely influences participants' performance. A possible explanation for such observation is that social cues may trigger neurobiological pathways similar to those triggered by ergogenic placebos, which in consequence, improves exercise performance (Davis, Hettinga et al. 2020). Although speculative, it is possible that the remote interventions adopted in this thesis (CHAPTER FOUR and CHAPTER SIX), minimised the effects of the researcher expectations, which may be supported by the significant findings reported in CHAPTER FIVE.

Laboratory-based randomised controlled trials (Hariton and Locascio 2018) are often adopted in sports sciences as they involve rigorous control over variables and random assignment of participants to treatment conditions. Such a controlled environment minimises confounding factors, enhances internal validity, and increases researchers' confidence in drawing conclusions. However, despite the controlled conditions, results might lack external validity (Cartwright 2007) and might not necessarily reflect applied settings or real-world conditions. Such a notion points to the distinction between efficacy and effectiveness of laboratory and remote designs. While laboratory-based studies can determine the efficacy (i.e., how a given treatment works under ideal, controlled conditions) of an intervention, its findings may not fully capture its effectiveness (i.e., how well it works in the real world) when implemented in applied contexts. Indeed, there were significant results only in the laboratory study (CHAPTER FIVE). The null findings reported in CHAPTER SIX raise doubts regarding the generalisation of results from CHAPTER FIVE to the complexity of applied settings. This disparity between the two chapters highlights the importance of considering the external validity of research findings. CHAPTER FIVE provided valuable insights into the efficacy of the intervention under controlled conditions and its respective psychophysiological responses, but the absence of significant results in the remote studies raises an important debate about the effectiveness of laboratory-based studies in applied settings.

It is undoubtful that laboratory studies play an important role in advancing our understanding regarding the psychophysiological mechanisms responsible for exercise performance in a controlled environment, and should not be disregarded. They allow researchers to conduct experiments that would be practically challenging to perform in a more applied environment while controlling for

potential confounding variables (e.g., environmental conditions). For example, assessing ventilatory responses to different interventions (such as CHAPTER FIVE), through the use of metabolic charts are challenging if participants do not have access to reliable, often expensive, portable analysers, which would allow them to perform self-assessment tests remotely. Nevertheless, submaximal tests for estimating parameters such as $\dot{V}O_2max$ have been previously validated for the general population (Bennett, Parfitt et al. 2016), which could be adopted in remote interventions. Self-assessment tests are, therefore, not always feasible to perform outside a laboratory-controlled environment, whereby the researcher is responsible for providing relevant information about the study and offering specialised knowledge about how to properly operate different equipment. Ultimately, the decision to perform experimental interventions either in a remote- or laboratory-based environment involves weighing the advantages and disadvantages of both, and it is up to the research team to discuss and make an informed choice regarding the most suitable approach, taking into account the specific aims of the study.

Limitations and future directions. Although virtual-reality software offers interesting opportunities to develop remote-based experimental interventions, it is important to consider some limitations. First, it is undoubtful that face-to-face research (e.g., in a laboratory setting) encompasses social interactions, which may be a key aspect in placebo effects research. In remote interventions, such social contact and information exchange between researchers and participants are limited, potentially affecting the results. Second, in nutritional interventions (such as in CHAPTER FOUR), it is challenging to ensure that participants administered a given ergogenic aid, at the designated time. More specifically, despite the efforts made to ensure proper control in CHAPTER FOUR, there are limitations regarding the administration of the drinks. Although participants were asked to complete a food diary before the time trials to check whether they ingested the drink at the designated time, and were asked after completion if they followed the instructions correctly, it was not feasible to physically confirm the accuracy of the information they provided. Third, time-zone differences between the participants in CHAPTER SIX during their competitive trials posed significant challenges to scheduling the trials, given that in some instances, the time differences between participants were 12 h. Fourth, although we reported high reproducibility of time trials performed on the virtual-reality software, the accuracy of measurements and differences between ergometers may affect the results. To cover such limitation, however, participants were asked to calibrate their equipment before each time trial, but again, this was not feasible to control in remote settings. Finally, given that remote research designs might rely on internet connectivity and in the case of this thesis, access to a smart bike and Zwift, reaching low-income countries or rural locations might not be always

easily achievable. However, whenever internet connectivity is compulsory, research groups can provide temporary internet access to participants in low-income communities through mobile hotspots, which could be mailed to them.

Irrespective of which kind of approach researchers choose to adopt, it is important to also weigh potential limitations of conducting sports science research in a controlled environment (i.e., laboratory setting). While controlled environments provide valuable insights and allow for greater control over different variables, they might not fully reflect applied conditions and lack ecological validity. For example, cycling competitions are extremely dynamic, where the behaviour of opponents, changes in course gradient and/or environmental conditions (i.e., wind speed, temperature) will ultimately have an impact on a given athlete's performance. Moreover, although familiarisation trials are recommended to adapt participants to a new environment and new equipment (e.g., a cycling ergometer), they may not replicate training and racing situations. Those nuances of such an unpredictable environment are challenging to quantify in a laboratory environment. Therefore, while conducting sports science research in controlled environments has merit, it is crucial for researchers to be aware of its potential limitations and consider complementary research approaches to gain a more comprehensive understanding of sports performance in applied settings.

Future research in sport and exercise sciences should aim to compare and integrate findings from both remote- and laboratory-based studies to advance our understanding of sports performance. Remote-based studies offer unique advantages, such as the ability to collect data in applied settings, recruit a large geographically diverse sample, and potentially allow for a larger application of findings. These studies can utilise wearable devices, sensors, and mobile applications to monitor participants' performance in their natural training or competitive environments. On the other hand, laboratory-based studies provide controlled conditions that allow for precise manipulation of variables and rigorous experimental designs. These studies can control for confounding variables (e.g., such as environmental conditions), and employ sophisticated equipment for detailed psychophysiological measurements. Future studies should adopt hybrid designs comparing responses in the laboratory and in a remote environment, to understand whether performance outcomes are comparable and if the physical presence of a researcher influence performance. For example, future studies could investigate the effects of beetroot juice supplementation both during 20-min time trials performed at participants' homes and during laboratory-based trials. Similarly, studies investigating competitive performance should investigate how participants' performance is influenced when competing against a dynamic real opponent and against a simulated avatar replicating a previous performance; or when being supervised by a researcher.

The effectiveness of virtual-reality cycling software for training purposes must be examined to determine its ability to elicit positive skill transfer and accurately simulate real-world scenarios. This is particularly relevant when considering the preparation of cyclists for challenging mountain stages like those in the Tour de France. While virtual reality offers several advantages described above associated with physical development and safety, its controlled nature may hinder the development of crucial technical skills. That is, unlike in actual mountain stages, where cyclists must navigate sharp turns, adjust to varying road conditions, and react to unexpected obstacles, virtual environments often lack these dynamic elements. Consequently, it remains uncertain whether the training provided by virtual-reality software fully prepares athletes to effectively handle the complexities and demands of real-world cycling. Further research is necessary to determine the extent to which virtual-reality training can truly replicate the intricacies of real-world conditions and elicit positive skill acquisition and transfer.

CONCLUSIONS

In conclusion, this thesis has highlighted the intricate relationship between performance, pacing, and the psychophysiological factors that influence athletic outcomes. The findings presented here underscore the potential impact of placebo effects through different interventions and the role of social contact during remote and laboratory designs.

The results of CHAPTER THREE demonstrated that performance and pacing are consistent during 20-min time trials on a virtual-reality platform, providing benchmark values that could assist coaches and cyclists in monitoring their training; and sports scientists aiming at conducting experimental research using virtual-reality platforms. In CHAPTER FOUR and CHAPTER SIX, performance and pacing were not altered by the administration of an acute dose of beetroot juice, or by the manipulation of competitive environments, respectively. More specifically, irrespective of whether athletes were correctly informed or deceived about the real purpose of the intervention (beetroot juice or opponents), performance and pacing were similar. The results reported in CHAPTER FIVE contrasted the findings from CHAPTER SIX and showed that cycling performance is only improved with the provision of accurate feedback, but not when they deceptively compete against an opponent whom they think has an advantage over them.

It seems that placebo effects research must consider the potential influence of social contact between researchers and participants. While conducting research in a laboratory setting allows for the investigation of psychophysiological mechanisms related to exercise performance, with the ability to control for confounding variables, this thesis highlights the intriguing potential of virtual-reality

software as an alternative when prioritising performance outcomes in applied settings. Researchers should consider the limitations of both designs in future interventions and make informed decisions regarding which approach is more appropriate.

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Appendix 1

Participants information sheet and consent form for experimental study 1 (CHAPTER THREE)

Reliability of 20-min cycling time trials using Zwift®

PARTICIPANT INFORMATION

A research study is being conducted at Canterbury Christ Church University (CCCU) by Guilherme Garcia Matta, under the supervision of Dr Philip Hurst.

Please refer to our Research Privacy Notice for more information on how we will use and store your personal data.

Background

Examining sport performance outcomes within the current COVID-19 climate is severely restricted. A need exists in using sport performance measures that are reliable, valid and ensure social distancing. Zwift® is an app for athletes that offers the opportunity to measure sport performance in cycling, running and triathlon, without the need for researchers to be in the same physical space as participants. Within Zwift, athletes ride their bicycles on a stationary trainer or run on a treadmill and perform a preselected distance that replicates the demands of exercising outdoors. Zwift is the most commonly used platform for virtual exercise and as of February, 2020, more than 1.6 million people worldwide are registered with the app. To our knowledge, no study has assessed the reliability of performance on Zwift and whether outcomes are consistent over time. Thus, the purpose of this study is to assess the reliability of cycling performance on Zwift.

What will you be required to do?

Prior the start of your participation, you will be asked to complete a health and fitness screening questionnaire to determine if you have any health risk factor and are eligible to participate. If any health-related conditions are identified, you will not be able to participate.

Before the start of your participation and after reading/completing all documentation, we will ask you to sign the informed consent document if you are happy to freely volunteer to participate. You will also have the opportunity to ask further questions regarding the sessions.

Participants in this study will be requested to perform three 20-min time trials on Zwift, separated by 5-7 days each. Distance covered, and average power output of the entire time trial and every 2-min interval will be collected after each trial. Every session should be performed at the same time of the day to avoid differences in the circadian effects, using the same equipment (i.e. bike or turbo trainer) and clothing. We also ask you to standardise your fluid intake and diet 24 hours prior the start of each session.

You are free to withdraw your consent to participate in this research project at any time without having to give a reason and all detailed information regarding your performance during the time trials will be disclosed to you in the earliest feasible time.

To participate in this research, you must:

Be a healthy cyclist (no injuries in the previous 2 months, no medical conditions), aged 18-50 years old, training for more than 4 times per week, aiming to compete in local or national competitions, familiar with time trials, Zwift user for more than 6 months and sign the consent forms. If you have any injuries, neurological conditions, or chronic renal, metabolic or respiratory diseases you will not be able to participate.

Given the unsupervised nature of the study, extra care when conducting the sessions must be taken and you should agree with the risks described in this document. After signing the consent form, you are ensuring you have read and understood the content relating to the risks associated with the study. You must also agree that the University has no responsibility/liability for any possible damage caused to your equipment as a result of your participation. The university or research team will not be liable to you in respect of any personal injury that you may suffer or sustain directly or indirectly as a result of participation in the research study.

You must ensure the electrical system is in good condition (i.e. no damaged sockets or wiring), not leaving any power cables trailing and keeping the electrical equipment away from fluids; to keep the amount of flammable materials (i.e. piece of paper) to a minimum; to remove any ignition sources from the exercising station; to make sure you have fire routes and extinguishers available; that your smoke detector or fire alarm are working properly and regularly checked; to

make your environment safe from slip or trip hazards; to familiarise yourself with the setup and the use of your training station; and to provide appropriate maintenance of your ergometer according to the specifications outlined within the equipment's booklet/website.

You are also strongly advised to perform the sessions only if there is anyone else present at your house or near the training station, that could summon first aid in the case it is necessary. You should only use the equipment you are already accustomed to, to set it out on appropriate even surface and to standardise the setup in a way that you do not need to move it between sessions. In the case you need to move or change your setup you must contact the research team and provide details about the modifications you have made to your equipment.

