COMPARISON OF ANAEROBIC AND AEROBIC FATIGUE ON VISUAL SKILLS

by

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DEDICATION

In memory of my *big boy*,

TYSON SHAW

(27 February 2005 - 23 March 2020)

I will miss you more each passing day
It hurts this heart so much
To know that you are far away
Your face I cannot touch
Or hold you close to me
For you are in another place
So far, far away
This love I have inside my son
Belongs to you.

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ABSTRACT

Exercise-induced fatigue is a common concern among individuals performing physical activities either for training and/or athletic performance. An enormous amount of research has been conducted on exercise-induced fatigue and its effect on physiological and physical functions. However, it is only supposed that maximal and supra-maximal exercise efforts may be responsible for decreases in sports vision performance and that physical conditioning may increase an athlete's ability to delay mental fatigue and thus deterioration in sports vision performance. However, previous research has demonstrated that anaerobic alactacid and anaerobic lactacid exercise improves components of sports vision (i.e. peripheral threshold detection and coincidence-anticipation) and may result in instantaneous improvements in sports vision performance. Thus, the primary aim of the study was to investigate the effects of short- and prolonged-duration maximal exercise effects on visual performance. The secondary aim was to examine and compare whether short- and long-duration maximal exercise most affects visual performance. Sixty untrained males were assigned to a control group (n = 30) or treatment group (TG) (n = 30) and underwent a sport vision test battery consisting of quantitative testing for accommodation facility, saccadic eye movements, speed of recognition, hand-eye coordination, peripheral awareness, and visual memory. One week later, the TG participants returned to complete a short supramaximal effort cycle ergometer test (SCT) immediately followed by the sports vision test battery. One week thereafter, TG participants returned a second time and completed a prolonged incremental maximal treadmill test (PTT) immediately followed by the sports vision test battery. In the SCT, significant ($p \leq 0.05$) changes were found for five of the six sports vision performance measures ($p = 0.000$), except visual memory ($p = 0.242$). In turn, following the PTT, significant changes were found for all sports vision performance measures ($p = 0.000$ for all measures). Results further indicate that only accommodation facility ($p = 0.005$) and saccadic eye movement ($p = 0.026$) were statistically different between the SCT and PTT with these variables being significantly higher following the PTT. This study's findings point to a beneficial immediate improvement in sports vision performance following short-supramaximal or prolonged-maximal exercise efforts, with the latter being found to be even more effective. Combining such exercise regimes as a functional warm-up may attenuate improvements in sports vision performance, especially in those sports requiring a great deal of visual processing and performance.

Keywords: Exercise-induced-fatigue; metabolic fatigue; treadmill running; visual fatigue; visual performance, visual skill; visual task.

DECLARATION

This thesis is a presentation of my original research work. Wherever the contribution of others is involved, every effort is made to indicate this clearly, with due reference to the literature and acknowledgement of collaborative research and discussions. The co-authors of the articles in the thesis, Dr. Gerrit J. Breukelman (Supervisor), Dr. Lourens Millard (Co-supervisor) and Prof. Ina Shaw (Advisor) hereby give permission to the candidate, Prof. Brandon S. Shaw, to include the articles as part of his Ph.D. thesis. The contribution (advisory and supportive) of these co-authors was kept within reasonable limits, thereby enabling the candidate to submit the thesis for examination purposes. This thesis serves as the fulfilment of the requirements for the Ph.D. degree in Human Movement Science within the Department of Human Movement Science in the Faculty of Science, Agriculture and Engineering at the University of Zululand.

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INTRODUCTION

Athletes use a variety of metabolic pathways to generate energy for training and/or competition. Problematically, a continual generation of energy depletes the energy stocks within the body. Depending on the form of exercise, sensations of fatigue and exhaustion will occur at different times during exercise (Ament & Verkerke, 2009). In the muscle cell, the major pathways for adenosine triphosphate (ATP) production include: (a) ATP from sarcoplasmic stores of creatine phosphate (PCr) at a rapid production; (b) anaerobic glycolysis at a slower production; or (c) ATP using aerobic pathways for glycolysis and fat metabolism at a slower, but very effective production (Ament & Verkerke, 2009).

Exercise-induced fatigue is a common concern among individuals performing physical activities either for training and/or athletic performance. An enormous amount of research has been conducted on exercise-induced fatigue and its effect on physiological and physical functions (Abd-Elfattah *et al*., 2015). Exercise-induced fatigue can result in a plethora of signs and symptoms including *inter alia*: impaired concentration and memory; post-exertional problems; multi-joint and muscle pain without redness or swelling; unrefreshing sleep; painful lymph nodes; headache and/or sore throat (Abd-Elfattah *et al*., 2015). While the effects of exercise-induced fatigue on athletic performance have been profoundly studied, the effect of such fatigue is not known in other domains, including vision studies that may affect athletic performance (Abd-Elfattah *et al*., 2015).

Although sports vision has only received attention in recent years (Millard *et al*., 2020a; Wimhurst, 2012), literature has proposed that exercise-induced fatigue may result in deterioration in visual performance. Despite this assumption, only recently have research studies begun to investigate if central fatigue affects the oculomotor system following acute exercise (Connell *et al*., 2016). As such, the restricted evidence available suggests that an acute, prolonged bout of submaximal exercise decreases saccadic velocity (Connell *et al*., 2016). Despite this finding, it is yet unknown if an acute, prolonged bout of exercise affects the other newly found sports vision skills (Millard *et al*., 2020a). In this regard, research has also found improvements in sensory task (peripheral threshold detection), sensory-motor task (coincidence-anticipation), and cognitive task (recall in central vision) performance (Gandevia, 2001), which themselves are critical for sports vision performance. In addition, the effects of acute, prolonged maximal exercise on vision may prove either to inhibit or excite the central nervous system (CNS), since simple exercise modalities like running may create excitatory responses at a CNS level (Fleury & Bard, 1990; Gandevia et al., 1996), that may stimulate the central mechanisms fundamental to sports vision performance. In this regard, only the study by Connell *et al*. (2016) has demonstrated a decrease only in a single visual task, namely; saccadic velocity, following acute, prolonged exercise. However, optimal athletic performance requires a host of other visual skills, such as accommodation facility, hand/eye coordination, speed of recognition, visual memory and peripheral awareness. Problematically, all such existing research focusing on the effect of exercise-induced fatigue has focused on prolonged aerobic exercise, which is not the primary metabolic pathway for all, or even the majority of sporting codes.

Previously, it was demonstrated that different types of metabolic fatigue, induced by anaerobic alactacid, anaerobic lactacid, sub-maximal aerobic, and maximal aerobic efforts have improved performance of a sensory task (peripheral threshold detection), a sensory-motor task (coincidence-anticipation), and a cognitive task (recall in central vision) (Fleury & Bard, 1990). These differences in the effect of fatigue on physical, cognitive or visual performance may be related to central or peripheral origins of fatigue. In this regard, fatigue can be attributed to various processes along the motor pathway, with peripheral fatigue attributed to the decline in force to processes at, or distal to, the neuromuscular junction, while central fatigue and concomitant decline in force are attributed to processes residing within the CNS (O'Leary et al., 2016).

In addition, simple exercise (such as running and cycling) may not sufficiently simulate the field-based sports fatigue that is purported to affect sports vision performance. In this regard, it may be that the mental fatigue arising from sports that require a great deal of cognitive and visual processing effort (i.e. to engage in visual tracking, decision-making, etc.) combined with exercise-induced fatigue may be responsible for decreases in visual performance. This demonstrates that the detrimental (or stimulatory) effects of exercise on cognitive functioning and visual performance may be task-specific (Decorte *et al*., 2012). In this regard, it may be that simple exercise, such as running and even if performed at maximal or supramaximal levels, may not sufficiently simulate training and/or competition conditions, which requires the exertion of cognitive control, which in turn, may result in appropriate mental and physical fatigue that negatively impacts visual performance. This is because sport, and not all exercise, requires active control of attention for visual tasks resulting in physical and simultaneous mental fatigue (Ackerman, Calderwood & Conklin, 2017).

In addition, vision, and sports vision, is much more than 20/20 eyesight. While the ability to see clearly is important, this aspect of static visual acuity is only a portion of a well-functioning visual system. This is because reading small fixed letters sitting in a dark room does not test most of the visual skills needed to hit a ball approaching an athlete at a high speed (Kumar, 2011). Athletes, coaches and conditioning specialists need to understand that very often poor athletic performance results from not the incorrect movement, but from the correct movement being performed at the incorrect time or place. In this regard, athletic performance requires a host of other visual skills, such as: saccadic eye movements; accommodation facility; hand/eye coordination; speed of recognition; visual memory and peripheral awareness (Millard *et al.*, 2020b). Vision is important for success in most exercise and sporting activities. Furthermore, it is reasonable to assume that any worsening or improvement of any visual skill's performance will influence an athlete's performance.

PROBLEM STATEMENT

Exercise-induced fatigue is a common concern among individuals performing physical activities either for training and/or athletic performance. While an enormous amount of research has been conducted on exercise-induced fatigue and its effect on physiological and physical functions, the effect of such fatigue is not known in other domains, including vision studies that may affect athletic performance (Abd-Elfattah et al., 2015). This is problematic in that exercise-induced fatigue affects a multitude of domains that could, in turn, affect visual performance, such as impaired concentration and memory (Abd-Elfattah et al., 2015).

OBJECTIVES

The primary objective of the study was to investigate the immediate effects of a short supramaximal effort cycle ergometer effort (SCT) and prolonged incremental maximal treadmill effort (PTT) on visual performance. The secondary objective was to examine and compare whether the SCT or PTT most affects immediate visual performance.

HYPOTHESIS

The null hypotheses of the proposed study are as follows:

- No significant change will be found in visual performance immediately following an SCT.
- No significant change will be found in visual performance immediately following a PTT.
- No significant difference will be found in visual performance following an SCT or a PTT.

THESIS STRUCTURE

This thesis is presented in article format as approved by the University of Zululand consisting of five major parts, namely, an introduction (Chapter One), while the literature reviews, methods and results specific to either the findings of the effect of the SCT on visual performance, the effect of the PTT on visual performance, and a comparison of the effects of the SCT and PTT are presented in Chapters Two, Three, Four and Five, respectively. The final Chapter (Six) contains a summary with conclusions, limitations and recommendations.

Chapter One presents the problem, and states the aim and the hypotheses of this study, as well as the structure of the thesis. Chapter Two provides a literature review. Chapter Three contains an experimental article entitled "Effects of a maximal cycling all-out test on visual task performance" submitted to *the Journal of Sports Science and Medicine*. Chapter Four is a second experimental article entitled "Effect of a prolonged maximal bout of exercise on visual performance" accepted at the *Asian Journal of Sports Medicine*. Chapter Five contains the final experimental article entitled "Short- versus long-duration maximal exercise effects on sport vision performance" submitted to *PLoS One*. The final Chapter (Six) contains a summary with conclusions, limitations and recommendations. While Chapter One, Two and Six utilise similar references according to the American Psychological Association (APA) style as prescribed by the University of Zululand, each article (and thus chapter) utilised the reference style as required by the relevant journal.

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CHAPTER TWO: LITERATURE REVIEW

INTRODUCTION

The literature review firstly explains the main biological exercise-driven metabolic pathways and how exercise-induced fatigue is thought to occur. Further, the literature review expands and elucidates on the acute physiological responses to and following various intensities of exercise, such as short-term, light- to moderate-intensity exercise, long-term, moderate to heavy submaximal aerobic exercise, and following maximal aerobic exercise. Further discussion occurs on the acute cognitive responses that could affect vision to and following those same various intensities of exercise and this chapter concludes with the limited available literature on the acute vision responses to and following various intensities of exercise.

In compiling the literature review, an electronic search was conducted on the following databases to review the scholarly literature related to anaerobic and aerobic fatigue on visual skills: Sport Discuss (1975–June 2021), EBM Reviews, PubMed (1966–June 2021), Current Contents, Science Direct, CISTI Source (1993–June 2021), Cochrane Database of Systematic Reviews, Google Scholar, and international e-catalogues. A keyword search yielded MeSH headings: "strenuous physical activity and vision", "all-out exercise and vision", "maximal exercise and vision", "supramaximal exercise and vision", "strenuous physical activity and cognitive function", "all-out exercise and cognitive function", "maximal exercise and cognitive function", "supramaximal exercise and cognitive function", "anaerobic effort and vision", "anaerobic fatigue and vision", "anaerobic effort and cognitive function", "anaerobic fatigue and cognitive function", "aerobic effort and vision", "aerobic fatigue and vision", "aerobic effort and cognitive function", and "aerobic fatigue and cognitive function"; which were fused and exploded. The searches were limited to peer-reviewed articles written in English. For discussion, original articles were identified and grouped.

