A Behavioural And Brain Science Perspective On Decision-making In Sport

Beth Louise Parkin

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Institute of Cognitive Neuroscience, UCL

Declaration

I confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Signed **Date**

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Abbreviations

ACC – Anterior Cingulate Cortex

ANOVA – Analysis of Variances

BART –Balloon Analogue Risk Task

CGT- Cambridge Gambling Task

cm- Centimeter

DLPFC – Dorsolateral Prefrontal Cortex

EMG – Electromyography

FDI - First Dorsal Interosseous

fMRI – Functional Magnetic Resonance Imaging

hf-tRNS – High Frequency Transcranial Random Noise Stimulation

HZ- Hertz

LTD- Long Term Depression

LTP – Long Term Potentiation

mA – Milliamp

MEP – Motor Evoked Potential

ms – Millisecond

NMDA- N-methyl-D-aspartate

OFC – Orbitofrontal Cortex

PC – Parietal Cortex

SD – Standard Deviation

SEM – Standard Error of the Mean

SSRT- Stop Signal Reaction Time

tACS - Transcranial Alternating Current

TBS – Theta Burst Stimulation

tDCS – Transcranial Direct Current Stimulation

tES – Transcranial Electrical Stimulation

TMS – Transcranial Magnetic Stimulation

tRNS – Transcranial Random Noise Stimulation

Publications

Parkin, B. L., Warriner, K., Walsh, V (in press). Gunslingers, Poker Players and Chickens 1: Decision Making under Physical Performance Pressure in Elite Athletes. Progress in Brain Research.

Parkin, B. L., & Walsh, V (in press). Gunslingers, Poker Players and Chickens 2: Decision Making under Physical Performance Pressure in Semi-elite Athletes. Progress in Brain Research.

Parkin, B. L., & Walsh, V (in press). Gunslingers, Poker Players and Chickens 3: Decision Making under Mental Performance Pressure in Junior-Elite Athletes. Progress in Brain Research

Parkin, B. L., Walsh V (Under review) Do the Physiological Effects of tDCS Transfer to Bilateral Montages at 1mA and 2mA. Neuropsychologia.

Some of the ideas in this work are also outlined in: Parkin, B. L., Ekhtiari, H., & Walsh, V (2015). Non-invasive human brain stimulation in cognitive neuroscience: a primer. *Neuron*, *87*(5), 932-945.

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1. Abstract

The elite athlete routinely performs impressive cognitive feats. Not only do they undertake complex decision-making seemingly intuitively, they do so under conditions of intense pressure, limited time and restricted resources. Decision-making refers to the cognitive processes that underpin the selection of one course of action from several alternatives (Reason, 1990); it is essential for high-quality performance in sport (Farrow & Raab, 2008; Jordet & Hartman, 2008; Paserman, 2007). Decision-making is the focus of the following thesis. In particular, undertaken in the Applied Cognitive Neuroscience Laboratory at UCL, this thesis has the translational goal of understanding and increasing insight into the decision-making of elite athletes. It focuses on how psychological knowledge can be of use in the 'real world', as well as aiming to learn about behaviour outside of a laboratory; this is undertaken by focusing on two areas. Initially the utility of transcranial electrical stimulation (tES) as a tool for modifying decision-making is explored to assess the potential for use in decision-making training in sport. The thesis then moves on to examining the influence that physical and mental performance pressures have on decision-making across different developmental stages of elite athlete expertise.

Chapter 2 provides a review of the background literature of topics relating to this thesis. **Chapter 3** assesses the potential application of tES techniques as a tool for enhancing the cognitive abilities underlying peak performance in athletes. It does so by examining the reliability of claims that transcranial direct current stimulation (tDCS) influences decision-making via direct replication of a key study in this field. In particular the seminal work of Fecteau, Pascual-leone, et al., (2007) who reported bilateral DLPFC tDCS to decrease risky decision-making on the Balloon Analogue Risk Task (BART). Despite closely reproducing the methodology, this chapter did not replicate the original findings of Fecteau, Pascual-leone, et al., (2007), and there was no evidence that tDCS affected decision-making. Consequently, in **Chapter 4**, the mechanistic basis of this failure to replicate was explored; in particular, the physiological effects of tDCS on brain excitability (measured via changes to the motor evoked potential (MEP) amplitude) were examined using the parameters applied in chapter 2 (i.e.,

bilateral electrode placement and increased stimulation intensity). Our knowledge of tDCS is based on work that has previously applied stimulation using a unilateral M1/contralateral orbit montage at 1mA. In experiment 1, using these parameters, the classical effects of anodal-excitation/cathodal-inhibition were reported. Experiments 2 and 3 revealed that the anodal-excitation/cathodal-inhibition effects of tDCS were not present when electrodes comprised a bilateral (right M1/left M1) montage for stimulation intensities of 1 and 2mA. Not only were these parameters used in chapter 2, they are common in the cognitive neuromodulation field and, thus, these results have wider consequences. This finding undermined tDCS as a potential candidate for application in elite athletes and, in **Chapter 5** the eligibility of transcranial random noise stimulation (tRNS) is assessed as an alternative approach. In line with previous work, the physiological underpinnings of tRNS were examined to assess the assumptions of excitation that underpin the rationale and justification of results of studies in this area. Again, parameters used in the application of this technique differ from those used to establish the original effects of cortical excitation (unilateral M1/contralateral orbit montage, 10 minutes). The results of this chapter reveal that the excitatory effects of tRNS do not withstand deviation from these parameters. More specifically, when increasing stimulation durations from 10 to 20 minutes (Experiment 1), and when using bilateral electrode arrays (Experiment 2), increased cortical excitation were not present. Together, the findings from these chapters led to the conclusion that tES methods are not robust enough to proceed with in investigations in elite athletes.