Make sure the screen is positioned in a comfortable position with suitable lightning configuration (e.g. brightness and contrast). All activities must take place in a clear and well-ventilated space and you should always wear appropriate footwear and clothing for the activity. If you find any issues with your setup or equipment, do not hesitate to contact the research team (details at the end of this document).

Most importantly, in the case you feel unwell, you should immediately cease the activity and contact your local GP. We will also request that you inform us the time when you plan to start the session, so we can send a follow-up message to ensure everything is fine.

Procedures

Each session will involve a 10-min warm-up in a self-selected intensity followed by 5-min rest (spinning your legs really slow, just so the time keeps running) and a 20-min time trial afterwards. You should treat each session as a competition, avoiding strenuous exercise during the 48-h preceding each test, and to follow your regular diet and fluid intake. You should also try to standardise the conditions between each session, performing the time trials at the same time of the day, at the same room, and using the same bike, turbo trainer and clothing. We also ask you to avoid drafting behind other cyclists and to also avoid using boost items on Zwift. After the end of each time trial, you will be requested to export the activity file in a .FIT format and to send it to the research team. The process of exporting the activity file will be explained to you beforehand.

Feedback

At the end of the study, you will receive a full detailed report of your performance during each time trial, describing the results of all parameters collected.

Confidentiality and Data Protection

The following categories of personal data (as defined by the General Data Protection Regulation (GDPR)) will be processed:

- Full name and contact details (e-mail and phone number)

We have identified that the public interest in processing the personal data is:

- Processing of personal data is necessary to identify the participants and provide them with proper feedback after data collection. Personal data will be used only to identify the participants during data processing and analysis.

Data can only be accessed by, or shared with:

- Guilherme Garcia Matta and the research team.

The identified period for the retention of personal data for this project:

- After the required ten-year retention period, all data and personal information will be destroyed.

If you would like to obtain further information related to how your personal data is processed for this project, please contact Guilherme Matta at g.matta392@canterbury.ac.uk.

You can read further information regarding how the University processes your personal data for research purposes at the following link: Research Privacy Notice - https://www.canterbury.ac.uk/university-solicitors-office/data-protection/privacy-notices/privacy-notices.aspx

Dissemination of results

The results of this study will be published in the University's library and potentially be sent for publication in Scientific Journals and conferences abstracts.

Process for withdrawing consent to participate

You are free to withdraw your consent to participate in this research project at any time without having to give a reason. To do this simply send an e-mail to g.matta392@canterbury.ac.uk stating your desire to withdraw.

You may read further information on your rights relating to your personal data at the following link: Research Privacy Notice - https://www.canterbury.ac.uk/university-solicitors-office/data-protection/privacy-notices/privacy-notices.aspx

Any questions?

Please contact:

Guilherme Matta

g.matta392@canterbury.ac.uk

OR

School of Human and Life Sciences

Sport and Exercise Sciences

ses@canterbury.ac.uk

CONSENT FORM

Title of Project: Reliability of 20-min cycling time trials using Zwift®

Name of Researcher: Guilherme Garcia Matta, under the supervision of Dr Philip Hurst.

Contact details:

Address:	Room Af50, School of Human and Life Sciences, North Holmes Road, Canterbury, Kent, CT11QU, UK.
Tel:	01227 782940 ext 3145
Email:	g.matta392@canterbury.ac.uk

Please initial box

1. I confirm that I have read and understand the participant information for the above project and have had the opportunity to ask questions.	
2. (If applicable) I confirm that I agree to any audio and/or visual recordings.	
3. I understand that any personal information that I provide to the researchers will be kept strictly confidential and in line with the University Research Privacy Notice	

4. I understand that my participation is voluntary and that I am free to withdraw my participation at any time, without giving a reason.

5. I agree to take part in the above project.

—

Name of Participant:	Date:	Signature:
Name of person taking consent *(if different from researcher)*	Date:	Signature:
Researcher:	Date:	Signature:

Copies: 1 for participant

1 for researcher

Appendix 2

Import and export instructions for experimental study 1 (CHAPTER THREE)

Study title:

Reliability of 20-min cycling time trials using Zwift®

Researcher:

Guilherme Matta, under the supervision of Dr Philip Hurst.

Dear participant,

Thank you for volunteering to take part in our study. Please find below a step-by-step guide on how to perform the sessions on Zwift.

After you download the workout protocol before the start of the first session, you can skip steps 1 and 2 on the following sessions, but you will still have to repeat steps 3 to 9.

If you have a heart rate sensor, we would appreciate if you could also use it during the time trials.

Please read through it carefully. If you have any questions, do not hesitate to contact me at g.matta392@canterbury.ac.uk or by phone at 07958690687.

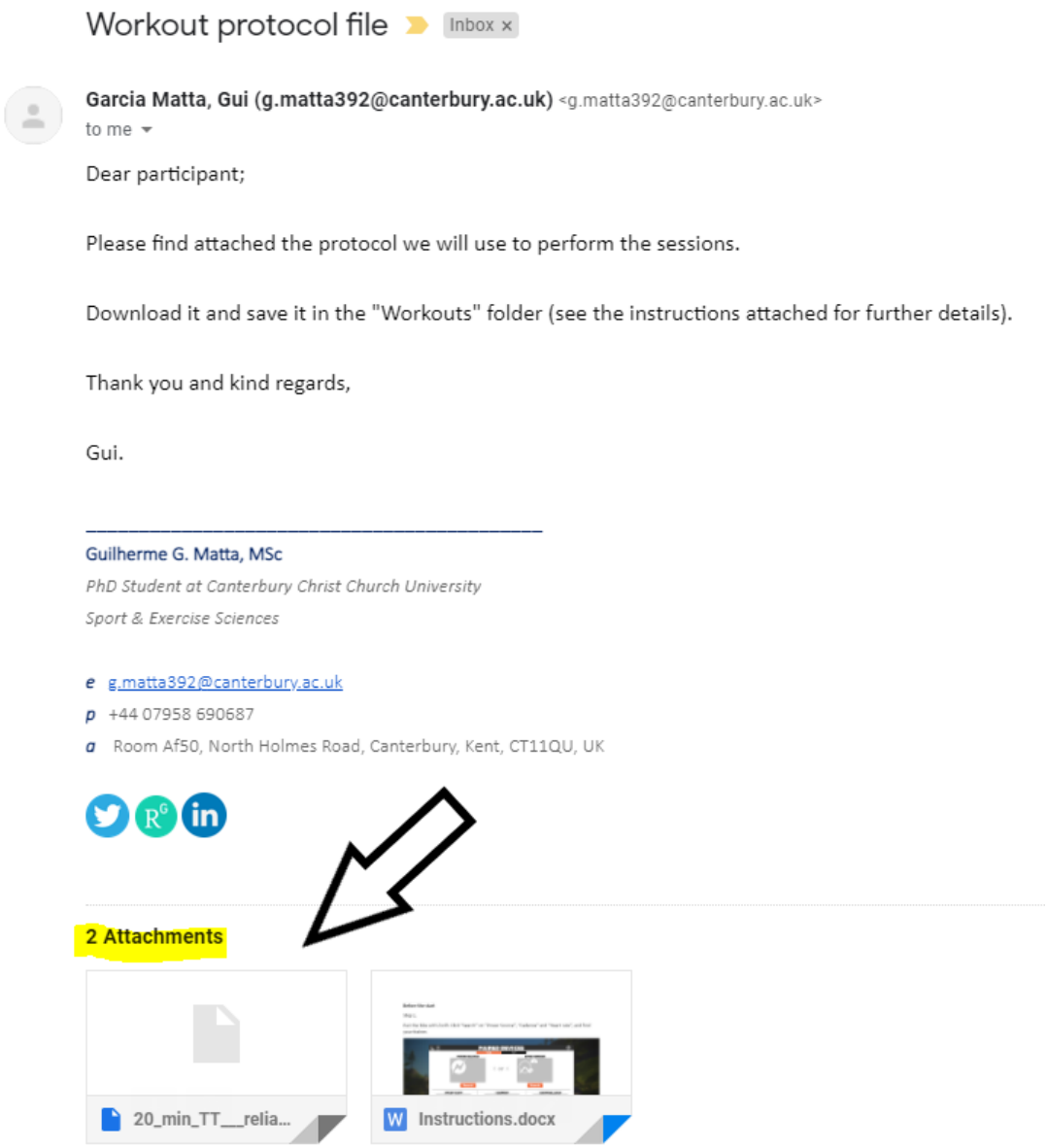
Kind regards,

Gui.

BEFORE THE START

STEP 1.

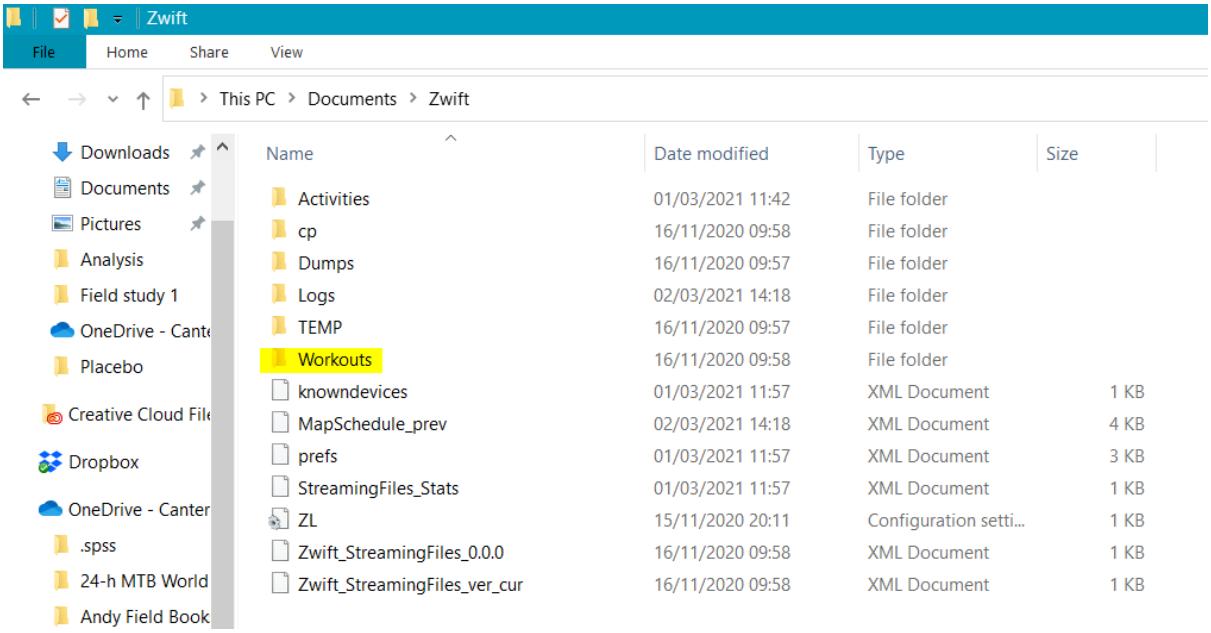
Download workout file from your e-mail.

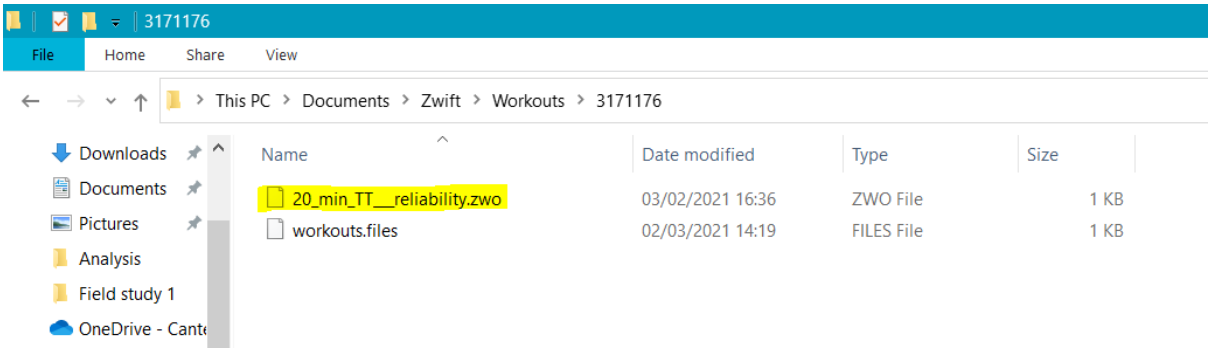


STEP 2.