EXERCISE-DRIVEN METABOLIC PATHWAYS AND EXERCISE-INDUCED FATIGUE

Humans use three metabolic energy systems to perform a variety of daily or sporting activities, namely: (1) phosphagen (ATP-PCr) system; (2) anaerobic energy system; and (3) aerobic energy system (Bertuzzi *et al.*, 2015). To perform daily activities and endurance events, adenosine triphosphate (ATP) re-synthesis needs to take place, and the aerobic energy system does so on a large scale in the human body (Bertuzzi *et al.*, 2015). To create energy for the working muscles, the aerobic energy system makes use of two substrates, namely fat-based molecules and carbohydrate molecules. Fatigue occurs in the aerobic energy system due to a lack of carbohydrate availability. In the human body, approximately one-third of the available carbohydrate is stored in the liver and the remaining two-thirds is stored in Type 1 muscle fibres, in the form of glycogen (Bertuzzi *et al*., 2015).

To enable the breakdown of glucose in the absence of oxygen, anaerobic exercise can be utilised (Bertuzzi *et al*., 2015). Anaerobic exercise incorporates activities of short duration, but high intensity, such as 400 meter sprints. In the anaerobic energy system, the PCr system needs to ensure the effective transfer of energy to re-synthesise ATP from adenosine diphosphate (ADP) and loose phosphates present in the muscle. In anaerobic exercise, the depletion of PCr in a muscle cell occurs within seven to nine seconds (sec) with almost all of the PCr depleted by 30 seconds. The depletion of PCr is caused directly by the decline in muscle anaerobic ATP production and/or a matching increase in ADP accumulation, which in turn causes fatigue development (Bertuzzi *et al*., 2015).

Exercise-induced fatigue is different from that of general fatigue in that both the sensitivity to and duration of the fatigue may be influenced by altering exercise design components of the exercise bout, including *inter alia* mode, intensity, duration, rest. This exercise-induced fatigue, or the mitigation thereof, is crucial to the performance of athletes in almost all training and competitive events (Cordeiro *et al*., 2017). This is because exercise-induced fatigue is characterised by sensations of tiredness and decrements in athletic performance (Cordeiro *et al*., 2017).

Mechanisms leading to exercise-induced fatigue have been the subject of much research (Semin *et al*., 2008). Despite the multitude of research on this topic, the exact mechanisms causing the development of exercise-induced fatigue remain largely unknown. This is because the determinant factors for fatigue, whether they be physiological or psychological, are specific to the individual events (Cordeiro *et al*., 2017). Further, exercise-induced fatigue can be divided into peripheral fatigue and central fatigue (Gandevia, 2001; van Hall *et al*., 1995). In this regard, the fatigue arising from alterations at or near the motor neuron, neuromuscular junction (NMJ) and sarcolemmal membrane may be broadly categorised as peripheral fatigue (Gandevia, 2001; Kirkendall, 1990). In turn, central fatigue is the fatigue arising from changes within the central nervous system (CNS) (van Hall *et al*., 1995). Presently, it is thought that exercise-induced fatigue involves a complex interaction between peripheral and central factors (Gandevia, 2001) and it may be suggested that every step in the chain of events that leads to voluntary contraction of skeletal muscle could be a culprit in fatigue (Kirkendall, 1990).

While exercise-induced fatigue is determined by a peripheral and/or a central component, it is thought that the former is due to changes within both the intra-cellular and inter-cellular compartments of skeletal muscle, including *inter alia* metabolic milieu of the working muscle, deficiencies in excitation-contraction coupling, accumulation of metabolites and/or depletion of available substrates for fuels (Amann, 2011; Kirkendall, 1990). The latter part of exercise-induced fatigue is thought to arise from central components, whereby the CNS fails to ‘‘drive’’ the motor neurons, resulting in a reduction in central motor drive (CMD) (Amann, 2011). However, there is also evidence that suggests the actual mechanism(s) leading to exercise-induced fatigue are specific to that type of sport or exercise, resulting in a "specificity of fatigue".

ACUTE PHYSIOLOGICAL RESPONSES TO AND FOLLOWING VARIOUS INTENSITIES OF EXERCISE

Certain exercises cause sudden decreases or increases in metabolic responses (Park *et al*., 2021; Shaw *et al*., 2015) and the physiological response to exercise is dependent on the duration and intensity of the exercise (Burton, Stokes & Hall, 2004). In this regard, intense exercise is associated with earlier onset of fatigue and decreased physiological and athletic performance (Park *et al*., 2021).

The prevailing global consensus that strenuous exercise leads to exercise-induced fatigue is the reason to date that most studies have investigated the effect of relatively short test durations and distances as a warm-up to more strenuous exercise or sporting activity as a means to, amongst others, mitigate exercise-induced fatigue (Mata-Garcia, Angulo & O'Mahony, 2007; Park *et al*., 2021). Specifically, a light- to moderate-intensity warm-up has been demonstrated to *inter alia* increase circulation, increase muscle temperature and decrease intramuscular resistance, increase range of motion and speed of contractility, increase oxygen availability and extraction and increase fat utilisation and decrease lactate production, all of which are purported to delay fatigue (Mata-Garcia, Angulo & O'Mahony, 2007).

The prevailing thought is that a gradual warm-up is required because a too strenuous warm-up will place unnecessary demands on the body, and specifically the musculoskeletal and cardiopulmonary systems, such as reducing electrocardiogram (ECG) ischemic responses during high-intensity exercise to follow (Mata-Garcia, Angulo & O'Mahony, 2007). While this may prove true and necessary in a health promotion or rehabilitative setting, it is only in the past several decades that literature has begun to investigate and propose more individualised warm-ups depending on the type of activity or sport to be engaged in (Samson *et al*., 2012). In this regard, a high-intensity warm-up may be required to improve the performance of the ensuing exercise or sporting activity. This is because high-intensity and "ramped" warm-ups have been demonstrated to increase the contribution of the anaerobic system to the following exercise or sporting activity, possibly by activating key regulatory enzymes related to anaerobic energy metabolism (Park *et al*., 2021). Further, numerous previous studies have demonstrated the existence of physiological "thresholds" (Keir *et al.,* 2015).

Numerous physiological changes occur during acute exercise, all aimed at meeting the increased demands necessary to perform that exercise. The demands of that exercise depend primarily on the intensity at which the activity is performed and secondarily on the duration of the activity (Plowman & Smith, 2014). Since aerobic exercise requires more energy and oxygen than other modes of exercise, it also results in more significant physiological changes and results in the most peripheral and central fatigue. Therefore, it is important to understand the acute physiological, cognitive and visual responses to and following exercise intensities to determine their potential impact on peripheral and central fatigue, and possibly on sports vision performance.

Acute physiological responses to and following short-term, light- to moderate-intensity exercise

With the onset of short-term, light- to moderate-intensity exercise, the cardiovascular system undergoes several immediate changes. In this regard, cardiac output (Q) initially increases until a plateau is reached within two minutes. This plateau occurs since Q is sufficient to transport the oxygen needed for ATP production during that exercise bout. This increase in Q arises from acute alterations in initial increases in heart rate (HR) and stroke volume (SV), both of which also plateau within two minutes (Rowell, 1993). As a result of these increases in HR and SV, systolic blood pressure (SBP) also rises concomitantly following an initial increase followed by a plateau. However, while SBP increases, diastolic blood pressure (DBP) remains unchanged or decreases slightly due to a decreased total peripheral resistance (TPR) due to peripheral vasodilation at the exercising muscle (Rowell, 1993).

With regards to short-term, light- to moderate-intensity exercise, the respiratory system acts in concert with the cardiovascular system. In this regard, since oxygen consumption (VO_2) increases linearly with increasing work rate at submaximal intensities, a concomitant abrupt increase is observed in pulmonary ventilation in the initial stages of exercise and is followed by a more gradual increase until a plateau is reached within two minutes, demonstrating a stable and proportional response to exercise (McArdle, Katch & Katch, 2014). This increase can be attributed to a combination of increases in breathing rate (BR) and tidal volume (VT) that corresponds to the increase in oxygen uptake and carbon dioxide output (Powers, Howley & Quindry, 2021). Following the onset of short-term, light- to moderate-intensity exercise, there is an immediate diversion of blood flow to working muscles (and away from non-essential organs) via vasodilation at the working muscle. With the onset of exercise, motor-unit recruitment is increased until adequate force production is met (McArdle, Katch & Katch, 2014).

Acute physiological responses to and following long-term, moderate to heavy submaximal aerobic exercise

The cardiovascular responses to long-term, moderate to heavy exercise include an initial increase in Q followed by a plateau, albeit at a greater magnitude than for short-term, light- to moderate-intensity exercise. Again these responses in Q are due to the increases and plateaus in HR and SV. However, during sustained moderate to heavy exercise, while HR begins an upward drift, SV begins a concomitant downward drift (Powers, Howley & Quindry, 2021). In response to long-term, moderate to heavy exercise, SBP initially increases, followed by a plateau and downward drift. These drifts of HR, SV and SBP, among others, in response to no change in exercise volume or workload, are part of a phenomenon known as cardiovascular drift. In turn, DBP does not undergo a substantial change. Total peripheral resistance (TPR) exhibits a curvilinear decrease during long-term heavy exercise due to vasodilation in exercising muscle and skin (McArdle, Katch & Katch, 2014).

During long-term, moderate to heavy submaximal aerobic exercise, abrupt increases are observed in pulmonary ventilation (due to increases in BR and VT) in the initial stages of exercise and are then followed by a more gradual increase until a plateau is reached (McArdle, Katch & Katch, 2014). This increase in minute ventilation is disproportionate in relation to oxygen consumption (Powers, Howley & Quindry, 2021).

Acute physiological responses to and following maximal aerobic exercise

High-intensity exercise is repeatedly required in many competitive sports (Cipryan, Tschakert & Hofmann, 2017). At the onset of maximal aerobic exercise, Q increases until plateauing at maximal exercise, again due to increases in HR and SV. However, it must be noted that at increased workloads, the increase in Q is achieved only by an increase in HR (Powers, Howley & Quindry, 2021). While the myocardial cells are capable of contracting at over 300 beats per minute ($b.min^{-1}$), they rarely beat faster than 210 $b.min^{-1}$, since a faster HR would not allow for adequate ventricular filling and it is this finding that is the basis for the age-predicted HR_{max} equation (i.e. 220 - age). Systolic blood pressure increases at the onset of exercise and plateaus at maximal exercise, while DBP again does not undergo a substantial change, even at maximal exercise. Total peripheral resistance decreases in a negative curvilinear pattern and reaches its lowest level at maximal exercise (McArdle, Katch & Katch, 2014).

With maximal aerobic exercise, there is an abrupt increase in pulmonary ventilation observed with the onset of exercise. This is followed by a steady increase until volitional exhaustion. While VO_2 increases linearly with work rate, an upper limit does exist to VO_2 and as such, above a certain work rate, VO_2 reaches a plateau and is known as the maximal oxygen uptake (VO_{2max}). Furthermore, once maximal exercise stops, BR may remain elevated for several hours following maximal exercise (Powers, Howley & Quindry, 2021).

ACUTE COGNITIVE RESPONSES TO AND FOLLOWING VARIOUS INTENSITIES OF EXERCISE

In addition to the cardiovascular, respiratory and muscular systems, exercise has substantial acute effects on numerous systems, including the CNS. This is so since the neural command centre above the medullary region initiates cardiorespiratory changes immediately before and at the onset of exercise. As exercise continues, feedback from the peripheral mechano- and chemo-receptors drives circulatory and tissue metabolism needs. Thus, exercise, even in its simplest form, taxes the CNS ultimately leading to central exercise-induced fatigue. However, the complexity of the CNS, and the methodologic difficulties in evaluating its neurochemistry, make it difficult to study the impact of exercise on the CNS (Anish, 2005). As such, while much literature has addressed exercise-induced fatigue mechanisms at a peripheral level, little is known about the role of exercise-induced fatigue on the CNS (Anish, 2005). Further, while research has focused on how central fatigue affects the recruitment of skeletal muscle, it is not known how central fatigue may affect cognition. This is problematic in that when it comes to exercise, the CNS has two main processes, excitation and inhibition.