In the second part of the thesis, the original goal of exploring decision-making in elite sport is returned to, with the aim of providing useful insights for applied populations. Much of the previous work in this area has largely ignored the highly stressful context in which athletes operate. In **Chapters 6, 7 and 8**, the influence that performance pressure has on decision-making is examined across three age groups, spanning the developmental trajectory of elite sport. Three categories of decision-making abilities were investigated, including fast reactive responses, as well as decision-making under risk and under uncertainty.

In **Chapter 6** the influence of physical exhaustion (completion of a maximal exertion exercise protocol) on decision-making was examined in world-class elite athletes (including six Olympic medal winners; mean age = 28). The results showed that, under physical pressure, indicators of decision-making were generally robust. Under physical pressure, elite athletes showed faster response times to perceptual stimuli. Physical pressure was also found to increase risk taking for decisions under risk, but did not influence decision-making under uncertainty. Moreover, elite athletes retained the ability to make appropriate bets according to probability outcomes, suggesting a possible calculated shift towards risk taking. **Chapter 7** employed a similar protocol in a sample of semi-elite athletes (mean age = 20), who were enrolled on a national talent development program and were undergoing training for possible Olympic competition in four-eight years. Under physical pressure, the decision-making of semi-elite athletes showed an increase shift towards increased risk taking - for both decisions under risk and uncertainty. Additionally, these athletes showed a reduced ability to optimally adjust betting behaviour according to reward and loss contingencies. Fast reactive responses to perceptual stimuli and response inhibition did not change as a result of physical pressure in this sample.

In **Chapter 8,** the influence of mental pressure (dual auditory memory task) was examined in elite junior athletes (mean age = 13) who are at the earliest stage of entry to elite sport, having undergone initial selection for inclusion on national talent development programs. For decision-making under risk, there was an interaction of mental pressure and gender, whereby under pressure males showed increased - and females decreased - risk-taking. There was no effect of mental pressure on decision-making under uncertainty. Moreover, under mental pressure, there were slower reaction times to perceptual stimuli. Mental pressure may act to impair tasks that have a high requirement for working memory resources.

Together, the findings from these chapters highlight that work undertaken in non-elite athletes may not transfer to elite athletes and that there are differences in decision-making capabilities within sub-categories of elite athletes. The findings also highlight a practical point: that of the limitations of statistical approaches based on group averages in the elite sporting environment, where an understanding of the individual is paramount. In the application of this work in a sport setting, the use of individualized profiling in feedback sessions is highlighted. Moreover, the different types of decision-making assessed in the study were used to form a taxonomy which sports professionals could use to conceptualize and discuss decision-making. This was done via the use of real-world analogies to develop a common accessible language to describe key concepts. The importance of embedding this work within the sporting culture is also highlighted.

Collectively, the data in this thesis has furthered our understanding of how psychology and cognitive neuroscience can be applied in elite sport to increase insights into decision-making. Moreover, the findings had unintended implications of advancing our understanding of tES, highlighting that parameters used in the application of these techniques should be based on the parameters used to establish the physiological effects.

2. Literature Review

2.1. Defining Decision-Making

Decision-making can be formally defined as the mental processes that underpin the selection of one course of action from various alternatives (Reason, 1990). Thus a decision-making situation presents the individual with more than one possible outcome to consider whenever there is uncertainty regarding the consequences of these outcomes. A decision maker forms expectations relating to these different choices and evaluates them according to judgments and values (Hastie & Dawes, 2010). The study of decision-making in cognitive science examines the ways in which humans form and integrate these expectations and subjective evaluations (Hastie & Dawes, 2010). Indeed, common processes are thought to underpin decision-making across the wide array of different domains in which they occur (Hardman & Hardman, 2009).