Paste or save workout file sent by e-mail to folder “Workouts”:

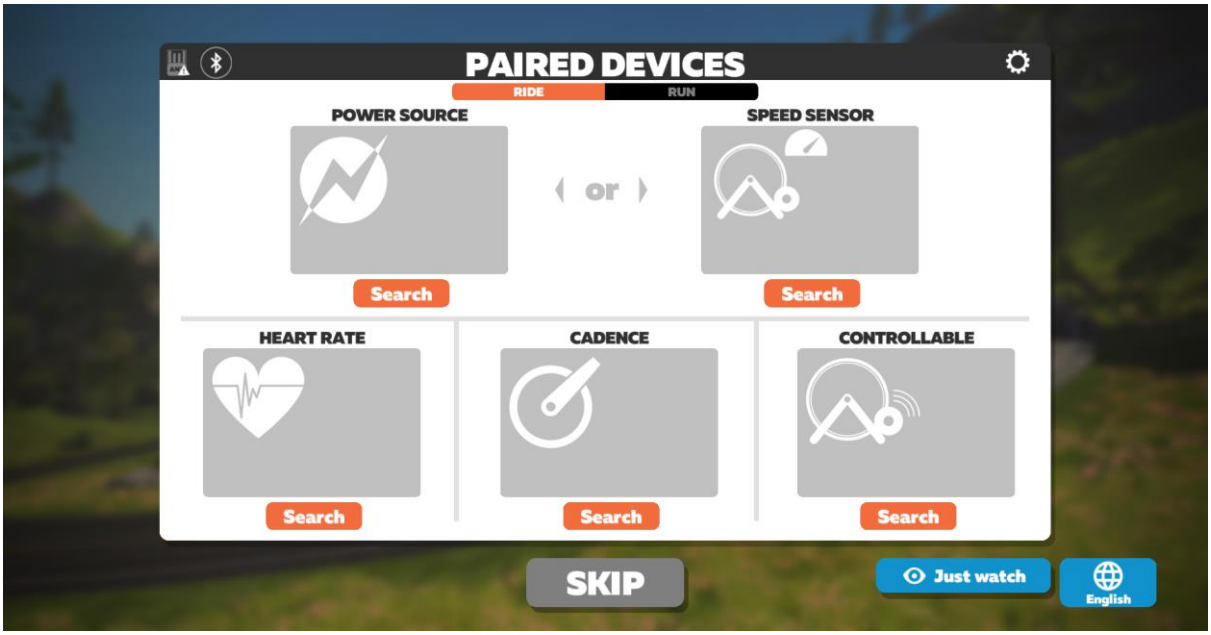
Documents > Zwift > Workouts





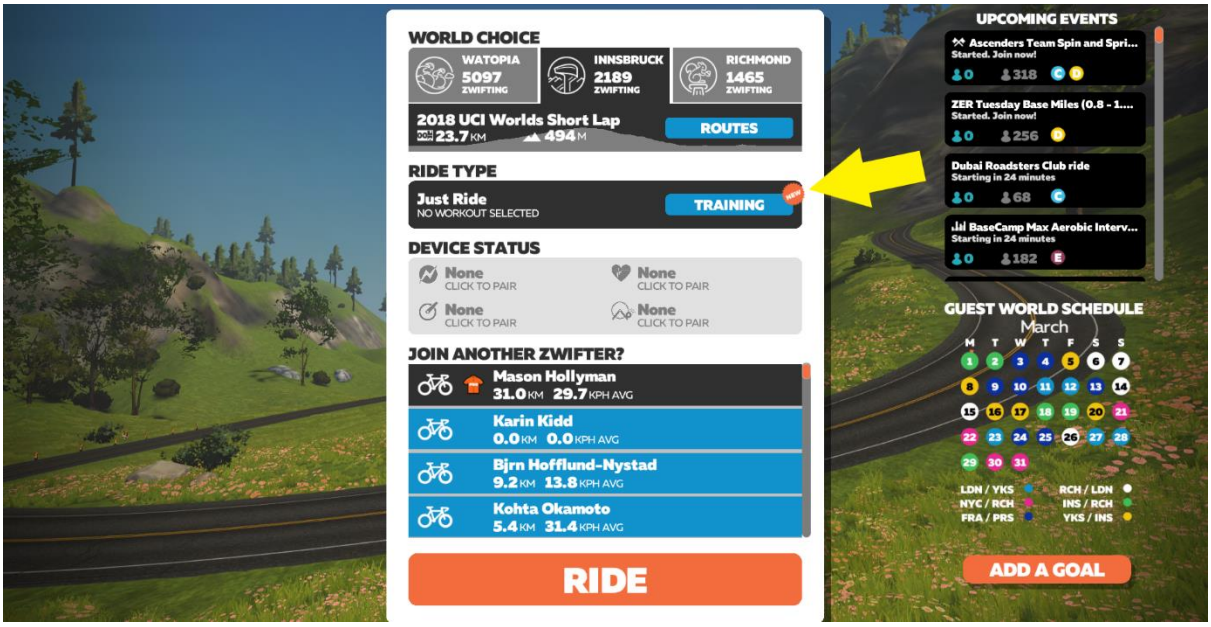
STEP 3.

Pair the bike with Zwift. Click “Search” on “Power Source”, “Cadence” and “Heart rate”, and find your trainer and heart rate monitor.

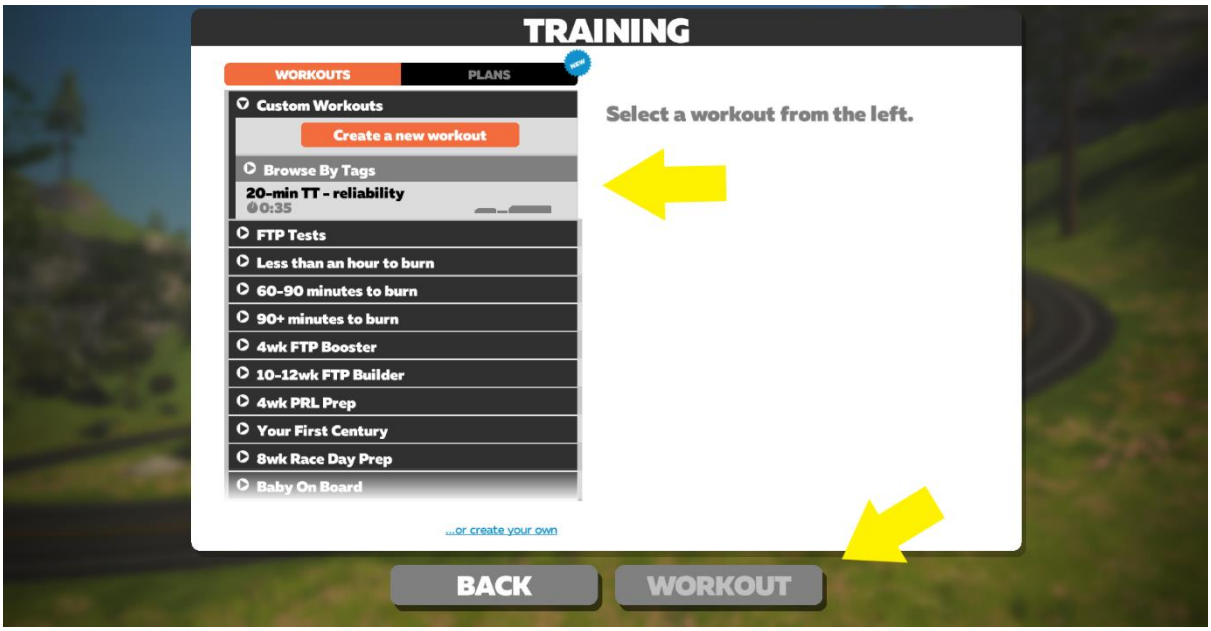


STEP 4.

Click “Training” under the “Ride Type” tab.

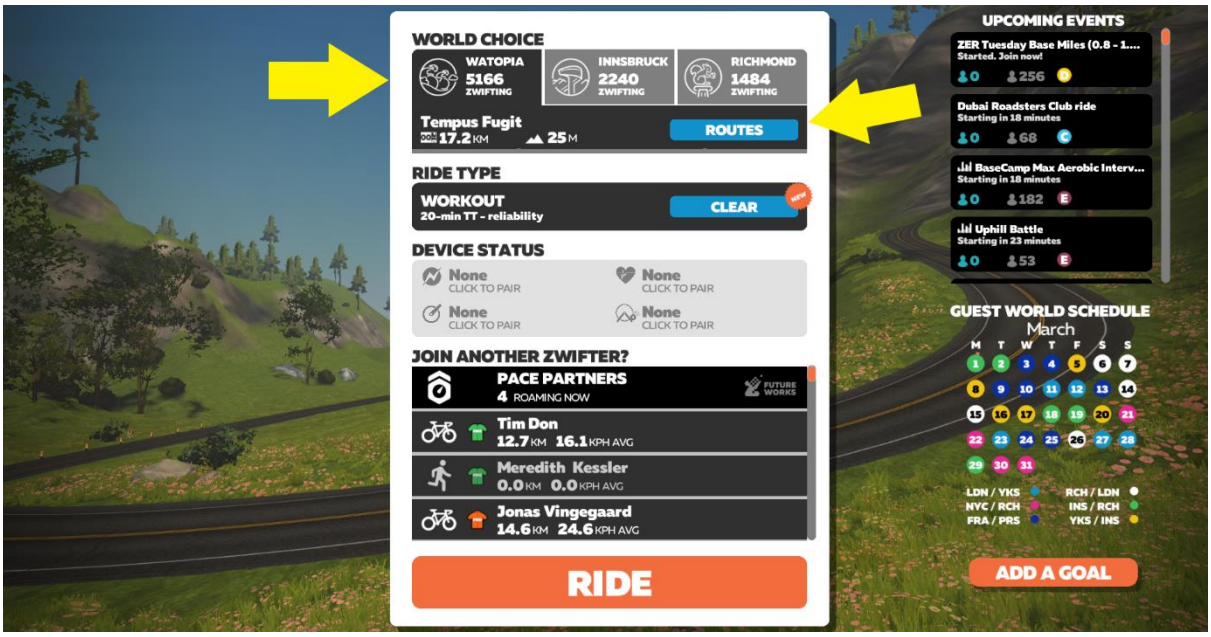


Select “Custom Workouts” and select the protocol “20-min TT – reliability”. Click “WORKOUT”.

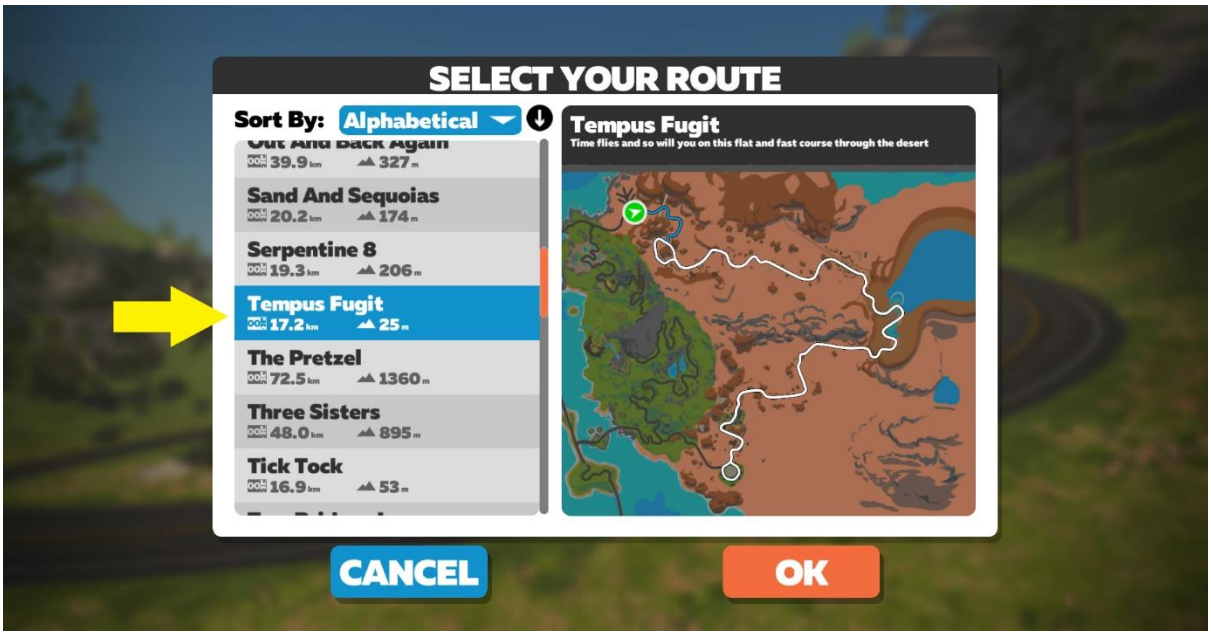


STEP 5.