Although much less studied than the physiological responses to acute exercise, recent studies have examined the relationship between acute exercise and cognition. In this regard, literature has demonstrated a largely positive effect of acute exercise on cognitive performance (Chang & Etnier, 2009). However, since the findings are mixed, it may be that task specificity is critical to the effect of acute exercise on cognition. Specifically, it may be that for a task or exercise bout that requires more motor or peripheral processes, a linear relationship exists (i.e. as intensity increases, cognitive function increases), whereas, for a task, exercise or sport that requires greater cognitive or central processes, an inverted-U relationship may exist (i.e. too much or too little intensity can lead to decreased cognitive performance) (Arent & Landers, 2003). Similarly, as initially reported by Humphreys and Revelle (1984), a dose-response relationship between arousal and cognitive performance may also be specific to the cognitive task to be performed. In this regard, original research by Fleury and Bard (1986), indicated that while performance in a cognitive task is significantly disturbed by the maximal aerobic exercise, other research by Fleury and Bard (1990) demonstrated that only the anaerobic alactacid and anaerobic lactacid exercise improved sensory task (peripheral threshold detection), a sensory-motor task (coincidence-anticipation), and a cognitive task (recall in central vision) performance.

ACUTE VISION RESPONSES TO AND FOLLOWING VARIOUS INTENSITIES OF EXERCISE

While major disagreements remain as to how closely vision is tied to cognition, cognition can affect the outcome of vision, especially in the several stages in visual processing, including, in addition to the inflexible early-vision stage, a pre-perceptual attention-allocation stage and a post perceptual evaluation, selection, and inference stage which accesses long-term memory (Pylyshyn, 1998). As such, any improvements in cognition following acute exercise may result in concomitant improvements in sports vision performance. However, to date, there are no studies that have examined the effect of various intensities of acute exercise on the different visual skills. This is despite the supposition that musculoskeletal fatigue, as experienced during sporting and/or training events, can reduce cognitive behaviour and visual skill (Millard *et al.*, 2020). In addition, Fleury and Bard (1986) originally demonstrated that since “anaerobic” and “aerobic” fatigue have differing effects on musculoskeletal and cognitive performance, these various fatigues may influence vision in differing ways.

With regards to visual skills and fatigue, fatigue has been demonstrated to negatively affect the visio-motor reaction time of athletes (Erikson, 2007). This may have a detrimental effect on the ability of an athlete to process a wide variety of information, which includes perceptual information. (Boksem, Meijman & Lorist, 2005). Specifically, in a study done by Connell *et al.* (2017) it was found that after three hours of strenuous cycling, there was a decrease in the velocity of rapid eye movements, which was independent of other visual processes, including dorsal cortical stream function. Furthermore, it was found that the reduction in saccade velocity was fatigue induced, and similar results were recorded after acute, and prolonged aerobic exercise (Connell *et al*., 2017). All these detrimental effects of exercise-induced fatigue on visual skills demonstrate that there is a direct link between aerobic exercise and brain-based fatigue in the corticospinal motor system, which in turn causes impairment of the oculomotor system (Connell *et al*., 2017). However, the fact that neurotransmitter levels and actions also experience complications during prolonged aerobic exercise, they are purported to also have a direct impact and cause impairment of the oculomotor system (Hasegawa *et al*., 2008).

However, the effects and mechanisms of anaerobic and aerobic exercise on visual skills are not yet established. Since the question of how specific energy-providing pathways affect exercise performance is a subject of growing interest to sports scientists, it is important to understand how acute exercise affects the host of visual skills, such as: saccadic eye movements; accommodation facility; hand/eye coordination; speed of recognition; visual memory; and peripheral awareness. Specifically, understanding dose-response relationships between exercise and sports vision performance are important for prescription and for advancing our understanding of potential mechanisms of the relationship.

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CHAPTER THREE: EFFECT OF A SHORT SUPRAMAXIMAL CYCLE ERGOMETER EFFORT ON VISUAL PERFORMANCE

Shaw, B.S., Breukelman, G.J., Millard, L. & Shaw, I. Effects of a maximal cycling all-out test on visual task performance. *Journal of Sports Science and Medicine*. Submitted. (Appendix A)

ABSTRACT

Research has primarily focused on the effect of exercise or fatigue on simple cognitive tasks and has neglected to investigate the effect of such exercise or fatigue on visual tasks. Also, when investigating exercise or fatigue, research has focused on prolonged aerobic exercise, which is not the primary metabolic pathway for all, or even the majority of sports. This study aimed to determine the effects of a maximal cycling all-out test on the performance of six visual tasks. Sixty untrained males (experimental group; n = 30, control group; n = 30) completed a baseline visio-spatial intelligence (VSI) test battery and one week later, the experimental participants returned to undertake a 30-second Wingate anaerobic test (30-WAnT) immediately followed by the same VSI test battery. Significant ($p < 0.05$) differences existed for all measures ($p = 0.000$), except visual memory ($p = 0.242$), following the 30-WAnT. These findings elucidate the need for an intense anaerobic warm-up when training visual skills or when visual skills form an integral part of athletic performance. Further, this study demonstrates how all-out anaerobic exercise affects vision in sports, allowing for the active development of strategies to take advantage of or mitigate the effect of all-out exercise.

KEYWORDS

Anaerobic exercise; exercise-induced-fatigue; metabolic fatigue; visual performance, visual skill; Wingate Anaerobic Test

1. Introduction

A common-held misconception in the sport sciences purports that fatigue develops during moderate- to high-intensity exercise when the capacity of the cardiorespiratory system fails to provide oxygen to the exercising muscles inducing ‘‘anaerobic’’ metabolism (Noakes, 2000). However, research has proven that other organs, other than the skeletal muscles, such as the heart are affected by exercise anaerobiosis (Noakes, 2000). Many athletes utilise anaerobic metabolism and experience exercise-induced fatigue in their sports. It is this fatigue that has been demonstrated to result in a variety of deleterious effects on athletic performance (Moxnes & Hausken, 2008), whether it be physical and/or cognitive (Nibbeling et al., 2014).

While most research has demonstrated the impact of physical activities on simple cognitive tasks, such research has neglected the effect of fatigue on other important tasks, such as visual tasks. Recent studies have shown that visual-motor abilities play a critical role in athletic performance (Burris et al., 2018; Millard et al., 2021b). It is for this reason that sports learning theory suggests that athletes need to assess and/or develop not only physical and motor abilities, but also visual and perceptual-cognitive skills (Hadlow et al., 2018; Williams & Ericsson, 2005). In this way, the assessment and training of visual skills have aroused the interest of athletes, coaches and sports scientists (Millard et al., 2020a).

While fatigue is commonly associated with deleterious physical and cognitive performance, previously, it has been demonstrated that different types of metabolic fatigue, induced by anaerobic alactacid, anaerobic lactacid, sub-maximal aerobic, and maximal aerobic efforts have improved performance of a sensory task (peripheral threshold detection), a sensory-motor task (coincidence-anticipation), and a cognitive task (recall in central vision) (Fleury & Bard, 1990). These differences in the effect of fatigue on physical, cognitive or visual performance may be related to central or peripheral origins of fatigue. In this regard, fatigue can be attributed to various processes along the motor pathway, with peripheral fatigue attributed to the decline in force to processes at, or distal to, the neuromuscular junction, while central fatigue and a concomitant decline in force are attributed to processes residing within the central nervous system (CNS) (O'Leary et al., 2016).

Studies have demonstrated that induced fatigue may result in deterioration in visual skills (Connell et al., 2017). This decrease in visual skill is as a result of exercise causing central- or brain-based fatigue in the corticospinal motor system, which in turn, impairs the oculomotor system (Connell et al., 2017). Problematically, all such existing research focusing on the effect of exercise-induced fatigue has focused on prolonged aerobic exercise, which is not the primary metabolic pathway for all, or even the majority of sporting codes. While central and peripheral fatigue have been explored following long-duration running or cycling (Millet et al., 2003), the type of fatigue induced by a short cycling bout is understudied (Fernandez-del-Olmo et al., 2011), nor have its effects on visual task performance. Further, although these studies provide interesting information about the accumulative effect of several cycling bouts over the muscle fatigue mechanisms, it is still unknown how a single and maximal cycling all-out test affects fatigue (Fernandez-del-Olmo et al., 2011). The "gold standard" of single and maximal cycling all-out tests is the 30-second Wingate anaerobic test (30-WAnT), which was developed at the Department of Research and Sport Medicine of the Wingate Institute for Physical Education and Sport, Israel, during the mid- and late 1970s (Bar-Or, 1987). In addition, previous studies have demonstrated that the 30-WAnT results in central and peripheral fatigue (Fernandez-del-Olmo et al., 2011).

Problematically, vision has a multitude of definitions in literature with none being as simple as only seeing. Appropriate visual information is critical for almost every sporting task. In this regard, athletic performance requires a host of other visual skills, such as: saccadic eye movements; accommodation facility; hand/eye coordination; speed of recognition; visual memory; and peripheral awareness (Millard et al., 2020a).

To date, insufficient information exists on how exercise-induced fatigue affects visual task performance. Consequently, this study aimed to investigate the effects of a maximal cycling all-out test on the performance of several visual tasks. It was hypothesised that a maximal cycling all-out test would improve the performance of several visual tasks.

2. Materials and methods

2.1. Participants

Sixty males participated in the study (mean age: 23.11±3.02 years). The inclusion criteria for the study was that the participant had to have a minimum of 20/20 vision, they should not have participated in any form of structured sport or exercise regime for the past six months, and none of the participants should have had previous experience with sports vision testing (Millard et al., 2020b). Participants were excluded from the study if they did not have 20/20 vision, had any form of visual disease or infection, physical disability and/or psychosocial distress (West, Rubin & Bronman, 2002) and if they presented with any relative or absolute contraindication to exercise or testing (Riebe et al., 2016). Participants received both written and oral information about the aims, data collection and data management of the project before providing written informed consent and were able to withdraw from the study at any time. Participants were divided into an experimental group (n = 30) or a control group (n = 30).

Participants' confidentiality and anonymity were ensured throughout the study. Ethical approval was obtained from the Institutional Review Boards of the University of Zululand (UZREC 171110-030-PGD-2021/27), South Africa. All procedures were performed in accordance with the Declaration of Helsinki.

2.2. Study design

Following written informed consent, participants underwent an optometric assessment to ensure 20/20 vision. When participants presented with 20/20 vision, they underwent a visio-spatial intelligence (VSI) test battery designed to measure the following six components of vision for both the first-division rugby players and non-athletes: 1) accommodation facility; 2) saccadic eye movements; 3) speed of recognition; 4) hand-eye coordination; 5) peripheral awareness and 6) visual memory (Millard et al., 2021b). The entire VSI test battery lasted approximately 25 minutes per participant. One week following this baseline testing, participants returned to undertake a 30-WAnT immediately followed by the same VSI test battery. Control group participants returned to undertake the same VSI test battery (without a treatment immediately beforehand) to determine if a learning effect occurred.

2.3. Procedures

2.3.1. Optometric assessments

Prior to participation in the study, participants underwent an optometric assessment to ensure 20/20 vision. Spectrum Eyecare software (Version 6.0.0, Digital Optometry, Republic of South Africa) was used to measure each participant's depth perception and visual acuity (Millard et al., 2021a).

2.3.2. Visio-spatial test battery

2.3.2.1. Accommodation facility. The study utilised the Hart Near Far Rock Test to assess accommodation facility, which is the function whereby the refractive power of the optical system of an eye can change, enabling images of both distant and near objects to be viewed clearly (Mcbrien & Millodor, 1987). The large Hart Chart was placed 3 meters away from the participants on a board, at head height (Du Randt et al., 2016). Participants were instructed to hold another smaller chart at arm's length away, after which they were tasked to read the first letter of the first line of the chart on the board three meters away and then proceed to read the first letter of the chart at arm's length away. Participants then read the second letter of the first line of the far chart, then the second letter of the first line of the near chart, and so forth for 30 seconds, after which the errors were subtracted from the score to determine the final score (Du Randt et al., 2016).

2.3.2.2. Saccadic eye movement. To evaluate saccadic eye movement (rapid, ballistic movements of the eyes that abruptly change the point of fixation), the study utilised standardised saccadic eye movement charts (Purves, 2001). Two charts were placed on a board, 1 meter apart, and 3 meters away from the participants. Participants were instructed to read the first letter on the lateral side of the left chart, and then rapidly move their eyes and not their heads, to the first letter on the lateral side of the right chart and read the first letter. The participant then altered focus to the second letter of the left chart once they had read the first letter of the left and right chart and this process continued for 30 seconds. After this test, errors were subtracted from the score to determine the final score. To ensure that subjects cannot remember the letters, standardised, yet adjustable saccadic eye movement charts were utilised that had letters going down vertically on both sides of the page (Du Randt et al., 2016).