On the main screen, select “Watopia” as the “World Choice” and click “Routes”.

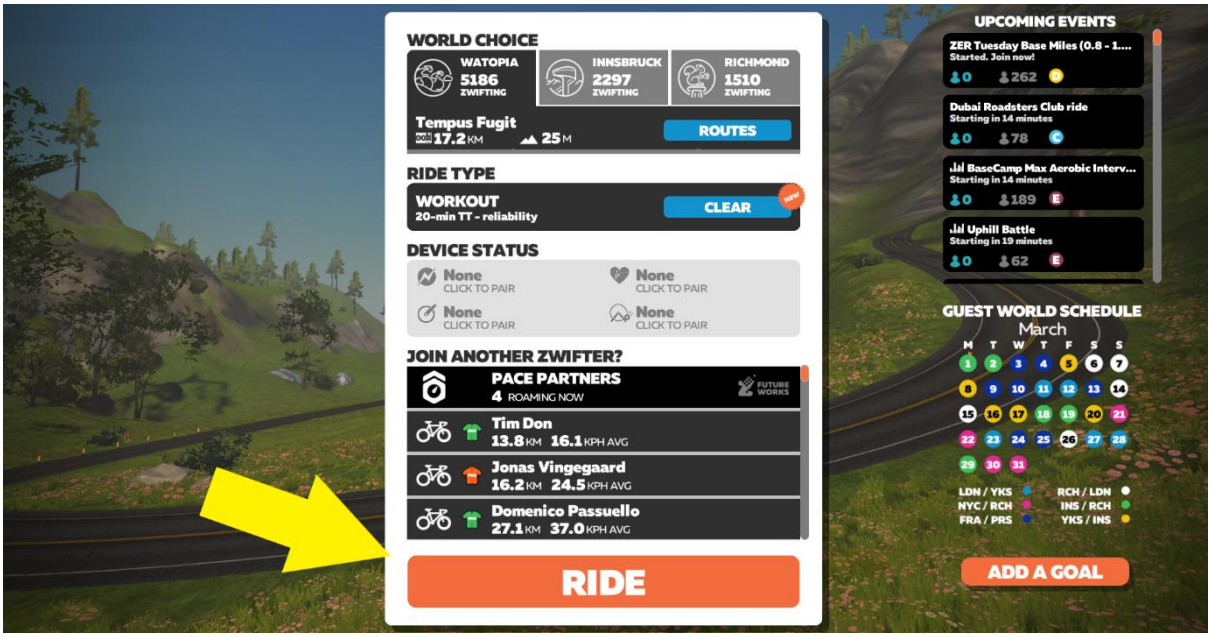


Scroll down the course list and select “Tempus Fugit”. Click OK.



STEP 6.

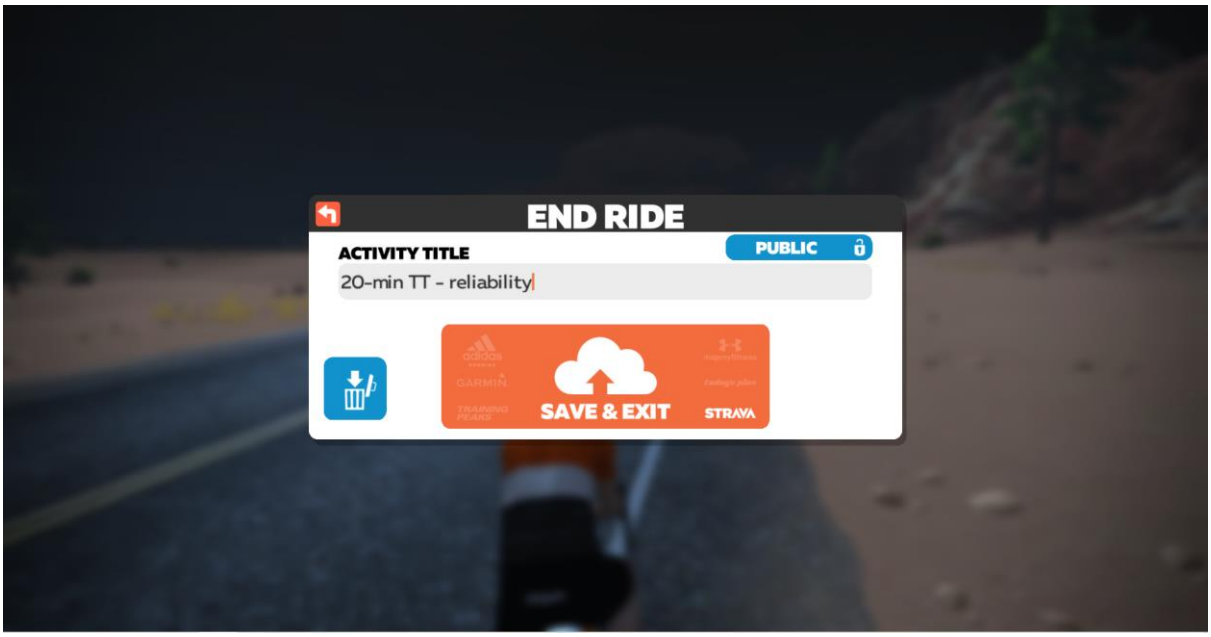
Click “RIDE”. Ride on!


WORLD CHOICE
WATOPIA
5186
ZWIFTING
INNSBRUCK
2297
ZWIFTING
RICHMOND
1510
ZWIFTING
Tempus Fugit
17.2 KM
25 M
ROUTES
RIDE TYPE
WORKOUT
20-min TT - reliability
CLEAR
DEVICE STATUS
None
CLICK TO PAIR
None
CLICK TO PAIR
None
CLICK TO PAIR
None
CLICK TO PAIR
JOIN ANOTHER ZWIFTER?
PACE PARTNERS
4 ROAMING NOW
Tim Don
13.8 KM 16.1 KPH AVG
Jonas Vingegaard
16.2 KM 24.5 KPH AVG
Domenico Passuello
27.1 KM 37.0 KPH AVG
RIDE
UPCOMING EVENTS
ZER Tuesday Base Miles (0.8 - 1....
Started. Join now!
0
262
Dubai Roadsters Club ride
Starting in 14 minutes
0
78
C
BaseCamp Max Aerobic Interv...
Starting in 14 minutes
0
189
E
Uphill Battle
Starting in 19 minutes
0
62
E
GUEST WORLD SCHEDULE
March
M T W T F S S
1 2 3 4 5 6 7
8 9 10 11 12 13 14
15 16 17 18 19 20 21
22 23 24 25 26 27 28
29 30 31
LDN / YKS
NYC / RCH
FRA / PRS
RCH / LDN
INS / RCH
YKS / INS
ADD A GOAL

AFTER THE END

STEP 7.

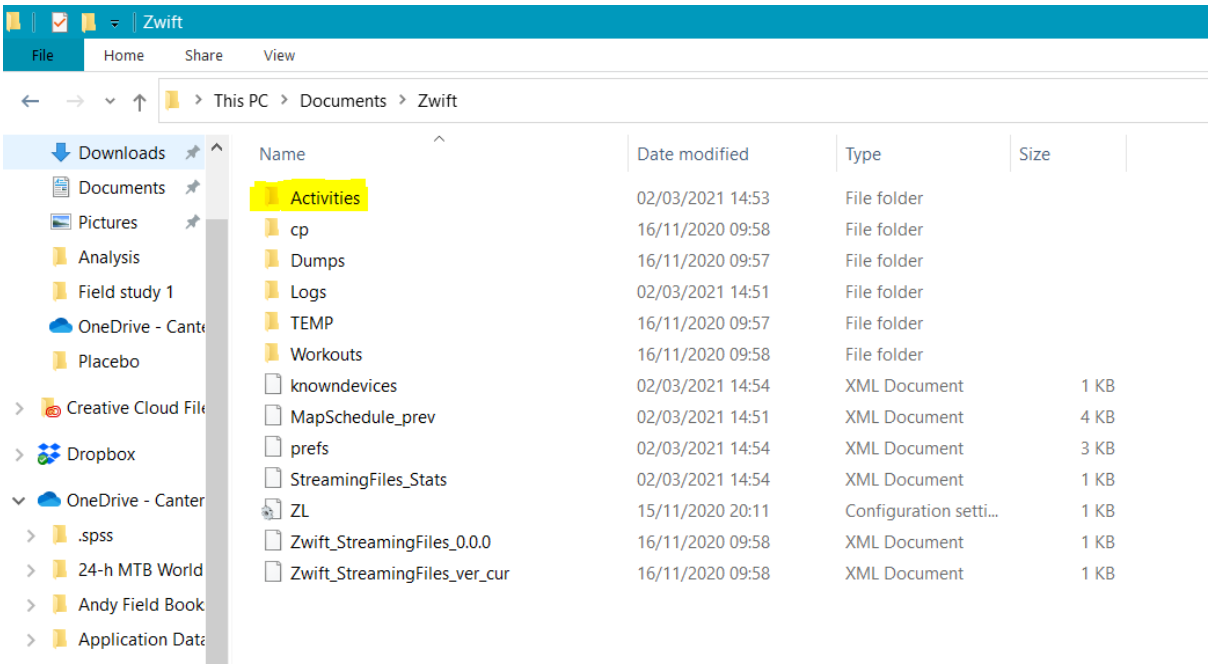
Save you workout by clicking “Save & Exit”.



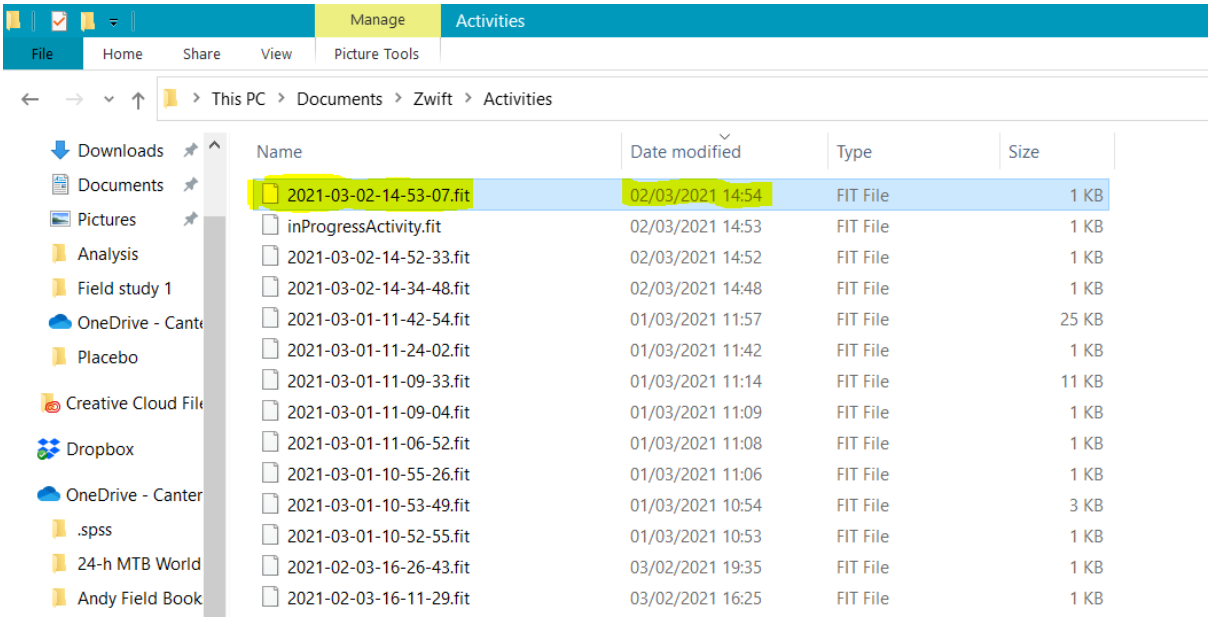
STEP 8.