2.3.2.3. Speed of recognition. Speed of recognition was measured by the Batak Pro, using the Evasion programme (Lobier et al., 2013; Quotronics Limited, 2011). This programme lights 12 LED lights randomly for 1 sec. The participant was required to strike the target while still lit. If a target was lit but only flickered, participants were not to strike the target and if they did so, 5 points were deducted from the final score (Quotronics Limited, 2011). In turn, when all of the lights in the center of the Batak Pro flickered, participants were required to evade the small central infrared beam. If caught by the beam, 5 points were deducted from the final score. All scores were automatically determined by the microcomputer with a maximum of 100 targets being illuminated.

2.3.2.4. Hand-eye coordination. Hand-eye coordination was evaluated using the Ball Wall Toss Test (Rizzo et al., 2019). A mark was measured 2 meters away from a wall at which participants were required to throw a standard tennis ball, and catch it, while alternating hands for 30 seconds (Du Randt et al., 2016). The number of successful catches was recorded.

2.3.2.5. Peripheral awareness. Peripheral awareness was measured using the Accumulator (60-seconds) Programme on the Batak Pro (Kruger et al., 2009; Quotronics Limited, 2011). In this programme, random LED targets were illuminated, and remained illuminated until it was struck by the participant. After being struck, another LED target would immediately light up (Quotronics Limited, 2011). The Batak Pro microcomputer automatically calculated a final score at the end of the test. There was no limitation on maximum score in the 60-second period.

2.3.2.6. Visual memory. Visual memory was assessed using the Flash Memory Programme on the Batak Pro (Quotronics Limited, 2011; Shurgin, 2018). In this programme, 6 targets were lit for ½ second. Following this, participants were required to remember the 6 targets that illuminated, as well as the order in which they lit up (Quotronics Limited, 2011). The Batak Pro microcomputer calculated the maximum score (out of a possible 54) at the end of the test.

2.3.3. 30-second Wingate anaerobic test (30-WAnT)

One week following the baseline visual task testing, participants underwent a 30-WAnT, immediately followed by the same visio-spatial test battery described above. The 30-WAnT was performed on a cycle ergometer (Model 834E, Monark Exercise AB, Vansbro, Sweden) as described by Inbar et al. (1996). The 30-WAnT was preceded by a five minute (min) warm-up at the inertial resistance of the equipment, including two bouts of four seconds performed in the final seconds of the second and fourth minutes. After a 10-min rest, the participants were instructed to pedal "all-out" for 30 sec against a resistance of 0.09 kg.body mass^{-1} (Souissi et al., 2010). Verbal encouragement was provided throughout the test. Each participant was then required to begin the visio-spatial test battery immediately after completing the 30-WAnT.

2.4. Statistical analysis

The Shapiro-Wilk Test was utilised to determine if the data was normally distributed. Dependent and independent t-tests were utilised to determine if any changes occurred at post-test both within- and between-groups, respectively. Hedges' correction was utilised to determine effect size between measures for baseline and after anaerobic treatment. The substantial effects for φ were divided into more fine-graded magnitudes as follows: $0.20 \leq \varphi < 0.50$ corresponded to a small effect size, $0.50 \leq \varphi < 0.80$ corresponded to a medium effect size, and $\varphi \geq 0.80$ corresponded to a large effect size. For all statistical analyses, the results were assumed to be significant at an alpha level of 0.05. The statistical analyses were conducted using IBM SPSS Statistics software, version 25 (IBM Corporation, Armonk, NY, USA). Results are presented as means and standard deviations.

3. Results

At baseline, the Shapiro-Wilke test demonstrated that the experimental and control groups were statistically different/heterogeneous for accommodation facility ($p = 0.000$) and saccadic eye movement ($p = 0.000$), but statistically similar/homogenous for speed of recognition ($p = 0.836$), hand/eye coordination ($p = 0.562$), peripheral awareness ($p = 0.446$), and visual memory ($p = 0.729$).

Paired t-test results indicate that for the experimental group for all measures, except visual memory ($p = 0.242$), statistically significant ($p < 0.05$) differences existed between the baseline and after-anaerobic treatment ($p = 0.000$ for all other measures). It, therefore, appears that the anaerobic treatment significantly influenced visual measures (Table 1).

Table 1. Effects of a maximal cycling all-out test on visual task performance

	Baseline (n = 30)	After 30-second Wingate anaerobic test (n = 30)
Accommodation Facility	15.645±2.26	18.742±2.59*
Saccadic Eye Movement	19.903±2.93	23.581±3.51*
Speed of Recognition	27.871±16.31	50.258±21.74*
Peripheral Awareness	22.258±4.10	26.484±3.83*
Hand-Eye Coordination	63.613±4.55	73.161±4.58*
Visual Memory	40.968±7.99	42.452±6.16

Data reported as means±standard deviations (SD). *: Statistical significance was set at $p \leq 0.05$;

In the control group, significant changes were found from baseline to re-test for accommodation facility (35.80±4.57 to 38.00±4.24; $p = 0.001$), saccadic eye movement (38.20±6.92 to 40.63±7.45; $p = 0.023$), peripheral awareness (65.37±11.65 to 68.80±7.80; $p = 0.045$), and visual memory (41.57±5.10 to 43.40±6.10; $p = 0.021$). This indicated that a learning effect did take place from baseline to re-test. No significant changes were observed for speed of recognition (28.80±18.56 to 30.37±20.06; $p = 0.200$), and hand/eye coordination (22.97±5.33 to 23.63±5.75; $p = 0.398$).

Further *post hoc* analysis using Hedges' correction effect size measure indicated a large effect size for accommodation facility ($g = 2.69$), saccadic eye movement ($g = 2.04$), speed of recognition ($g = 1.37$), hand/eye coordination ($g = -1.30$), peripheral awareness ($g = 2.46$), and confirmed only a small effect size between measures for baseline and after the anaerobic treatment ($g = 0.21$). For the control group, a medium effect size was found between measures for baseline and re-test with re-test providing a slightly higher mean score for accommodation facility ($g = 0.66$), saccadic eye movement ($g = 0.43$), peripheral awareness ($g = 0.38$), and visual memory ($g = 0.44$).

For the experimental group, participants were found to be homogenous for average power ($p = 0.29$), minimum power ($p = 0.28$), but heterogenous for peak power ($p = 0.04$), power drop ($W.kg^{-1}$) ($p = 0.01$) and power drop (W.sec-1.kg-1) ($p = 0.03$). In order to quantify the work bout effect and magnitude, this study found that the experimental group's peak power was 7.07 ± 1.02 $W.kg^{-1}$ and fatigue index was $49.4 \pm 7.6\%$.

4. Discussion

This study aimed to investigate the effects of a maximal cycling all-out test on the performance of several visual tasks. A new experimental approach was used to assess the neurophysiological mechanisms underpinning fatigue and its role in visual task performance. Results of this study indicate that all measured visual task performances improved following a 30-WAnT. Due to the novelty of this study, only the study of Fleury and Bard (1990) supports the findings of this study when they found that anaerobic alactacid and anaerobic lactacid exercise improved sensory task (peripheral threshold detection), a sensory-motor task (coincidence-anticipation), and a cognitive task (recall in central vision) performance. This study also determined that in the control group, a learning effect did occur with four of the six measured visual skills. Interestingly, while the control group improved their visual memory from baseline to re-test, visual memory was the only visual skill not improved following the anaerobic treatment. This may indicate that anaerobic exercise may have a detrimental effect on visual memory. However, further studies will be needed to confirm this finding.

While fatigue has been associated with deleterious declines in physical and cognitive performance, this study demonstrates that short-term anaerobic exercise using the 30-WAnT improved visual task ability. This may be because central fatigue is more likely to be identified after prolonged running, rather than cycling (Millet & Lepers, 2004). In addition, Decorte et al. (2012) found that cycling to exhaustion leads to peripheral fatigue that develops early during constant-load intense cycling, while central fatigue appears to be present toward the end of the exercise after locomotor running. In this regard, future studies should determine the effect of prolonged running to fatigue on visual task performance. This would allow researchers to investigate and compare the impact of these two fatiguing events on the capacity of the CNS when performing visual tasks. This may also provide an insight regarding the mechanisms of the regulation of neural drive in visual task performance during exhaustive locomotor exercise.

Since movement is preceded and accompanied by brain activities related to the preparation and execution of movement (movement related cortical potentials) and it is entirely plausible that fatigue can indeed deleteriously affect visual task performance, it may be that short-term maximal anaerobic exercise does not sufficiently simulate field-based sports fatigue that is purported to affect visual task performance. It may be that short-term maximal anaerobic exercise may result in positive excitatory and inhibitory muscle responses, not only at the musculoskeletal level (Gandevia, 2001) but also at the CNS level. Although the mechanisms underlying these improvements in visual task performance have not yet been studied, it may be that short-term maximal anaerobic exercise provides "excitability" of the underlying motor cortex, "excitability" of the motoneurons utilised in visual task response and an enhanced "strength" of the mono- and oligosynaptic corticofugal connections (Gandevia, 2001). Irrespective of the underlying mechanism, it appears that the sweeping improvements in visual task performance in this study following a maximal cycling all-out test provide appeal for the use of an intense, short-term warm-up when training visual skills or when visual skills form an integral part of athletic performance.

5. Conclusion

The importance of these findings is that they indicate that different physiological systems may determine visual performance under different exercise conditions. Hence, sports scientists need to consider all visual skills or tasks that an athlete must possess in their given sport and how the bioenergetics of that sport affect the said visual skills. Rather than simply continuing to accept that exercise-induced fatigue is inherently negative to performance, these findings should direct contemporary sports scientists to challenge old dogmas of fatigue's role in athletic performance uncritically. More importantly, this study may provide insight on the necessity of specific exercise modalities for use in warm-ups when training visual skills or when visual skills form an integral part of athletic performance. These findings will assist athletes, coaches and sports scientists to understand how exercise-induced fatigue or all-out exercise, and specifically the different types of metabolic fatigue, affects vision in their sporting discipline. This will also allow them to actively develop strategies to take advantage of or mitigate the effects of all-out exercise or exercise-induced fatigue on their athletes' performance.

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CHAPTER FOUR: EFFECT OF A PROLONGED INCREMENTAL MAXIMAL TREADMILL EFFORT ON VISUAL PERFORMANCE

Shaw, B.S., Breukelman, G.J., Millard, L. & Shaw, I. (2022). Effect of a prolonged maximal bout of exercise on visual performance. *Asian Journal of Sports Medicine*. Accepted. (Appendix B)

Abstract

Background: Despite it being purported that acute, prolonged maximal periods of exercise may impair visual performance, little/no research on this topic is forthcoming. In fact, research has demonstrated that sub-maximal and maximal acute exercise may actually improve cognitive and sensory tasks, and thus possibly improve visual performance.

Objectives: This study aimed to ascertain the influence of an acute, prolonged maximal bout of exercise on visual performance.

Methods: A quantitative study was undertaken with 60 untrained males being divided into a control group (CON; n = 30) or treatment group (TRE; n = 30). Both groups completed a baseline vision test battery consisting of accommodation facility, saccadic eye movement, speed of recognition, peripheral awareness, visual memory and hand-eye coordination using the following tests; Hart Near Far Rock, saccadic eye movement, evasion, accumulator, flash memory and Ball Wall Toss tests. Two weeks later participants returned for follow-up testing using the same vision test battery, with the TRE participants first engaging in a standardized incremental maximal treadmill protocol immediately prior to their vision testing.

Results: Following the incremental maximal treadmill protocol, statistical analyses indicated that statistically significant ($P \leq 0.05$) differences existed for accommodation facility, saccadic eye movements, speed of recognition, hand-eye coordination, peripheral awareness, and visual memory between pre-test and after the aerobic treatment ($P=0.00$ for all measures).

Conclusions: This study indicates that an acute, prolonged maximal bout of running improves visual performance. As such, an appropriate prolonged maximal warm-up may be required as opposed to a standardised and general warm-up when preparing an athlete for visual skills training or for participation in an athletic event that requires optimal visual performance.

Keywords: Aerobic Exercise, Exercise-Induced Fatigue, Metabolic Fatigue, Treadmill, Visual Fatigue, Visual Task

1. Background

The influence of a prolonged maximal bout of exercise on an individual's physical and/or cognitive performance has long been of interest to researchers in the fields of sport performance (1). Since movement is preceded and accompanied by brain activities related to the preparation and execution of movement, it is entirely plausible that exercise-induced fatigue can indeed deleteriously affect visual performance, through central and or peripheral pathways. Problematically, different modes of exercise affect such pathways differently with central fatigue more likely after prolonged running (i.e. 30 kilometres), rather than cycling (2, 3). This may be so since 30 minutes of treadmill walking or running at speeds of 1.9 to 2.2 meters per second ($m.sec^{-1}$) (~6.84-7.92 kilometres per hour ($km.h^{-1}$)) may require more active control of attention (i.e. for postural stability, control of vestibular and visual information centres (4) leading to more central fatigue.

In addition, exercise-induced fatigue is found to have a deleterious effect on physical performance leading to mental fatigue (5). The reverse of this relationship is also true in that mental fatigue has also been found to result in physical performance decreases (6). Further complicating this relationship are the detrimental effects of prolonged maximal exercise on cognitive functioning, resulting in mental fatigue (7) and potentially worsening visual performance. It is this effect of prolonged maximal exercise on central and peripheral pathways combined with mental fatigue that is purported to affect visual performance. Despite this supposition, only recently have laboratory studies begun to examine central fatigue in the oculomotor system following acute, prolonged exercise (8). In this regard, the limited findings available suggest that an acute, prolonged bout of submaximal exercise impairs saccadic velocity (8). However, it is still unknown how an acute, prolonged bout of exercise will impact on the other newly identified visual skills important for athletic performance (9). This is because previous research has actually demonstrated improvements in sensory task (peripheral threshold detection), sensory-motor task (coincidence-anticipation), and cognitive task (recall in central vision) performance (10), all of which are critical in certain visual performances. Further, it is not known how an acute, prolonged bout of maximal exercise may affect vision since exercise has two main effects on the central nervous system (CNS), including not only inhibition, but also excitation. In this regard, it may be plausible that simple exercise modalities, such as running create excitatory responses at a CNS level (11), that may actually stimulate the mechanisms underlying sports vision performance. As such, it remains to be determined whether an acute, prolonged bout of maximal exercise affects other components of vision or specific visual task performance. This study's findings would be the first, to the authors' knowledge, providing evidence of the stimulatory effects of an acute, prolonged bout of maximal running on visual performance. In addition, this study novelly explores the effect of an acute, prolonged bout of maximal running on six visual tasks, demonstrating a global visual effect. Further, while previous research has demonstrated impaired saccadic velocity following submaximal exercise (8), the present study will determine the effect of maximal exercise on visual performance. This is important in that prolonged submaximal aerobic exercise is not the primary exercise modality for all, or even the majority of sporting codes. As such, findings of this study could assist conditioning specialists in understanding how different exercise modalities affect visual performance in their sporting discipline. This study hypothesized that an acute, prolonged bout of maximal running would improve visual performance.

2. Objectives

The objective of the study was to determine the influence of an acute, prolonged maximal bout of exercise on visual performance.

3. Methods

3.1. Participants

Sixty-one males (mean age: 23.11±3.02 years) were recruited through local advertisements in or near the South African cities of Richards Bay and Kwadlangezwa using non-probability convenience sampling. Participants volunteered to participate in this study and were divided into a control group (CON; n=30) or treatment group (TRE; n=31). To be included in the study participants were required to have a minimum of 20/20 vision, no visual disease or infection, physical disability, psychosocial distress, no participation in any form of structured exercise for the past six months, no previous experience with sport vision testing, no reading and/or speech impediment and/or no relative or absolute contraindication to exercise or testing (12, 13, 14). The participants gave informed consent subsequent to gaining information regarding the aims, data collection and data management of the study. The University of Zululand's Institutional Review Board gave ethical approval for the study (UZREC 171110-030-PGD-

2021/27). All procedures were conducted according to the Declaration of Helsinki for studies involving human participants.

3.2. *Procedures*

In this single-blind study, the same qualified sport scientist was responsible for data collection for all tests (Figure 1). All quantitative data were recorded manually by the investigator using existing, standardized protocols for Hart Near Far Rock Test, saccadic eye movement charts and Ball Wall Toss. In turn, further quantitative data were recorded electronically for the standardized optometric assessment via the Spectrum Eyecare (Version 6.0.0 Digital Optometry, South Africa) and for speed of recognition, peripheral awareness and visual memory via the Batak Pro's (Quotronics Limited, Surrey, United Kingdom) software.

Participants underwent an optometric assessment to assess depth perception and visual acuity using Spectrum Eyecare software (Version 6.0.0 Digital Optometry, South Africa) to ensure 20/20 vision.

Once participants presented with 20/20 vision, six components of vision were measured using a visio-spatial intelligence (VSI) test battery; accommodation facility; saccadic eye movements; speed of recognition; hand-eye coordination; peripheral awareness and visual memory (12). After two weeks, participants returned to undertake an incremental maximal treadmill protocol immediately followed by the same vision test battery.

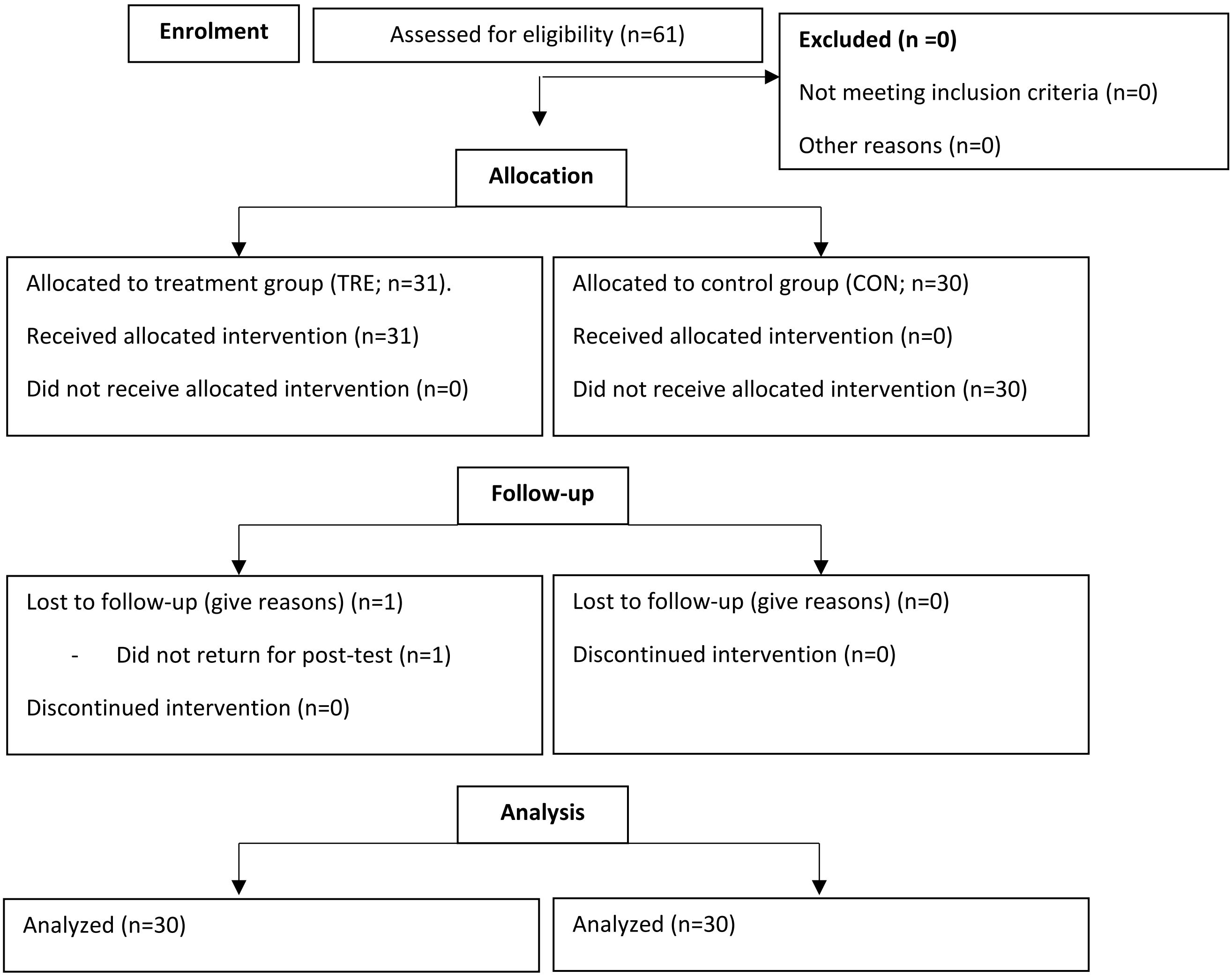

Figure 1. CONSORT flow diagram of study

3.2.1. Vision test battery

This study made use of the Hart Near Far Rock Test to assess accommodation facility (15). While participants held the small Hart Chart at an arm's length, the large Hart Chart was placed three meters away from the participants on a board, at head height (16). On the "go" signal, participants were required to recite the first letter, of the first line of the large chart positioned 3 meters (m) away and then the first letter of the small chart arm's length away, followed by the second letter, of the first line of the distant chart, then the second letter of the first line of the immediate chart and so forth for 30 seconds (sec). After 30 seconds, the mistakes were deducted from the score to define the ultimate score (16).

Saccadic eye movement was assessed using saccadic eye movement charts (17). In this test, two charts were placed on a board, one meter apart, and 3m away from the participants. To limit memorisation, standardised, adjustable saccadic eye movement charts were utilised (16). On the "go" signal, participants recited the first letter on the lateral side of the left chart, and then quickly recited the first letter on the lateral side of the right chart without moving their heads, followed by the second letter of the left chart and right chart and so forth for 30 sec. At the end of the 30 sec, mistakes were deducted from the score to define the ultimate score.

Speed of recognition was measured using the Batak Pro's (Quotronics Limited, Surrey, United Kingdom) built-in Evasion Programme (18). In this programme, 12 light-emitting diode (LED) lights lit up randomly. Participants were required to touch each light if it remained constantly lit for 1 sec. However, if a light only flickered, participants were not to strike the target and if they did so, five points were deducted from the final score. Participants were required to evade the small central infrared beam when all of the lights in the middle of the Batak Pro flashed, and if detected by the beam, five points were deducted from the final automatically determined score.

The Ball Wall Toss was utilised to assess hand-eye coordination (19). In this test, a target was marked on a wall two meters away from the participant. On the "go" signal, participants were required to throw and catch a standard tennis ball with alternating hands for 30 sec and the amount of successful catches was recorded as the final score (16).

Peripheral awareness was measured using the Batak Pro's (Quotronics Limited, Surrey, United Kingdom) built-in Accumulator Programme (20). This programme causes random LED lights to become lit, and remained so until touched by the participant. After being touched by the participant, another LED target would immediately light up for a period of 60 sec. The final score was calculated automatically by the Batak Pro microcomputer.

Visual memory was assessed using the Batak Pro's (Quotronics Limited, Surrey, United Kingdom) built-in Flash Memory Programme (21). For this programme, six lights became lit for half a second. At the end of the sequence, participants were required to remember which six targets were illuminated, as well as the order in which they lit up. Scores were computed by the Batak Pro's microcomputer.

3.3. Intervention

Following a two-week wash-out period after vision pre-tests, TRE participants returned to the laboratory and took part in a single bout of incremental maximal treadmill protocol (22). Since participants were sedentary, the present study made use of a protocol utilising low initial speeds and small increments between stages (20) instead of protocols starting with high speeds and large increments between stages, such as the Bruce protocols. Participants were positioned on the treadmill (Johnson T8000 PRO treadmill, Johnson Health Tech. Co., Ltd, Taiwan) and initially walked at 2.0 kilometres per hour ($km.h^{-1}$) and 1% grade for 2 minutes. The protocol then increased to 5.5 $km.h^{-1}$ and 1% grade, with 0.2 $km.h^{-1}$ increments being added every 15 seconds. Grade was kept constant throughout until 16 $km.h^{-1}$ was reached, at which point grade increments increased by 0.5% every 30 sec. Participants then immediately took part in the same vision test battery as at pre-test. To determine if a learning effect occurred across the experimental period, CON participants returned and undertook the same vision test battery without performing the incremental maximal treadmill protocol immediately beforehand.