Go to the Zwift file in your computer and click “Activities”:

Documents > Zwift > Activities



Select the activity file according to the date and time of the session.



STEP 9.

Send the activity file (described above) to g.matta392@canterbury.ac.uk

Appendix 3

Recruitment poster for experimental study 1 (CHAPTER THREE)

Appendix 4

Participants information sheet and consent form for experimental study 2 (CHAPTER FOUR)

Acute effects of dietary nitrate supplementation on cycling time trial performance

PARTICIPANT INFORMATION

A research study is being conducted at Canterbury Christ Church University (CCCU) by Guilherme Garcia Matta, under the supervision of Dr Philip Hurst.

Please refer to our Research Privacy Notice for more information on how we will use and store your personal data.

Background

The supplementation of beetroot juice pre-exercise has been shown to improve endurance performance (Ormsbee et al., 2013), and benefits are associated with its high NO_3^- content. Larsen et al. (2007), showed that the ingestion of NO_3^- (0.1 mmol·kg-1/day for 3 days) resulted in a significantly lower oxygen cost through different ranges of cycling work rates, resulting in enhanced efficiency. Similarly, Hurst et al. (2020) showed that an acute dose of beetroot juice (containing ~4.1 mmol of NO_3^-), improves 5-km running performance by around 1.4% compared to baseline. A systematic review (McMahon, Leveritt & Pavey, 2017) analysing the combined results of 47 studies investigating the ergogenic effects of NO_3^-, showed convincing evidence that dietary NO_3^- supplementation elicits improvements in endurance exercise performance. Thus, the aim of this study is to analyse if an acute dose of beetroot juice containing a large concentration of NO_3^- improves 20-min cycling time trial performance.

What will you be required to do?

Prior the start of your participation, you will be asked to complete a health and fitness screening questionnaire to determine if you have any health risk factor and are eligible to participate. If any health-related conditions are identified, you will not be able to participate.

Before the start of your participation and after reading/completing all documentation, we will ask you to sign the informed consent document if you are happy to freely volunteer to participate. You will also have the opportunity to ask further questions regarding the sessions.

Participants in this study will be requested to perform three 20-min time trials on Zwift, separated by 5-7 days each, in the following order: 1) familiarisation; 2) baseline; 3) experimental (beetroot juice or placebo conditions). In the three sessions, you should aim to produce the highest power output. On the third session you will be requested to ingest 70 mL of nitrate-rich beetroot juice (containing 0.5 g of NO3-; Beet It; James White Drinks Ltd.®, Ipswich, United Kingdom, UK) or 70 mL of nitrate-depleted beetroot juice (placebo, containing ~0.0047 mmol of NO3-; Beet It; James White Drinks Ltd., Ipswich, United Kingdom, UK). You will be randomly assigned to either the beetroot juice group or the placebo group after the second time trial, and you will be informed about which group you were assigned to. The substances will be prepared in advance by the research team and mailed to your address. You will be asked to self-administer the substance 2 h before the start of the time trial and to fast during the time between the supplementation and the time trial (water will be permitted *ad libitum*). This was chosen based on previous research showing that plasma nitrate peak after ~2 h after ingestion.

Distance covered, and average power output of the entire time trial and every 2-min interval will be collected after each trial. Every session should be performed at the same time of the day to avoid differences in the circadian effects, using the same equipment (i.e. bike or turbo trainer) and clothing. We also ask you to standardise your fluid intake and diet 24 hours prior the start of each session.

You are free to withdraw your consent to participate in this research project at any time without having to give a reason and all detailed information regarding your performance during the time trials will be disclosed to you in the earliest feasible time

To participate in this research, you must:

Be a healthy cyclist (no injuries in the previous 2 months, no medical conditions), aged 18-50 years old, training for more than 4 times per week, aiming to compete in local or national competitions, familiar with time trials, Zwift user for more than 6 months and sign the consent forms. You must also have not taken any form of nitrate supplementation for performance purposes in the 2 months before the start of your participation and report not having beetroot allergy. If you have any injuries, neurological conditions, or chronic renal, metabolic or respiratory diseases you will not be able to participate.

Given the unsupervised nature of the study, extra care when conducting the sessions must be taken and you should agree with the risks described in this document. After signing the consent form, you are ensuring you have read and understood the content relating to the risks associated with the study. You must also agree that the University has no responsibility/liability for any possible damage caused to your equipment as a result of your participation. The university or research team will not be liable to you in respect of any personal injury that you may suffer or sustain directly or indirectly as a result of participation in the research study.

You must ensure the electrical system is in good condition (i.e. no damaged sockets or wiring), not leaving any power cables trailing and keeping the electrical equipment away from fluids; to keep the amount of flammable materials (i.e. piece of paper) to a minimum; to remove any ignition sources from the exercising station; to make sure you have fire routes and extinguishers available; that your smoke detector or fire alarm are working properly and regularly checked; to make your environment safe from slip or trip hazards; to familiarise yourself with the setup and the use of your training station; and to provide appropriate maintenance of your ergometer according to the specifications outlined within the equipment's booklet/website.

You are also strongly advised to perform the sessions only if there is anyone else present at your house or near the training station, that could summon first aid in the case it is necessary. You should only use the equipment you are already accustomed to, to set it out on appropriate even surface and to standardise the setup in a way that you do not need to move it between sessions. In the case you need to move or change your setup you must contact the research team and provide details about the modifications you have made to your equipment.

Make sure the screen is positioned in a comfortable position with suitable lightning configuration (e.g. brightness and contrast). All activities must take place in a clear and well-ventilated space and you should always wear appropriate footwear and clothing for the activity. If you find any

issues with your setup or equipment, do not hesitate to contact the research team (details at the end of this document).

Most importantly, in the case you feel unwell, you should immediately cease the activity and contact your local GP. We will also request that you inform us the time when you plan to start the session, so we can send a follow-up message to ensure everything is fine.

Procedures

Each session will involve a 10-min warm-up in a self-selected intensity followed by 5-min rest (or slowly spinning your legs, just to keep the time running) and a 20-min time trial afterwards. You should treat each session as a competition, avoiding strenuous exercise during the 48-h preceding each test, and to follow your regular diet and fluid intake. During the first two time trials you will not receive any substances, but on the third, you will be asked to self-administer 70 mL of beetroot juice containing a high concentration of NO_3^-, or 70 mL of a placebo (containing a very low dose of NO_3^-, which does not elicit any ergogenic effects), that has been shown to improve endurance performance. You should also try to standardise the conditions between each session as much as you can, performing the time trials at the same time of the day, at the same room, and using the same bike, turbo trainer and clothing. We also ask you to avoid drafting behind other cyclists and to also avoid using PowerUps items on Zwift. After the end of each time trial, you will be requested to export the activity file in a .FIT format and to send it to the research team. The process of exporting the activity file will be explained to you beforehand.

Feedback

At the end of the study, you will receive a full detailed report of your performance during each time trial, describing the results of all parameters collected.

Confidentiality and Data Protection

The following categories of personal data (as defined by the General Data Protection Regulation (GDPR)) will be processed:

- Full name and contact details (e-mail and phone number)

We have identified that the public interest in processing the personal data is:

- Processing of personal data is necessary to identify the participants and provide them with proper feedback after data collection. Personal data will be used only to identify the participants during data processing and analysis.

  Data can only be accessed by, or shared with:

- Guilherme Garcia Matta and the research team.

  The identified period for the retention of personal data for this project:

- After the required ten-year retention period, all data and personal information will be destroyed.

  If you would like to obtain further information related to how your personal data is processed for this project, please contact Guilherme Matta at g.matta392@canterbury.ac.uk.

  You can read further information regarding how the University processes your personal data for research purposes at the following link: Research Privacy Notice - https://www.canterbury.ac.uk/university-solicitors-office/data-protection/privacy-notices/privacy-notices.aspx

Dissemination of results

The results of this study will be published in the University's library and potentially be sent for publication in Scientific Journals and conferences abstracts.

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Any questions?

Please contact:

Guilherme Matta

g.matta392@canterbury.ac.uk

OR

School of Human and Life Sciences

Sport and Exercise Sciences

ses@canterbury.ac.uk

CONSENT FORM

Title of Project: **Acute effects of dietary nitrate supplementation on cycling time trial performance**

Name of Researcher: Guilherme Garcia Matta, under the supervision of Dr Philip Hurst.

Contact details:

Address:	Room Af50, School of Human and Life Sciences, North Holmes Road, Canterbury, Kent, CT11QU, UK.
Tel:	01227 782940 ext 3145
Email:	g.matta392@canterbury.ac.uk

Please initial box

1.	I confirm that I have read and understand the participant information for the above project and have had the opportunity to ask questions.	
2.	(If applicable) I confirm that I agree to any audio and/or visual recordings.	
3.	I understand that any personal information that I provide to the researchers will be kept strictly confidential and in line with the University Research Privacy Notice	
4.	I understand that my participation is voluntary and that I am free to withdraw my participation at any time, without giving a reason.	

5. I agree to take part in the above project. ☐

—

Name of Participant:	Date:	Signature:
Name of person taking consent *(if different from researcher)*	Date:	Signature:
Researcher:	Date:	Signature:

Copies: 1 for participant

1 for researcher

Appendix 5

Leaflet used in experimental study 2 (CHAPTER FOUR)

Beetroot juice as a powerful ergogenic aid

June 2021

CANTERBURY CHRIST CHURCH UNIVERSITY

Sport and Exercise Sciences

Authored by: Guilherme Matta

Canterbury Christ Church University

An acute dose of beetroot juice ingested pre-exercise improves endurance performance

General information

This study aims to compare how the knowledge of ingesting a beetroot juice or a placebo affects cycling performance. In a typical study examining how nutritional interventions affectsperformance, we would usually adopt what is called a double-blinded randomised controlledtrial, in which both the participants and the researchers are blinded to which drink is being administered in each session (i.e. a placebo or an ergogenic aid). However, if an athlete receives a placebo believing it is an ergogenic aid, he might experience a placebo effect and respond positively to the intervention, improving performance. For that reason, we want to examine what happens when athletes are 100% sure about which drinks are being administered, in an open-label study-design (no information will be withheld from the participants), and whether this improves performance to a greater extent than when they areunsure of what they have taken.

Thus, this leaflet contains general information about what to expect from the ingestion of a single dose of beetroot juice before an exercise task. If you have any questions or concerns, do not hesitate to contact the research team:

Gui Matta

g.matta392@canterbury.ac.uk.

Nitrates

Dietary nitrate has been growing in popularity as a sports supplement, after several studies reported improvements in exercise performance in a range of sports. Nitrates can befound in different foods, but mainly in leafy vegetables and **beetroot**. As a sport supplement,studies have shown that dietary supplementation might decrease the oxygen cost, which in turn enhances exercise efficiency and tolerance. Thus, previous studies have shown that nitrates are a powerful ergogenic aid, which has minimal side-effects.

The Australian Institute of Sport have also recognised the performance enhancing benefits of nitrate and its ability to significantly improve performance, being extensively usedby Australian elite athletes and respected nutritionists/physiologists (see appendix at the endof this document).