3.4. Statistical Analysis

SPSS Statistics software, version 25, was utilised in the statistical analyses (IBM Corporation, Armonk, NY, USA). The results are presented as means and standard deviations. Data analysis involved the determination of normality of data using the Shapiro-Wilk Test, and dependent and independent t-tests to determine if any changes occurred both within- and between-groups, respectively. Post hoc analysis of effect size was determined using Hedges' correction, with effect sizes of 0.2 to 0.5 being a small effect size, 0.5 to 0.8 being a medium effect size, and effect sizes equal to and larger than 0.8 being considered a large effect size. A probability of $P \leq 0.05$ was set for the study.

4. Results

Of the 31 participants enrolled in the TRE, one participant was excluded from the study as a result of a failure to attend the post-test. At pre-test, the CON were found to be homogenous for accommodation facility (P=0.94) and saccadic eye movement (P=0.23), for speed of recognition (P=0.10), hand/eye coordination (P=0.26), and visual memory (P=0.66), but heterogeneous peripheral awareness (P=0.00). In turn, the TRE were heterogeneous for accommodation facility (P=0.00) and saccadic eye movement (P=0.00), but homogenous for speed of recognition (P=0.84), hand/eye coordination (P=0.56), peripheral awareness (P=0.45), and visual memory (P=0.73).

Following the incremental maximal treadmill protocol, statistical analyses indicated that statistically significant (P≤0.05) differences existed for all vision measures between the pre-test and after the prolonged maximal bout of exercise (P=0.00 for all vision measures) (Table 1). It therefore appears as if the prolonged maximal bout of treadmill running significantly influenced all visual performance measures.

Table 1. Effects of a prolonged maximal bout of exercise on visual performance

	Pre-test (n=30)	**Post-test (n=30)**
Accommodation facility	15.65±2.26	19.61±3.02*
Saccadic eye movement	19.90±2.93	24.48±3.75*
Speed of recognition	27.87±16.31	54.94±18.57*
Peripheral awareness	22.26±4.10	26.32±3.46*
Hand-eye coordination	63.61±4.55	74.13±5.43*
Visual memory	40.97±7.99	41.65±5.82*

Data reported as means±standard deviations (SD); Post-test: Following an incremental maximal bout of exercise protocol; *: Probability was set at P≤0.05; sec: seconds.

For the CON, significant changes were found from pre- to post-test for accommodation facility (35.80±4.57 to 38.00±4.24; P=0.00), saccadic eye movement (38.20±6.92 to 40.63±7.45; P=0.02), peripheral awareness (65.37±11.65 to 68.80±7.80; P=0.05), and visual memory (41.57±5.10 to 43.40±6.10; P=0.02). No significant changes were observed for speed of recognition (28.80±18.56 to 30.37±20.06; P=0.20), and hand/eye coordination (22.97±5.33 to 23.63±5.75; P= 0.40).

Post hoc analysis revealed a large effect size between pre- and post-test measures; accommodation facility (g=2.25), saccadic eye movement (g=1.90), speed of recognition (g=1.72), hand/eye coordination (g=1.53), and peripheral awareness (g=2.43). However, only a small effect size was found between measures for pre-test and after the prolonged maximal bout of exercise for visual memory (g=0.09). Conversely, only a medium effect size was found between measures for pre- and post-test for the CON for accommodation facility (g=0.66), saccadic eye movement (g=0.43), peripheral awareness (g=0.38), and visual memory (g=0.44).

5. Discussion

The main aim of this study was to determine the influence of an acute, prolonged maximal bout of exercise on visual performance. This study found that accommodation facility, saccadic eye movements, speed of recognition, hand-eye coordination, peripheral awareness, and visual memory improved following a single bout of incremental maximal treadmill running.

Contrary to this study, previous research has found that progressive treadmill exercise that recruited glycogen and oxygen does not affect a visual detection task (23). However, it must be noted that the study of Fleury et al. (23) utilised a physically fit population whereas the present study utilised sedentary participants. Also, previous research has demonstrated that a submaximal cycle test (at 75% of maximal work capacity (Wmax)) improved simple cognitive tasks important for visio-spatial intelligence (VSI), such as simple reaction time and even complex measures of working memory and attention (24). Previous research has demonstrated that 180 min of stationary cycling at a work rate equivalent to 60% of maximal aerobic capacity impairs a single visual task, namely saccade velocity (8). When compared to this study, the contrary findings could be due to the use of a submaximal intensity being insufficient to result in excitation of the CNS. This is especially true since a submaximal effort may especially be insufficient to excite the CNS in their well-trained cyclists (VO_{2max}: 57 ± 1 ml·kg·min^{-1}). Further, in addition to intensity, the long duration of cycling in the study of Connell et al. (8) may have been more suited to central fatigue and it may be that a time-course exists between prolonged exercise and visual performance, as it does with cognitive function (25). This is because prolonged exhaustive exercise may be more efficient at inducing hypoglycaemia and muscular glycogendepletion (26) than the current study's shorter, albeit maximal, exercise bout.

While the mechanisms explaining how an acute, prolonged maximal bout of treadmill running can improve visual skills are yet to be explored, a substantial amount of research has investigated the effects of acute exercise on cognitive function (27). Some of these findings may also explain the acute improvements in visual performance following acute exercise. In this regard, acute exercise has been found to have a generally positive effect on cognitive functioning, especially in areas of prefrontal cortex-dependent cognition (28). This may too be the case in improving visual performance, since frontal brain areas are also now identified in generating the contents of visual perception. Specifically, the frontal cortical area, the frontal-eye field (FEF), has been shown to have fast visual responses (29). In addition, acute exercise has been demonstrated to have a positive influence on time trial performance, exercise capacity (time to exhaustion) and subjective effort. This is because acute exercise central or brain catecholamines, which increases arousal by activating the reticular formation in what is termed the "catecholamines hypothesis" (30). In addition to catecholamines, other neurochemicals, such as hypothalamic–pituitary–adrenal cortex (HPA) axis hormones and brain-derived neurotrophic factor (BDNF) may also play a role in arousal and possible improvements in visual performance following acute, prolonged maximal exercised (30). Further, while stimulating as well as detrimental effects of exercise on cognitive functioning have previously been reported, and such effects may also exist on visual performance, fatigue effects may be task specific (1). In this regard, it may be that this study's prolonged maximal bout of treadmill running may not sufficiently simulate training and/or competition conditions, which requires the exertion of cognitive control, which in turn, may result in appropriate mental, combined with physical, fatigue that negatively impacts visual performance. This is because sport requires active control of attention for visual tasks resulting in not only physical, but also simultaneous mental fatigue (31). In addition, treadmill running may not sufficiently simulate the field-based sports fatigue that is purported to affect visual task performance.

The importance of these findings is that they indicate that sport scientists need to consider all visual skills or tasks that an athlete must possess in their given sport and how the bioenergetics of that sport affects the said visual skills. Rather than simply continuing to accept that exercise-induced fatigue is inherently negative to performance, these findings challenge sport scientists' beliefs regarding fatigue's role in athletic performance. These findings will assist athletes and conditioning specialists in understanding how different all-out physical efforts from the various physiological energy pathways may affect vision in their sporting discipline. Our study had several strengths, one of which was the use of experimental evidence to determine that an acute, prolonged maximal bout of treadmill running actually improves visual performance. Further, this study made use of an independent control group and not a crossover design to avoid nonconstant variances for all observations and to account for the possibility of carryover effects or bias from the previous treatment (32). In addition, this study did not only assess a single visual skill, but rather six different visual skills (i.e. accommodation facility, saccadic eye movement, speed of recognition, peripheral awareness, visual memory and hand-eye coordination) in determining if visual improvements were a global phenomenon or finding, rather than an isolated or haphazard effect. This study also utilised sedentary participants in order to avoid the training effects or adaptations that could have been present and that could have affected performance and recovery from the acute, prolonged maximal bout of treadmill running.

5.1.Limitations

The sample of the study was not systematically drawn and utilised a male-only sample since females have central limitations in oxygen delivery when compared to males (33), which could have affected exercise responses. This study also utilised untrained participants and it is plausible that trained participants may respond differently to a prolonged maximal bout of exercise (23). It is also important to note that this study only utilised six visual skills based across a broad spectrum. However, a multitude of visual skills exist and are being discovered (34) that may have been affected by a prolonged maximal bout of treadmill running. In addition, this study did not compare all out (maximal) prolonged exercise with submaximal aerobic exercise. This study also did not compare the effect of different modalities of prolonged maximal exercise (i.e. cycling vs running) since each make use of different pathways to influence central fatigue (2, 3), and thus may affect visual performance differently. However, it was proposed that prolonged maximal exercise would most likely affect visual performance due to running requiring more active control of attention (i.e. for postural stability, control of vestibular and visual information centres (4)) leading to more central fatigue, and thus have more of an effect on visual performance than cycling.

5.2.Conclusions

This study indicates that prolonged maximal bout of exercise improves visual performance. As such, an appropriate prolonged maximal warm-up may be required as opposed to a standardised and general warm-up when preparing an athlete for visual skills training or for participation in an athletic event that requires optimal visual performance.

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CHAPTER FIVE: COMPARISON OF EFFECTS OF A SHORT SUPRAMAXIMAL CYCLE ERGOMETER EFFORT VERSUS A PROLONGED INCREMENTAL MAXIMAL TREADMILL EFFORT ON VISUAL PERFORMANCE

Shaw, B.S., Breukelman, G.J., Millard, L. & Shaw, I. Short- versus long-duration maximal exercise effects on sport vision performance. *PLoS One*. Submitted. (Appendix C)

Abstract

Objective

It is supposed that maximal and supra-maximal exercise efforts may be responsible for decreases in sports vision performance and that physical conditioning may increase an athlete's ability to delay mental fatigue and thus deterioration in sports vision performance. However, previous research has demonstrated that anaerobic alactacid and anaerobic lactacid exercise improves components of sports vision (i.e. peripheral threshold detection and coincidence-anticipation) and may result in instantaneous improvements in sports vision performance. Thus, the primary aim of the present study was to investigate the effects of short- and prolonged-duration maximal exercise effects on visual performance. The secondary aim was to examine and compare whether short- and long-duration maximal exercise most affects visual performance.

Methods

60 sedentary males were assigned to a control group (CG) (n = 30) or treatment group (TG) and underwent a sports vision test battery consisting of quantitative testing for accommodation facility, saccadic eye movements, speed of recognition, hand-eye coordination, peripheral awareness, and visual memory. One week later, the TG participants returned to complete a short supramaximal effort cycle ergometer test (SCT) immediately followed by the sports vision test battery. At week two, TG participants returned and completed a prolonged incremental maximal treadmill test (PTT) immediately followed by the sports vision test battery.

Results

In the SCT, significant ($p \leq 0.05$) changes were found for five of the six sports vision performance measures ($p = 0.000$), except visual memory ($p = 0.242$). In turn, following the PTT, significant changes were found for all sports vision performance measures ($p = 0.000$ for all measures). Results further indicate that only accommodation facility ($p = 0.005$) and

saccadic eye movement ($p = 0.026$) were statistically different between the SCT and PTT with these variables being significantly higher following the PTT.

Discussion

We conclude that beneficial immediate improvements in sport vision performance can be achieved following short-supramaximal or prolonged-maximal exercise efforts, with the latter being found to be even more effective. Combining such exercise regimes as a functional warm-up may attenuate improvements in sports vision performance, especially in those sports requiring a great deal of visual processing and performance.

Introduction

Athletes use a variety of metabolic pathways to generate energy for training and/or competition. However, depending on the form of exercise or sporting discipline, sensations of fatigue and exhaustion will occur at different times during exercise [1,2]. It is this fatigue that has been demonstrated to result in a variety of deleterious effects on athletic performance [3], whether it be physical and/or cognitive [4,5].

With regards to visual skills and fatigue, fatigue has been demonstrated to negatively affect the visio-motor reaction time of athletes [6]. This may have a detrimental effect on the ability of an athlete to process a wide variety of information, which includes perceptual information [7]. Specifically, in a study by Connell et al. [8] it was found that after three hours of strenuous cycling, there was a decrease in the velocity of rapid eye movements, which was independent of other visual processes, including dorsal cortical stream function. Furthermore, it was found that the reduction in saccade velocity was fatigue induced, and similar results were recorded after acute, and prolonged aerobic exercise [8]. All these detrimental effects of exercise-induced fatigue on visual skills demonstrate that there is a direct link between aerobic exercise and brain-based fatigue in the corticospinal motor system, which in turn causes impairment of the oculomotor system [8]. However, since neurotransmitter levels and actions are affected during prolonged aerobic exercise, they are purported to also have a direct impact on and cause impairment of the oculomotor system [9].