Nitrates and exercise performance

Several studies investigating the acute effects of nitrate ingestion in the form of **beetroot juice**, reported improvements in endurance performance. For example, one study [1] found improvements in performance of 2.7% and 2.8% during 4- and 16-km cycling time- trials, respectively, after an acute ingestion of beetroot juice, a difference of around 20 wattsin average power output. Similarly, another study [2] reported improvements in power outputand time to completion during a 10-km cycling time trial. In a study [3] analysing the results of **80 individual studies** (basically every single study published to date about nitrate supplementation), the authors reported a clear improvement in endurance exercise performance of ~3%.

Altogether, the results of the studies mentioned above and many others [4-7], make it clear thatnitrate supplementation is a powerful ergogenic aid for endurance athletes. Thus, a single dose of beetroot juice might substantially benefit cycling performance.

It is also important to note that the previous studies failed to find any serious side-effects after beetroot juice supplementation. Besides being a powerful ergogenic aid, we are confident that it is also safe and offers minimal risks.

The drink you will get

Beetroot group

Beet It Sport Shot (70mL)

- Concentrated beetroot juice (98%)
- 400mg of natural nitrate
- 7x more concentrated than than beetroot juice
- Batch-tested
- Convenient reliable form

Placebo group

In case you are assigned to the placebo group, you will receive an identical bottle, but this willbe a nitrate-depleted drink, having absolutely no ergogenic effects. This drink was also prepared by the same brand as the Beet It Sport Shot, and for consistency purposes, the bottles are the same.

What elite athletes are saying about beetroot juice supplementation?

Pawal Celinski

Team GB triathlete

"Beetroot is one of the healthiest vegetables in the world and there are only few products of such high quality and naturalness as Beet It Sport products. I find it is perfect for my long- distance efforts, my training becomes more effective and my body has faster regeneration. Most other energy shots contain artificial/chemical substances, but Beet It Sport offers 100% natural energy – I can't imagine using anything else!"

David Conroy

Irish Junior Cyclo-cross National Champion

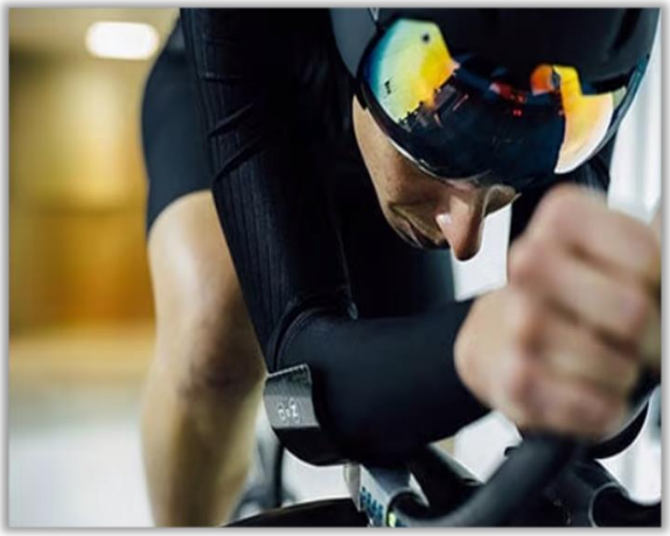
"Beet It Sport has been an awesome aidto my performance. I rarely usesupplements because I feel most supplements are easily replaced with real food. However, Beet It Sport is suchan easy way to maximise the proven performance benefits of nitrates found concentrated in beetroot. I always use the Nitrate 400 shots 3 hours before the race to maximise my performance"

Elen Davies

Represented Great Britain at the European Championships and England at the Commonwealth Games

Team GB at the 50km World Championshipsin 2019

"I have been using Beet It Sport shots since the first study was published 10 years ago. I find they improve my stamina and I use themon training session days and long run days. Inthe build up to key events, I take one every morning and evening of the week before andtake 2 shots 2hrs before on race day – they make me feel stronger and give me a performance gain."



Vittoria Bussi

Vittoria is an Italian Professional Cyclist whoin 2018, set the new Women's UCI hour record, cycling 48.007 kilometres (29.830 miles).

"I drink Beet It Sport Nitrate 3000 around 10 days before important competitions, as it naturally increases the level of nitrate inyour body. It has been scientifically proven that nitrate affects the efficiency of oxygenconsumption and I can tell you, this was crucial in breaking a world record."

Source: https://beet-it.com/beet-it-sport/ambassadors/

References

1. Lansley KE, Winyard PG, Bailey SJ, et al. Acute dietary nitrate supplementation improves cycling time trial performance. *Medicine & Science in Sports & Exercise.* 2011;43(6):1125-1131.
2. Cermak NM, Gibala MJ, Van Loon LJ. Nitrate supplementation's improvement of 10-km time-trial performance in trained cyclists. *International journal of sport nutrition and exercise metabolism.* 2012;22(1):64-71.
3. Senefeld JW, Wiggins CC, Regimbal RJ, Dominelli PB, Baker SE, Joyner MJ. Ergogenic effect of nitrate supplementation: A systematic review and meta-analysis. *Medicine and science in sports and exercise.* 2020;52(10):2250.
4. Jones AM. Dietary nitrate supplementation and exercise performance. *Sports medicine.* 2014;44(1):35-45.
5. Jones AM, Thompson C, Wylie LJ, Vanhatalo A. Dietary nitrate and physical performance. *Annual review of nutrition.* 2018;38:303-328.
6. Thompson C, Wylie LJ, Fulford J, et al. Dietary nitrate improves sprint performance and cognitive function during prolonged intermittent exercise. *European journal of applied physiology.* 2015;115(9):1825-1834.
7. Jones AM, Vanhatalo A, Seals DR, Rossman MJ, Piknova B, Jonvik KL. Dietary Nitrate and Nitric Oxide Metabolism: Mouth, Circulation, Skeletal Muscle, and Exercise Performance. *Medicine and Science in Sports and Exercise.* 2020.

Appendix 6

Australian Institute of Sport Supplement Framework used in experimental study 2 (CHAPTER FOUR)

AIS SPORTS SUPPLEMENT FRAMEWORK

BEETROOT JUICE (Nitrates) GROUP A

Beetroot juice is a rich source of dietary nitrate, also found in other vegetables (particularly leafy greens), some fruits and processed meats. Dietary nitrate can be used to enhance the availability of nitric oxide, which plays an important role in the regulation of blood pressure, blood flow and muscle contraction. Increasing dietary nitrate intake has been shown to enhance exercise performance.

Beet IT Sport Shot (70mL)

- Concentrated beetroot juice (98%)
- 400mg natural nitrate
- 7 x more concentrated than beetroot juice
- Convenient, reliable form
- $4 per shot
- Batch-tested

Other Beetroot Products (e.g. juices, powders, gels)

- Lower nitrate e.g. juice = 800mg/L
- Often unspecified nitrate content
- Organic vegetable products lower in nitrate
- Check other ingredients and batch-testing status
- What is the cost per mg/nitrate?

BENEFITS OF NITRATES

- VASODILATOR (increase oxygen to muscles & lowers blood pressure)
- INCREASED EXERCISE CAPACITY (reduced energy cost of exercise)
- MUSCLE CONTRACTION & PERFORMANCE
- IMMUNE HEALTH

WHEN TO CONSIDER ITS USE

- Prolonged submaximal exercise eg. endurance events of 4-30mins e.g. running, cycling
- To support training for aerobic fitness
- High-intensity intermittent events with short duration sprint efforts in individual and team sports
- During exposure to hypoxic conditions e.g. altitude training

HOW TO USE IT

Research to date uses a variety of strategies and timing of supplementation, including single acute dose, top up acute dose, and chronic loading to obtain performance benefits.

Acute Dose:

2-3 hrs PRE - EXERCISE = 350 - 600mg NITRATE

Chronic Supplementation* (3-15 days):

FOR 3 DAYS PRE-EVENT = 350 - 600mg NITRATE PER DAY + 2-3 hrs PRE - EVENT = 300 - 600mg NITRATE

*May be useful for highly trained athletes where performance gains seem harder to obtain

Avoid using mouthwash or chewing gum with beetroot juice, as they interfere with its benefit.

E.g. *For 3 days prior:*
AM: 1 Beet IT Sport shot
PM: 1 Beet IT Sport shot
\+
Race Day: (2.5hrs pre-event)
2 x Beet IT Sport shots

AIS · ACTAS · NSWIS · NTIS · Queensland Government · SASI · FTIS · Victorian Institute of Sport · wais

BEETROOT JUICE (Nitrates)

FOOD FIRST PHILOSOPHY

The nitrate content of vegetables can vary considerably depending on soil quality, climate and time since harvest. Whilst encouraging a higher daily vegetable intake is likely to have numerous health benefits, including increasing nitrate intake, supplementation is more consistent and reliable when seeking a specific performance benefit.

Approximate amount of food equal to 1 x Beet IT Sports Shot (400mg nitrate):

Beetroot
1 large (200g)

Bok choy
1 medium (120g)

Rocket lettuce
2 cups (150g)

Parsley
2 cups (150g)

Silverbeet spinach
150g cooked (1 cup)

Baby spinach
2 cups (150g)

Fresh beetroot juice
(500mL)

Celery
2.5 cups (250g)

While nitrate is present in processed meats as an added preservative, sourcing nitrate from processed meats is not encouraged. Consuming nitrate in its natural form is likely to protect against any potentially-harmful compounds.

CONCERNS & CONSIDERATIONS

Beetroot juice, particularly in concentrated form can cause mild gut discomfort. Practise in training first.

Aerobic fitness levels impact the performance benefit in highly trained endurance athletes (V02max > 65).

Few studies have investigated the impact of nitrate supplementation on female athletes.

Mistaken use of nitrite or nitrite salt as supplements can be toxic. Stick to natural source of nitrates such as vegetables.

Beetroot juice may cause a temporary pink colour to urine and stools. This is a harmless side effect.

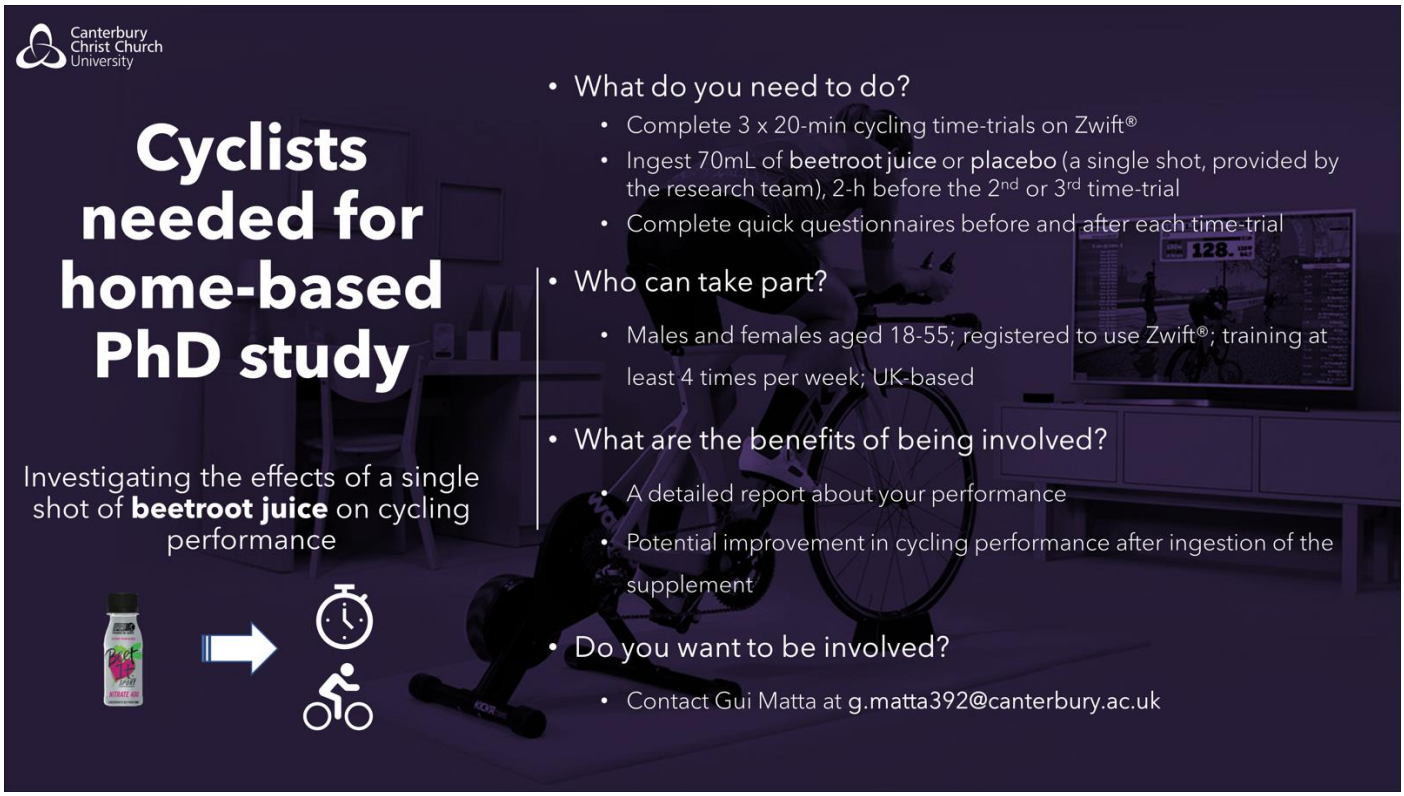
Chronic use of nitrate supplementation has not be studied long term.