On the contrary, research also exists that shows neither (a) short anaerobic alactacid efforts recruiting phosphocreatine, (b) supramaximal efforts (anaerobic lactacid) recruiting glycogen without oxygen, and (c) progressive (partially anaerobic) efforts recruiting glycogen and oxygen do not affect visual detection tasks [10]. This is because it may be that some exercise modalities may not sufficiently simulate the field-based sports fatigue that is purported to affect sports vision performance. However, this supposition is yet to be proven. Taking a step further, research even suggests that exercise may even result in immediate improvements in visual skills. In this regard, it may be that short-term maximal anaerobic exercise may result in positive excitatory and inhibitory muscle responses, not only at the musculoskeletal level, but also at the CNS level [11]. Although the mechanisms underlying these improvements in sports vision performance have not yet been studied, it may be that short-term maximal anaerobic exercise provides "excitability" of the underlying motor cortex, "excitability" of the motor neurons utilized in vision task response and an enhanced "strength" of the mono- and oligosynaptic corticofugal connections [11].

The importance of these findings is that they may indicate that dissimilar exercise conditions may affect sports vision performance differently. Hence, sports scientists need to consider all visual skills or tasks that an athlete must possess in their given sport and how the bioenergetics of that sport affects the said visual skills. Therefore, the primary aim of the present study was to investigate the effects of short- and long-duration maximal exercise effects on visual performance. The secondary aim was to examine and compare whether short- and prolonged-duration maximal exercise most affects visual performance.

Materials and Methods

This study took place in a dedicated Visio-Spatial Intelligence (VSI) Laboratory in KwaZulu-Natal Province, South Africa. Sedentary males (n = 60; mean age: 23.11±3.02 years) volunteered for participation in this study and were assigned to a control group (CG) (n = 30) or treatment group (TG) (n = 30) based on the following criteria: participants were required to have 20/20 or more vision, should have no regular participation in exercise or sports in the past six months, and should not have had any prior experience with sports vision testing [12]. Exclusionary criteria included participants that presented with any relative or absolute contraindication to exercise or testing [13] or presented with an eye infection, visual disease, physical disability or psychosocial distress [14]. Following an explanation of the study, participants provided written informed consent. This study was approved by the relevant Institutional Review Boards of the University of Zululand (UZREC 171110-030-PGD-2021/27), South Africa.

Baseline testing involved sports vision testing for accommodation facility, saccadic eye movements, speed of recognition, hand-eye coordination, peripheral awareness, and visual memory as described previously [15]. Accommodation facility (refractive power of the optical system of an eye) was measured using the Hart Near Far Rock Test, which involved reading the 1st letter on a large chart positioned three metres away followed by reading the 1st letter on a smaller chart held at arm's length after which the 2nd letter was read and so on for 30 seconds (sec) [16,17]. Saccadic eye movement (rapid, ballistic movements of the eyes that abruptly change the point of fixation) was measured using standardized saccadic eye movement charts [18], which involved reading the 1st letter on a left chart positioned three metres away followed by reading the 1st letter on a right chart also three metres away, but one meter apart from the left chart. After the 1st letter was read, the 2nd letter was read on both charts and so on for 30 sec (16,19). Speed of recognition was measured by the Batak Pro, using a pre-programed *Evasion Programme* [20,21]. Hand-eye coordination was measured using the Ball Wall Toss Test, which required participants to throw and catch a standard tennis ball at a wall two metres away with alternating hands, and catch it for 30 sec. [16,22]. Peripheral awareness was measured by the Batak Pro, using a pre-programed *Accumulator Programme* [21,23]. Similarly, visual memory was assessed using the pre-programed *Flash Memory Programme* on the Batak Pro [21,24].

One week later, TG participants returned to the laboratory and undertook a short supramaximal effort cycle ergometer test (SCT) immediately followed by the sports vision test battery described above. The cycle ergometer test was performed using a protocol as previously described [25] using a cycle ergometer (Model 834E, Monark Exercise AB, Vansbro, Sweden).

At week two, TG participants again returned to the laboratory, but this time undertook a prolonged incremental maximal treadmill test (PTT) immediately followed by the sports vision test battery described above. The treadmill test was performed using a protocol as previously described [26] using a motorized treadmill (Johnson T8000 PRO treadmill, Johnson Health Tech. Co., Ltd, Taiwan). Control group participants returned to the laboratory and only undertook the described sports vision test battery without any treatment beforehand.

Data analysis

Statistical analyses were conducted using IBM SPSS Statistics software, Version 25 (IBM Corporation, Armonk, NY, USA). In addition to means and standard deviations, the present study determined the normality of the data using the Shapiro-Wilk Test. Following this, parametric dependent and independent t-tests were utilized to determine if any changes occurred at post-test both within- and between-groups, respectively. Hedges' g was utilized to determine effect size between measures for baseline and after the treatments. Effect sizes were graded as follows: effect sizes between 0.20 and 0.50 were considered small, and effect sizes between 0.50 and 0.80 were considered medium, while effect sizes above ≥ 0.80 were considered large [27]. In addition, a repeated measures Analysis of Variance (ANOVA) was used to compare the group means and the response to each of the SCT and PTT conditions. A significance level of $p \leq 0.05$ was utilized in this study.

Results

At baseline, the Shapiro-Wilk Test found that treatment and control groups were statistically different/heterogeneous for accommodation facility ($p = 0.000$) and saccadic eye movement ($p = 0.000$), but statistically similar/homogenous for speed of recognition ($p = 0.836$), hand/eye coordination ($p = 0.562$), peripheral awareness ($p = 0.446$), and visual memory ($p = 0.729$).

Results indicate that five of the six sports vision performance measures significantly ($p < 0.05$) improved immediately following the SCT ($p = 0.000$). However, visual memory remained unchanged ($p = 0.242$). In turn, all six of the sport vision performance measures significantly improved following the PTT ($p = 0.000$). Paired t-test results further indicate that only accommodation facility ($p = 0.005$) and saccadic eye movement ($p = 0.026$) were statistically different between the SCT and PTT with these variables being significantly higher following the PTT (Table 1).

Table 1. Effect of short- and long-duration maximal exercise on sport vision performance

	Baseline (n = 30)	Following SCT (n = 30)	Following PTT (n = 30)
Accommodation Facility	15.65±2.26	18.74±2.59*	19.61±3.02*,**,†
Saccadic Eye Movement	19.90±2.93	23.58±3.51*	24.48±3.75*,**,†
Speed of Recognition	27.87±16.31	50.26±21.74*	54.94±18.57*,†
Peripheral Awareness	22.26±4.10	26.48±3.83*	26.32±3.46*,†
Hand-Eye Coordination	63.61±4.55	73.16±4.58*	74.13±5.43*,†
Visual Memory	40.97±7.99	42.45±6.16	41.65±5.82*

Data reported as means±standard deviations (SD). *: Within-group statistical significance at $p \leq 0.05$; ** Between-group statistical significance at $p \leq 0.05$; †: Repeated-measures ANOVA significance at $p \leq 0.05$; Short supramaximal effort cycle ergometer test (SCT); Prolonged incremental maximal treadmill test (PTT)

The repeated-measures ANOVA results indicate a significant difference between the baseline, after the SCT and after the PTT (p = 0.000 for all measures), with the exception of visual memory (p = 0.41). Hedges' g also found a large effect size for accommodation facility (g = 2.69), saccadic eye movement (g = 2.04), speed of recognition (g = 1.37), hand/eye coordination (g = 1.30), peripheral awareness (g = 2.46), and confirmed only a small effect size between baseline and immediately after the SCT (g = 0.21). This was similar following the PTT, when a large effect size was found for accommodation facility (g = 2.25), saccadic eye movement (g = 1.90), speed of recognition (g = 1.72), hand/eye coordination (g = 1.53), and peripheral awareness (g = 2.43). In contrast to the SCT, a small effect size was found for visual memory following PTT (g = 0.09).

For the CG, significant changes were found from baseline to re-test for accommodation facility (35.80±4.57 to 38.00±4.24; p = 0.001), saccadic eye movement (38.20±6.92 to 40.63±7.45; p = 0.023), peripheral awareness (65.37±11.65 to 68.80±7.80; p = 0.045) and visual memory (41.57±5.10 to 43.40±6.10; p = 0.021). No significant changes were observed for speed of recognition (28.80±18.56 to 30.37±20.06; p = 0.200), and hand/eye coordination (22.97±5.33 to 23.63±5.75; p = 0.398). In addition, Hedges' g found a medium effect size for accommodation facility (g = 0.66), saccadic eye movement (g = 0.43), peripheral awareness (g = 0.38) and visual memory (g = 0.44).

Discussion

The results showed a beneficial effect of a single bout of maximal or supramaximal exercise on sports vision performance measures. Specifically, this study demonstrated that a short supramaximal cycle ergometer effort immediately improved accommodation facility, saccadic eye movements, speed of recognition, hand-eye coordination, peripheral awareness, but not visual memory. In turn, a prolonged incremental maximal treadmill effort improved all six of the sports vision performance measures and was better at improving accommodation facility and saccadic eye movement when compared to the supramaximal cycling effort.

While the findings of this study are unique, since movement is preceded and accompanied by brain activities related to the preparation and execution of movement, it is plausible that exercise-induced fatigue can indeed deleteriously affect visual task performance. However, simple repetitive movement exercises, such as cycling and running, and even if maximal in nature, may not sufficiently simulate the field-based sports fatigue that is purported to affect sports vision performance. This is because it may be that the mental fatigue arising from sports that require a great deal of cognitive and visual processing effort (i.e. to engage in visual tracking, decision-making, etc.) combined with exercise-induced fatigue may be responsible for decreases in visual performance. However, this supposition may prove to be task-/sport-specific in that while running as an exercise modality may require more active control of attention and leading to more central fatigue [28,29], this study refutes this supposition. In this regard, the present study found that prolonged running improved all six of the sports vision performance measures and was essentially better at improving accommodation facility and saccadic eye movement when compared to the cycling effort.

Thus, this study suggests that while trained athletes with enhanced physical conditioning may reduce their physical fatigue, such conditioning may not always reduce mental fatigue and mitigate on-field deteriorations in sports vision performance. Thus, athletes may require both task-/sport-specific and sport-specific vision training that as close as possible mimics their sport competition setting, in addition to simple strength and conditioning activities to improve on-field performance.

In conclusion, this study's findings suggest that both a supramaximal cycling effort and a prolonged incremental maximal treadmill effort immediately improves sports vision performance. As such, it may be that these simple exercise modalities excitatory and inhibitory responses at a CNS level [11], may actually stimulate the mechanisms underlying sports vision performance. Although these mechanisms have not yet been investigated, it may be that these exercise modalities provide excitability of the motor cortex, an enhanced strength of the mono- and oligosynaptic corticofugal connections, and excitability of motor neurons themselves that are utilized in visual task response [11]. Regardless of the mechanism underlying the improvements in sports vision performance in this study and rather than simply continuing to accept that exercise-induced fatigue is inherently negative to performance, these findings challenge sports scientists' beliefs regarding fatigue's role in athletic performance. In this regard, the extensive improvements in this study following both a short supramaximal effort cycle ergometer effort and a prolonged incremental maximal treadmill effort suggests that this type of intense exercise may be required as part of a functional warm-up for those sports that require an optimal level of sports vision performance.

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CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

Sports vision, which is the assessment and training to enhance sports vision skills is becoming increasingly important in many sports (Wimhurst, 2012). This is because it is essential to determine how to mitigate those factors that decrease performance, while simultaneously enhancing those that improve visual and concomitant athletic performance. By ascertaining if any weaknesses lie in these areas, sports scientists may have an opportunity to assist an athlete to enhance not only these visual skills but also their resultant performance in their sport. This is because athletes that utilise their visual system to its maximum potential will observe improved athletic performance and gain a competitive edge.

While it is thought that exercise-induced fatigue can affect vision, limited information exists in this regard. In addition, these studies have exclusively focused on aerobic modes of exercise. This is problematic in that most sports are entirely anaerobic in nature (i.e. sprinting) or have a large anaerobic component (i.e. soccer). As such, this study novely determined the immediate effects of a short supramaximal effort cycle ergometer effort (SCT) and prolonged incremental maximal treadmill effort (PTT) on visual performance, and specifically six visual skills, namely: saccadic eye movements; accommodation facility; hand/eye coordination; speed of recognition; visual memory; and peripheral awareness.