Before engaging in supplement use, you should refer to the specific supplement policies of your sport or institute and seek professional advice from an accredited sports dietitian (www.sportsdietitians.com.au).

Athletes are reminded that they are responsible for all substances that enter their body under the 'strict liability' rules of the World Anti-Doping Code. All supplements have doping risk of some kind. Some supplements are riskier than others. Athletes should only use batch-tested supplements. The Sport Integrity Australia app provides a list of more than 400 batch-tested products. While batch-tested products have the lowest risk of a product containing prohibited substances, they cannot offer you a guarantee (www.sportintegrity.gov.au/what-we-do/supplements-sport).

Appendix 7

Recruitment poster for experimental study 2 (CHAPTER FOUR)



Appendix 8

Participants information sheet and consent form for experimental study 3 (CHAPTER FIVE)

Effects of exogenous ketone ingestion on competitive cycling performance and pacing

PARTICIPANT INFORMATION

A research study is being conducted at Canterbury Christ Church University (CCCU) by Guilherme Garcia Matta, under the supervision of Dr Damian Coleman.

Please refer to our Research Privacy Notice for more information on how we will use and store your personal data.

Background

Cycling performance and pacing are affected by several physiological, psychological and biomechanical parameters acting in combination that influences the outcome of a time trial. However, external cues, such as the presence of opponents and their behaviour during a race, have been shown to also affects an athlete's performance. For example, several studies have investigated how the presence of a virtual opponent affects performance and shown that different environments elicit different responses to exercise. Overall, the literature has shown that the presence of an opponent during a time trial elicit improvements in cycling performance, however, most studies used virtual avatars, instead of real performances from other cyclists, limiting the extrapolation of results.

Similarly, the ingestion of exogenous ketones both before and during exercise has received increased attention in the last decade, with conflicting results. Several reports from professional cycling teams can be found online, suggesting that cyclists have been using ketone drinks during

Grand Tours since 2012, but it became most popular in 2019. There are currently, no studies investigating how exogenous ketones affect 20-min cycling time trial in a simulated competition and how it affects the performance of other opponents who have not received any ergogenic aids.

Thus, the aim of this study is to 1) investigate the physiological and psychological responses of different real opponents on cycling performance and pacing; and 2) investigate whether exogenous ketone ingestion affects performance and pacing in a simulated race.

What will you be required to do?

Prior the start of your participation, you will complete a health and fitness screening questionnaire to determine if you have any health risk factor.

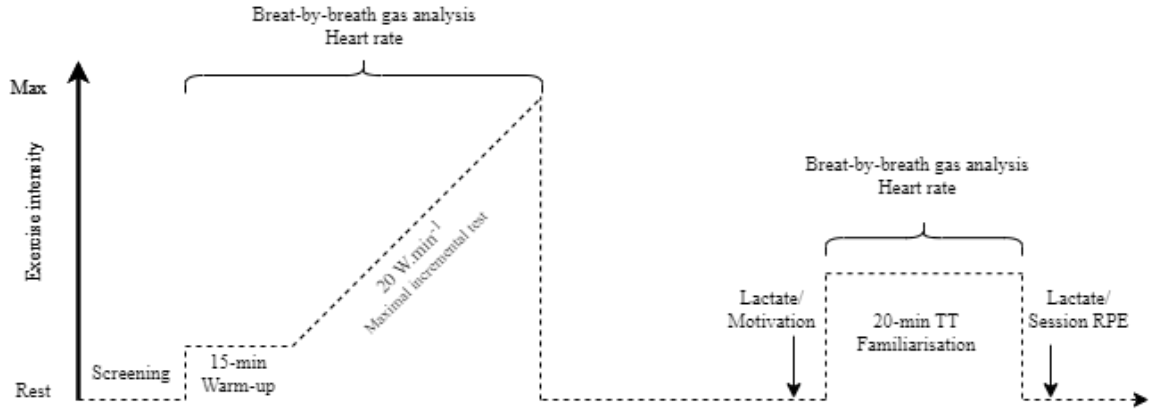
Participants in this study will be required to visit the Physiology Lab of the Canterbury Christ Church University in 6 occasions. You will be requested to perform 6x 20-min time trials, and a maximal incremental test ($\dot{V}O_2$max test), separated by 5-7 days each. Every session will be performed on the same electromagnetically-braked ergometer (Velotron, RacerMate®, Seattle, USA) and a flat-road virtual design will be developed using the RacerMate® software to simulate a typical road and visual display will be projected onto a screen.

Before the start of session 1, you will be requested to sign the informed consent and have the opportunity to ask questions regarding the visits. Then, you will be requested to complete a maximal incremental test (V̇O2max test) and a 20-min time trial as a familiarisation. In the second trial, you will be requested to complete a 20-min individual time trial as baseline. In the third and fourth sessions, you will compete against a virtual avatar replicating the performance of another participant of similar performance than you (i.e., less than 2% difference in the power output achieved during the baseline trial). In the last two sessions the participants will be split into two groups: 1) exogenous ketone or 2) control group. If you are assigned to the exogenous ketone group, you will be requested to ingest a drink containing 500 mg of ketone ester/kg of body mass before one time trial and compete against a virtual avatar riding at 2% higher power outputs from your best performance during one of the previous competitions. In the other session, you will compete against the performance of another participant in the control group. If you are assigned to the control group, you will compete against an avatar riding at 2% higher power outputs than your best competition time trial; and

against a virtual avatar replicating the performance of another participant in the endogenous ketone group. The design of the study is described in the detail in the figure below.

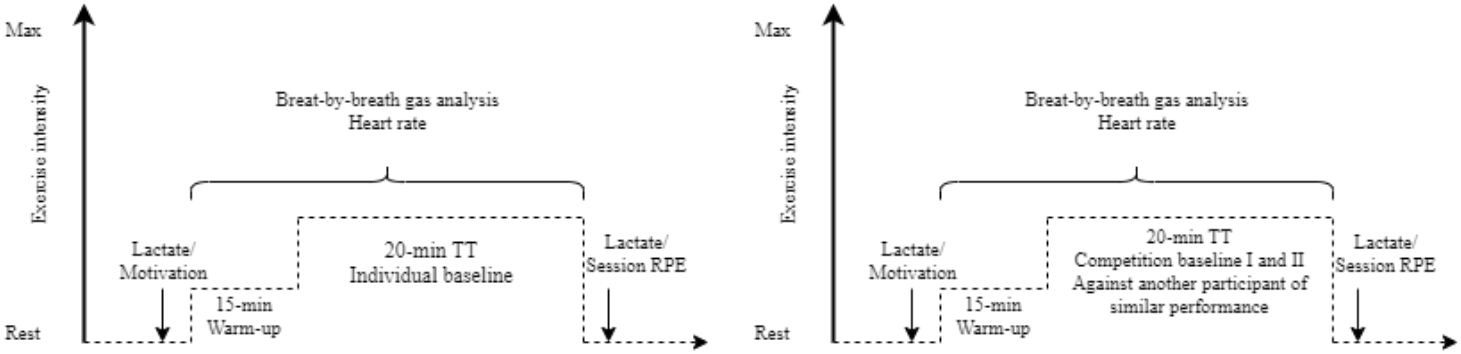
If you are assigned to the ketone group, you should take the drink 30 min before the start of one of the last two sessions (this will be randomised and disclosed to you after the 4th session). We will give you the drink after the completion of the 4th time trial, so you are allowed to self-administer the drink before attending the laboratory.

Session 1

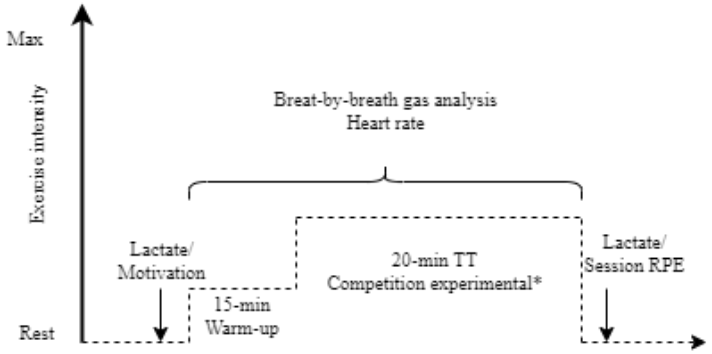


Session 2

Sessions 3 and 4



Sessions 5 and 6



Participants will be split into exogenous ketone or control group and:

1) Compete against a PACER replicating their performance during their best competition baseline, but power output increased by 2%; OR

2) Compete against a participant of the opposite group (ketogenic vs control group)

→ Ketogenic group will receive the substance before the PACER TRIAL

Procedures

Before each session, you will be asked to complete a motivation questionnaire, provide a small blood sample from a fingertip (to measure lactate concentration) and perform a standardised warm-up based on a perceived exertion scale (6-20 Borg scale). During each session, heart

rate and oxygen consumption will be continuously measured (you will be requested to wear a facemask that will measure breath-by-breath gas exchanges). After the end, we will collect another small blood sample from a fingertip and you will rate your overall exertion of the time trial.

To participate in this research, you must:

Be a healthy men or women (no injuries in the previous 2 months, no medical conditions), aged 18-50 years old, performing at least 6 hours of cycling per week, familiar with time trials and sign the consent forms. If you have any injuries, neurological conditions, or chronic renal, metabolic or respiratory diseases you will not be able to participate.

Feedback

At the end of the study, you will receive a detailed report of your performance during each time trial and physiological parameters, including $\dot{V}O_2max$ (maximal oxygen uptake) and physiological thresholds.

Confidentiality and Data Protection

The following categories of personal data (as defined by the General Data Protection Regulation (GDPR)) will be processed:

- Full name and contact details (e-mail and phone number)

We have identified that the public interest in processing the personal data is:

- Processing of personal data is necessary to identify the participants and provide them with proper feedback after data collection. Personal data will be used only to identify the participants during data processing and analysis.

Data can only be accessed by, or shared with:

- Guilherme Garcia Matta and Dr Damian Coleman.

The identified period for the retention of personal data for this project:

- After the required ten-year retention period, all data and personal information will be destroyed.

If you would like to obtain further information related to how your personal data is processed for this project please contact Guilherme Matta at g.matta392@canterbury.ac.uk.

You can read further information regarding how the University processes your personal data for research purposes at the following link: Research Privacy Notice - https://www.canterbury.ac.uk/university-solicitors-office/data-protection/privacy-notices/privacy-notices.aspx

Dissemination of results

The results of this study will be published in the University's library and potentially be sent for publication in Scientific Journals and conferences abstracts.

Process for withdrawing consent to participate

You are free to withdraw your consent to participate in this research project at any time without having to give a reason. To do this simply send an e-mail to g.matta392@canterbury.ac.uk stating your desire to withdraw.

You may read further information on your rights relating to your personal data at the following link: Research Privacy Notice - https://www.canterbury.ac.uk/university-solicitors-office/data-protection/privacy-notices/privacy-notices.aspx

Any questions?

Please contact:

Guilherme Matta

g.matta392@canterbury.ac.uk

OR

School of Human and Life Sciences

Sport and Exercise Sciences

ses@canterbury.ac.uk

CONSENT FORM

Title of Project: **Effects of exogenous ketone ingestion on competitive cycling performance and pacing**

Name of Researcher: Guilherme Garcia Matta, under the supervision of Dr Damian Coleman.

Contact details:

Address:	Room Af50, School of Human and Life Sciences, North Holmes Road, Canterbury, Kent, CT11QU, UK.
Tel:	01227 782940 ext 3145
Email:	g.matta392@canterbury.ac.uk

Please initial box

1. I confirm that I have read and understand the participant information for the above project and have had the opportunity to ask questions.	
2. (If applicable) I confirm that I agree to any audio and/or visual recordings.	
3. I understand that any personal information that I provide to the researchers will be kept strictly confidential and in line with the University Research Privacy Notice	

4. I understand that my participation is voluntary and that I am free to withdraw my participation at any time, without giving a reason.

5. I agree to take part in the above project.

—

Name of Participant:	Date:	Signature:
Name of person taking consent *(if different from researcher)*	Date:	Signature:
Researcher:	Date:	Signature:

Copies: 1 for participant

1 for researcher

Appendix 9

Recruitment poster for experimental study 3 (CHAPTER FIVE)

Appendix 10

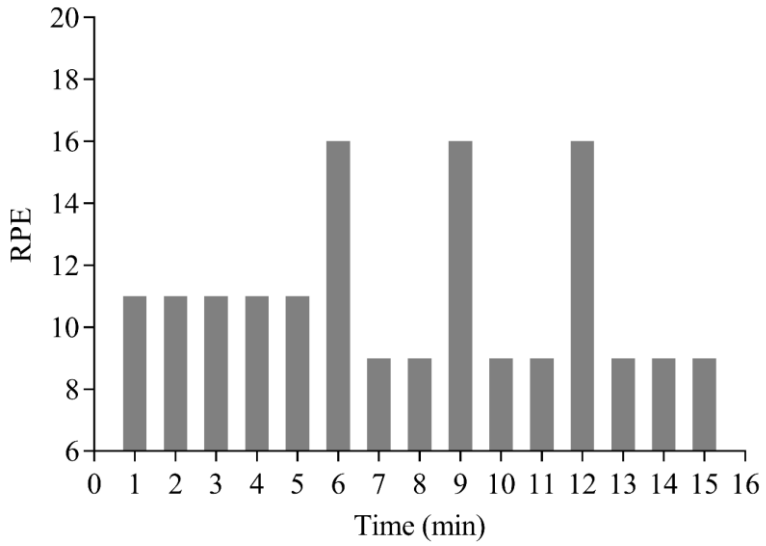
Warm-up protocol used during experimental study 4 (CHAPTER FIVE)

Warm-up routine:

5 mins @ RPE 11

3x 1 min @ RPE 16 / 2 min @ RPE 9

3 mins @ RPE 9



6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very Hard
18	
19	Extremely hard
20	Maximal exertion

Appendix 11

Matthews Motivation Questionnaire used during experimental study 4 (CHAPTER FIVE)

MOTIVATION

Please, answer some questions about your attitude to the testing session you are about to perform. Rate your agreement with the following statements by assigning one of the following answers. Make sure you answer every question.

0 = not at all 1 = a little bit 2 = somewhat 3 = very much 4 = extremely

1	I expect the content of the task will be interesting	0	1	2	3	4
2	The only reason to do the task is to get an external reward	0	1	2	3	4
3	I would rather spend the time doing the task on something else	0	1	2	3	4
4	I am concerned about not doing as well as I can	0	1	2	3	4
5	I want to perform better than most people do	0	1	2	3	4
6	I will become fed up with the task	0	1	2	3	4
7	I would be disappointed if I failed to do well on the task	0	1	2	3	4
8	I am eager to do well	0	1	2	3	4
9	I am committed to attaining my performance goals	0	1	2	3	4
10	Doing the task is worthwhile	0	1	2	3	4
11	I expect to find the task boring	0	1	2	3	4
12	I feel apathetic about my performance	0	1	2	3	4
13	I want to succeed on the task	0	1	2	3	4

14	The task will bring out my competitive drives	0	1	2	3	4
15	I am motivated to do the task	0	1	2	3	4

Appendix 12

Participants information sheet and consent form for experimental study 4 (CHAPTER SIX)

Effects of different opponents on competitive cycling performance and pacing

PARTICIPANT INFORMATION

A research study is being conducted at Canterbury Christ Church University (CCCU) by Guilherme Garcia Matta, under the supervision of Dr Philip Hurst.

Please refer to our Research Privacy Notice for more information on how we will use and store your personal data.

Background

Cycling performance is determined by internal and external environments. Athletes' internal state (i.e. physiological disturbance) and external environments, such as presence of competitors, might influence how exercise is regulated. Indeed, head-to-head competitions elicit improvements in performance, affecting athletes' expectations and motivations, leading to changes in the self-regulatory process during exercise. In such social environments, the actions of opponents have a direct effect on an athlete's performance. However, most studies used virtual avatars instead of real opponents, limiting the application of the results.

This study aims to analyse the effects of different opponents on cyclists performance and pacing, using real opponents of similar level of performance.

What will you be required to do?

Prior the start of your participation, you will be asked to complete a health and fitness screening questionnaire to determine if you have any health risk factor and are eligible to participate. If any health-related conditions are identified, you will not be able to participate.

Before the start of your participation and after reading/completing all documentation, we will ask you to sign the informed consent document if you are happy to freely volunteer to participate. You will also have the opportunity to ask further questions regarding the sessions.

Participants in this study will be requested to perform four 20-min time trials on Zwift, separated by 3-5 days each, in the following order: 1) familiarisation; 2) baseline; 3) 1vs1 competition 1; 4) 1vs1 competition 2. During the 3rd and 4th trials, you will be matched based on your performance achieved during the baseline trial (time trial 2) to two other participants of similar level, and you will be assigned to 1vs1 competitions.

In all sessions, you should aim to produce the highest power output and to win the simulated races. The distance covered, and average power output of the entire time trial and every 2-min interval will be collected after each trial. Every session should be performed at the same time of the day to avoid differences in the circadian effects, using the same equipment (i.e. bike or turbo trainer) and clothing. We also ask you to standardise your fluid intake and diet 24 hours prior the start of each session.

You are free to withdraw your consent to participate in this research project at any time without having to give a reason and all detailed information regarding your performance during the time trials will be disclosed to you in the earliest feasible time.

To participate in this research, you must:

Be a healthy cyclist (no injuries in the previous 2 months, no medical conditions), aged 18-55 years old, training for more than 4 times per week, familiar with time trials, Zwift user for more than 6 months and sign the consent forms. If you have any injuries, neurological conditions, or chronic renal, metabolic or respiratory diseases you will not be able to participate.

Given the unsupervised nature of the study, extra care when conducting the sessions must be taken and you should agree with the risks described in this document. After signing the consent form, you are ensuring you have read and understood the content relating to the risks associated with the study. You must also agree that the University has no responsibility/liability for any possible damage caused to your equipment as a result of your participation. The university or research team will not be liable to you in respect of

any personal injury that you may suffer or sustain directly or indirectly as a result of participation in the research study.

You must ensure the electrical system is in good condition (i.e. no damaged sockets or wiring), not leaving any power cables trailing and keeping the electrical equipment away from fluids; to keep the amount of flammable materials (i.e. piece of paper) to a minimum; to remove any ignition sources from the exercising station; to make sure you have fire routes and extinguishers available; that your smoke detector or fire alarm are working properly and regularly checked; to make your environment safe from slip or trip hazards; to familiarise yourself with the setup and the use of your training station; and to provide appropriate maintenance of your ergometer according to the specifications outlined within the equipment's booklet/website.

You are also strongly advised to perform the sessions only if there is anyone else present at your house or near the training station, that could summon first aid in the case it is necessary. You should only use the equipment you are already accustomed to, to set it out on appropriate even surface and to standardise the setup in a way that you do not need to move it between sessions. In the case you need to move or change your setup you must contact the research team and provide details about the modifications you have made to your equipment.

Make sure the screen is positioned in a comfortable position with suitable lightning configuration (e.g. brightness and contrast). All activities must take place in a clear and well-ventilated space and you should always wear appropriate footwear and clothing for the activity. If you find any issues with your setup or equipment, do not hesitate to contact the research team (details at the end of this document).

Most importantly, in the case you feel unwell, you should immediately cease the activity and contact your local GP. We will also request that you inform us the time when you plan to start the session, so we can send a follow-up message to ensure everything is fine.

Procedures

Each session will involve a 10-min warm-up in a self-selected intensity followed by 5-min rest (or slowly spinning your legs, just to keep the time running) and 20-min time trials afterwards. The first two sessions will be composed by a familiarisation and a baseline trial, but the next two will be simulated 1vs1 competitions. You should treat each session as a real competition,

avoiding strenuous exercise during the 48-h preceding each test, and to follow your regular diet and fluid intake. You should also try to standardise the conditions between each session as much as you can, performing the time trials at the same room, and using the same bike/turbo trainer and clothing. We also ask you avoid using PowerUp items. After the end of each time trial, you will be requested to export the activity file in a .FIT format and to send it to the research team. The process of exporting the activity file will be explained to you beforehand.

Feedback

At the end of the study, you will receive a full detailed report of your performance during each time trial, describing the results of all parameters collected.

Confidentiality and Data Protection

The following categories of personal data (as defined by the General Data Protection Regulation (GDPR)) will be processed:

- Full name and contact details (e-mail and phone number)

We have identified that the public interest in processing the personal data is:

- Processing of personal data is necessary to identify the participants and provide them with proper feedback after data collection. Personal data will be used only to identify the participants during data processing and analysis.

Data can only be accessed by, or shared with:

- Guilherme Garcia Matta and the research team.

The identified period for the retention of personal data for this project:

- After the required ten-year retention period, all data and personal information will be destroyed.

If you would like to obtain further information related to how your personal data is processed for this project, please contact Guilherme Matta at g.matta392@canterbury.ac.uk.

You can read further information regarding how the University processes your personal data for research purposes at the following link: Research Privacy Notice - https://www.canterbury.ac.uk/university-solicitors-office/data-protection/privacy-notices/privacy-notices.aspx

Dissemination of results

The results of this study will be published in the University's library and potentially be sent for publication in Scientific Journals and conferences abstracts.

Process for withdrawing consent to participate

You are free to withdraw your consent to participate in this research project at any time without having to give a reason. To do this simply send an e-mail to g.matta392@canterbury.ac.uk stating your desire to withdraw.

You may read further information on your rights relating to your personal data at the following link: Research Privacy Notice - https://www.canterbury.ac.uk/university-solicitors-office/data-protection/privacy-notices/privacy-notices.aspx

Any questions?

Please contact:

Guilherme Matta

g.matta392@canterbury.ac.uk

OR

School of Human and Life Sciences

Sport and Exercise Sciences

ses@canterbury.ac.uk

CONSENT FORM

Title of Project: **Effects of different opponents on competitive cycling performance and pacing**

Name of Researcher: Guilherme Garcia Matta, under the supervision of Dr Philip Hurst.

Contact details:

Address:	Room Af50, School of Human and Life Sciences, North Holmes Road, Canterbury, Kent, CT11QU, UK.
Tel:	01227 782940 ext 3145
Email:	g.matta392@canterbury.ac.uk

Please initial box

1. I confirm that I have read and understand the participant information for the above project and have had the opportunity to ask questions.	
2. (If applicable) I confirm that I agree to any audio and/or visual recordings.	
3. I understand that any personal information that I provide to the researchers will be kept strictly confidential and in line with the University Research Privacy Notice	

4. I understand that my participation is voluntary and that I am free to withdraw my participation at any time, without giving a reason.

5. I agree to take part in the above project.

—

Name of Participant:	Date:	Signature:
Name of person taking consent *(if different from researcher)*	Date:	Signature:
Researcher:	Date:	Signature:

Copies: 1 for participant

1 for researcher

Appendix 13

Recruitment poster for experimental study 4 (CHAPTER SIX