Results of this study demonstrated that in the SCT, changes were found for five of the six sports vision performance measures, except visual memory. In turn, following the PTT, significant changes were found for all sports vision performance measures. Results further indicate that only accommodation facility and saccadic eye movement were statistically different between the SCT and PTT with these variables being significantly higher following the PTT. As such, this study's findings point to a beneficial immediate improvement in sports vision performance following short-supramaximal or prolonged-maximal exercise efforts, with the latter being found to be even more effective. While fatigue has been associated with deleterious declines in physical and cognitive performance, this study demonstrates that maximal and supramaximal exercise efforts improved visual task ability.

While it is clear that movement and exercise can result in peripheral and central fatigue and can further deleteriously affect visual task performance, it may be that short-term rhythmical and "simple" tasks of cycling and running do not sufficiently stimulate or tax the central nervous system (CNS) to replicate the field-based sports fatigue that is purported to affect visual task performance (Millet & Lepers, 2004). It also may be that while the intensities of the treatments were maximal or supramaximal, the duration of the treatments may have been insufficient to create peripheral fatigue, since central fatigue appears to be present toward the end of the exercise bouts (Decorte *et al.,* 2012).

The findings of this study indicate that short-term supramaximal and maximal exercise may result in positive excitatory and inhibitory muscle responses, not only at the musculoskeletal level (Gandevia, 2001), but also at the CNS level. Although the mechanisms underlying these improvements in visual task performance have not yet been studied, it may be that short-term maximal anaerobic exercise provides “excitability” of the underlying motor cortex, “excitability” of the motoneurons utilised in visual task response and an enhanced “strength” of the mono- and oligosynaptic corticofugal connections (Gandevia, 2001). Irrespective of the underlying mechanism, it appears that the sweeping improvements in visual task performance in this study following a maximal cycling all-out test provide appeal for the use of an intense warm-up when training visual skills or when visual skills form an integral part of athletic performance.

LIMITATIONS

There are some limitations in this research that merit remark. One such possible design limitation is that this study did not utilise a randomised crossover design whereby the participants could have served as their own controls. However, analysis of data from the crossover design poses several problems that need to be accounted for, including non-constant variances for all observations and the possibility of carryover effects or bias from the previous treatment (Boon & Roes, 1999). Another possible limitation, was the utilisation of a male-only sample. However, this was instituted because females have central limitations in oxygen delivery when compared to males (Jahn *et al*., 1999), which could have affected exercise responses. In addition, this study utilised sedentary participants and it is possible that trained participants, as originally investigated by Fleury *et al*. (1981) may respond differently to the SCT and PTT, especially based on the nature of their previous training. While this study utilised six pertinent visual skills, a multitude of visual skills exist and are being discovered (Barret *et al*., 2017) that may have been affected by SCT and PTT. Another possible limitation of this study relates to the 25-minute timeline of the visio-spatial test battery, whereby the recovery flow may allow the last visual parameter to recover more than the first tested parameter.

This study also did not compare the effect of different exercise modalities of prolonged maximal exercise (i.e. cycling vs running) since each make use of different pathways to influence central fatigue (Decorte *et al*., 2012; Millet & Lepers, 2004), and thus may affect visual performance differently.

FURTHER RESEARCH

Against the background of this study's findings, future research should compare the effect of different modalities of prolonged maximal exercise (i.e. cycling versus running). This is because these modalities make use of different pathways to influence central fatigue (Decorte *et al*., 2012; Millet & Lepers, 2004), and thus may affect visual performance differently. In addition, it may be that while the intensities of the present study's treatments were maximal or supramaximal, the duration of the treatments may have been insufficient to create peripheral fatigue, since central fatigue appears to be present toward the end of the exercise bouts (Decorte et al., 2012). Findings from such research may also allow researchers to investigate and compare the impact of these two fatiguing events on the capacity of the CNS when performing visual tasks. This may also provide an insight regarding the mechanisms of the regulation of neural drive in visual task performance during prolonged, exhaustive exercise. Future studies should also aim to establish the optimum period or recovery that results in the most enhanced visual performance following a bout of maximal or supramaximal exercise. This would provide sports scientists with an optimal duration between the exercise bout and the main performance.

CONCLUSIONS

While the effects and mechanisms of maximal and supramaximal exercise efforts on visual performance are not yet known, the improvements in visual performance following both treatments in this study demonstrates a direct link between these modes of exercise and excitatory effects on the corticospinal motor system, which in turn improves oculomotor system (Connell *et al*., 2017). Further, it appears that peripheral exercise-induced fatigue may not play a role in affecting visual performance under normal conditions. In this regard, it may be that the magnitude of sensory feedback or cognitive involvement of a sport or exercise modality may be more critical to alterations in visual performance.

As such, rather than simply continuing to accept that exercise-induced fatigue is inherently negative to performance, these findings should direct contemporary sports scientists to challenge old dogmas of "fatigue's" role in athletic performance uncritically. Hence, athletes, coaches and conditioning specialists need to consider all visual skills or tasks that an athlete must possess in their given sport and how the bioenergetics of that sport affect the said visual skills. More importantly, this study may provide insight on the necessity of specific exercise modalities for use in warm-ups when training visual skills or when visual skills form an integral part of athletic performance. These findings will assist athletes, coaches and conditioning specialists to understand how exercise-induced fatigue or all-out exercise, and specifically the different types of metabolic fatigue, affects vision in their sporting discipline. This will also allow them to actively develop strategies to take advantage of or mitigate the effects of all-out exercise or exercise-induced fatigue on their athletes' performance.

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APPENDIX A: ARTICLE ONE - Shaw, B.S., Breukelman, G.J., Millard, L. & Shaw, I. Effects of a maximal cycling all-out test on visual task performance. *Journal of Sports Science and Medicine*. Submitted.

Article submission

To hakan@uludag.edu.tr

Cc hakangur2001@gmail.com

Abstract.docx 20 KB	Article With Author det... 46 KB	Author Details.docx 20 KB	Biography of authors.d... 20 KB	ChecklistforAuthorsSub... 38 KB	CopyrightTransferState... 43 KB
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Good day,

Kindly find attached article for submission to JSSM. I trust all of the documentation is in order. Please let me know if you need anything else.

Kind Regards

APPENDIX B: ARTICLE TWO - Shaw, B.S., Breukelman, G.J., Millard, L. & Shaw, I. (2022). Effect of a prolonged maximal bout of exercise on visual performance. *Asian Journal of Sports Medicine*. Accepted.

List Of Primary Accepted, Needs Payment

10

Shows 1 to 1 of 1

#	ID	Title	Author	Submitted Date	Accepted Date	Review (Completed/Total)
1	119406	Effect of a prolonged maximal bout of exercise on visual performance [Revision 1]	Blind Author	2021-09-07 07:15:28	2021-11-19 10:57:23	2 / 2

APPENDIX C: ARTICLE THREE - Shaw, B.S., Breukelman, G.J., Millard, L. & Shaw, I. Short- versus long-duration maximal exercise effects on sport vision performance. *PLoS One*. Submitted.

Submissions Being Processed for Author Lourens Millard, Ph.D

Page: 1 of 1 (1 total submissions) Display 10 results per page.

Action	Manuscript Number	Title	Initial Date Submitted	Current Status
View Submission Send E-mail	PONE-D-21-29246	Short- versus long-duration maximal exercise effects on sport vision performance	Sep 9 2021 9:48AM	Under Review

Page: 1 of 1 (1 total submissions) Display 10 results per page.

<< Author Main Menu

APPENDIX D: ETHICAL CLEARANCE CERTIFICATE

UNIVERSITY OF ZULULAND
RESEARCH ETHICS COMMITTEE
(Reg No: UZREC 171110-030)

RESEARCH & INNOVATION
Website: http://www.unizulu.ac.za
Private Bag X1001
KwaDlangezwa 3886
Tel: 035 902 6273
Email: ViljoenD@unizulu.ac.za

ETHICAL CLEARANCE CERTIFICATE

Certificate Number	**UZREC 171110-030 PGD 2021/27**						
Project Title	**Comparison of anaerobic and aerobic fatigue on visual skills**						
Principal Researcher/ Investigator	B.S Shaw						
Supervisor and Co-supervisor	Dr G.J Breukelman			Mr L Millard			
Department	Human Movement Science						
Faculty	Science and Agriculture						
Type of Risk	Low Risk – Desktop, field work or laboratory						
Nature of Project	Honours/4th Year		Master's		**Doctoral**	x	Departmental

The University of Zululand's Research Ethics Committee (UZREC) hereby gives ethical approval in respect of the undertakings contained in the above-mentioned project. The Researcher may therefore commence with data collection as from the date of this Certificate, using the certificate number indicated above.

Special conditions:

(1) This certificate is valid for 1 year from the date of issue.
(2) Principal researcher must provide an annual report to the UZREC in the prescribed format [due date-29 March 2022]
(3) Principal researcher must submit a report at the end of project in respect of ethical compliance.
(4) The UZREC must be informed immediately of any material change in the conditions or undertakings mentioned in the documents that were presented to the meeting.

The UZREC wishes the researcher well in conducting research.

pp

Professor Mashupye R. Kgaphola
University Research Ethics Committee
Deputy Vice-Chancellor: Research & Innovation

29 March 2021

CHAIRPERSON
UNIVERSITY OF ZULULAND RESEARCH ETHICS COMMITTEE (UZREC)
REG NO: UZREC 171110-30
24 -03-
RESEARCH & INNOVATION OFFICE

APPENDIX E: INFORMED CONSENT FORM

INFORMED CONSENT DECLARATION

(Participant)

Project Title: Comparison of Anaerobic and Aerobic Fatigue on Visual Skills.

Prof. Brandon S. Shaw from the Department of Human Movement Science, University of Zululand has requested my permission to participate in the above-mentioned research project.

The nature and the purpose of the research project, and of this informed consent declaration have been explained to me in a language that I understand.

I am aware that:

1. The purpose of the research project is to discern if metabolic fatigue affects visual skill, and to determine which aspect of visual skill is most affected by which type of metabolic fatigue.

2. The University of Zululand has given ethical clearance to this research project and I have seen/ may request to see the clearance certificate.

3. By participating in this research project I will be contributing towards the field of sport science in determining if metabolic fatigue affects visual skill. This will allow athletes, coaches and conditioning specialists to actively develop strategies to mitigate the effects of exercise-induced fatigue on their or their athletes' performance.

4. I will participate in the project by completing a visual skills test battery and two exercise tests (i.e. anaerobic Wingate 30-second test and aerobic treadmill protocol).

5. My participation is entirely voluntary and should I at any stage wish to withdraw from participating further, I may do so without any negative consequences.

6. I will not be compensated for participating in the research.

7. The researcher intends publishing the research results in the form of journal articles. However, confidentiality and anonymity of records will be maintained and that my name and identity will not be revealed to anyone who has not been involved in the conduct of the research.

8. I will receive feedback regarding the results obtained during the study.

9. Any further questions that I might have concerning the research or my participation will be answered by Prof. Brandon S. Shaw via email shawb@unizulu.ac.za or telephonically 035-902-6847/6391.

10. By signing this informed consent declaration, I am not waiving any legal claims, rights or remedies.

11. A copy of this informed consent declaration will be given to me, and the original will be kept on record.

I, ……………………………………………………………………….. have read the above information / confirm that the above information has been explained to me in a language that I understand and I am aware of this document's contents. I have asked all questions that I wished to ask and these have been answered to my satisfaction. I fully understand what is expected of me during the research.

I have not been pressurised in any way and I voluntarily agree to participate in the above-mentioned project.

…………………………………. ………………………………….

Participant's signature **Date**

RESEARCHER'S DECLARATION

I, Brandon S. Shaw declare that:

- I explained the information in this document to

  ……………………………………………………………..……………………..………..

- requested him/her to ask questions if anything was unclear and I have answered them as best I can.
- I am satisfied that s/he sufficiently understands all aspects of the research so as to make an informed decision on whether or not to participate.
- The conversation took place in isiZulu / English
- I did not use an interpreter

…………………………………. …………………………………

Researcher's signature **Date**

APPENDIX F: LANGUAGE EDITOR LETTER

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18 November 2021

To whom it may concern,

RE: EDITING OF PHD SUBMISSION ON BEHALF OF MR. B SHAW

This letter serves to confirm that Mr Brandon Stuwart Shaw of the Department of Human Movement Science, Faculty of Science, Agriculture and Engineering at the University of Zululand, did submit a full proposed PHD submission to myself for editing and proofreading.

The editing process has been completed and the full document was returned to Mr Shaw, with suggested changes to be confirmed by Mr Shaw himself.

For any further queries, please feel free to contact me directly on the details above.

Kind regards,

Megan Erasmus Gauld