2.1.1. Types of Decision-making

The degrees to which different cognitive processes contribute to a decision depend on the characteristics of the decision in question. One axis by which decisions can be differentiated is according to how much information about an expected outcome is available (Starcke & Brand, 2012). When an outcome is not guaranteed a decision is said to involve risk (Gigerenzer, 2014). At one end of this continuum is certainty, when information is most abundant. Here only one outcome could arise from a particular choice (Starcke & Brand, 2012). As information relating to the outcome of the decision diminishes, the categorization of decision type moves from decision-making under risk to decision-making under uncertainty (Starcke & Brand, 2012; Volz & Gigerenzer, 2012). Decision-making under risk is where there is explicit information (or this can be calculated) about both the decision outcomes and their probabilities of occurrence (Gigerenzer, 2014). Thus in these situations it is possible to deduce optimal responses via cognitive calculations (Volz & Gigerenzer, 2012). A real world example of decision-making under risk is the decision to enter a raffle. When buying a ticket one can either win or lose, with the precise odds of winning calculated as 1/ the number of tickets sold (Hardman & Hardman, 2009). Outside of the laboratory these types of decisions are infrequent and usually occur in gambling scenarios (Volz & Gigerenzer, 2012). Decision-making under uncertainty, on the other hand, refers to situations where decision outcomes are known but the probabilities of their occurrence are unknown or unknowable (Gigerenzer, 2014). In these situations one has to judge advantageous outcomes through trial and error learning. In real life as the future is almost always uncertain, these types of decision scenarios are common (Volz & Gigerenzer, 2012). Real world examples include deciding where to live, whether to attend university or whom to marry (Hardman & Hardman, 2009).

Decision-making is explored in the laboratory with the use of tasks that attempt to simulate yet simplify these distinct types of decision-making. These tasks provide measures of decision-making behavior, with a particular focus on assessing an individual's preference for risk taking. Risk taking can be defined both in terms of the variance of reward outcomes, a definition stemming from economics, and in terms of exposure to negative outcomes, a definition stemming from clinical psychology (Schonberg, Fox, & Poldrack, 2011). This latter definition is in keeping with the lay persons' perception of risk, as demonstrated by a psychometric study exploring attitudes underlying this construct (Slovic, 1997). Perceptions of risk were shown to involve a *dread* component representing the potential of disastrous consequences and a lack of control, as well as an *unknown* component relating to the unobservable costs risky behaviours may entail (Slovic, 1997). Examples of real world risk taking are outlined in the Domain Specific Risk Attitude Scale (Weber, Blais, & Betz, 2002), high-risk activities include extreme sports, smoking, illegal drug use, cheating on a tax return and unprotected sex.

2.2. Theories of Decision-making

There are a number of key theories relating to how we make decisions. Those outlined in the following section include Dual Process Thinking (Evans & Stanovich, 2013; Kahneman, 2013), Heuristics (Gigerenzer & Gaissmaier, 2011) and Prospect Theory (Kahneman & Tversky, 1979) .

2.2.1. Dual Process Thinking

The dual process theories propose that there are two systems or modes of thinking which we use to make decisions, intuition (System 1) and deliberation (System 2) (Newell, Lagnado, & Shanks, 2015). It is proposed that these two systems broadly differentiate the processes underlying decision-making under risk and under uncertainty (Volz & Gigerenzer, 2012). The characteristics attributed to these two systems, across a number of theories, are outlined in Table 2.1. The intuitive System 1 is proposed to be automatic, responsive and thought to operate outside of rational control. It permits fast decision-making that does not require working memory resources, via the use of heuristics, or simple rules of thumb, that can be applied generically for quick effect. System 1 is thought responsible for processing information relating to gains and losses of decision outcomes (Evans & Stanovich, 2013; Kahneman, 2013).

The deliberative System 2, on the other hand, is purported to be slow, rational and effortful and is responsible for higher order cognitions or analytical approaches to decision-making (Evans & Stanovich, 2013; Kahneman, 2013). System 2 is particularly attributed to deliberating on information relating to probability outcomes, as well as the inhibition of unwanted behavioural impulses (Starcke & Brand, 2012). Applying the ‘head-heart’ distinction of human reasoning System 1 would be the ‘heart’ and System 2 the ‘head’ (Evans & Stanovich, 2013; Kahneman, 2013).

System 1 (Intuitive)	*System 2 (Deliberative)*
Working memory independent	Working memory dependent
Autonomous	Mental simulation
Fast	Slow
High capacity	Capacity limited
Non- conscious	Conscious
Contextualized	Abstract
Automatic	Controlled
Associative	Rule based
Independent of cognitive ability	Correlated with cognitive ability

Table 2.1: A list of the characteristics attributed of System 1 and System 2 thinking across different theories, taken from Newell et al., (2015).

Volz & Gigerenzer (2012) proposed that System 1 and System 2 thinking are tools for different types of decision-making (Volz & Gigerenzer 2012). In particular, for decision-making under risk, the rational analytical processes of System 2 are favoured given there is available information for computations to be based upon. Conversely, decision-making under uncertainty requires the skills of the intuitive System 1. In these types of decisions optimal solutions can not be calculated from conscious deliberation (Volz & Gigerenzer 2012) (**Figure 2.1**). In addition, it has been proposed that there are a number of factors that may bias the mode of processing used for decision-making. For example, the intuitive System 1 is thought to take precedence under high cognitive load, as these conditions consume the processing resources of the deliberative System 2. In addition there is preference for the intuitive System 1 under time pressure, asunder these conditions the slow effortful cognitions of the deliberative System 2 are insufficient (Gigerenzer & Gaissmaier, 2011).

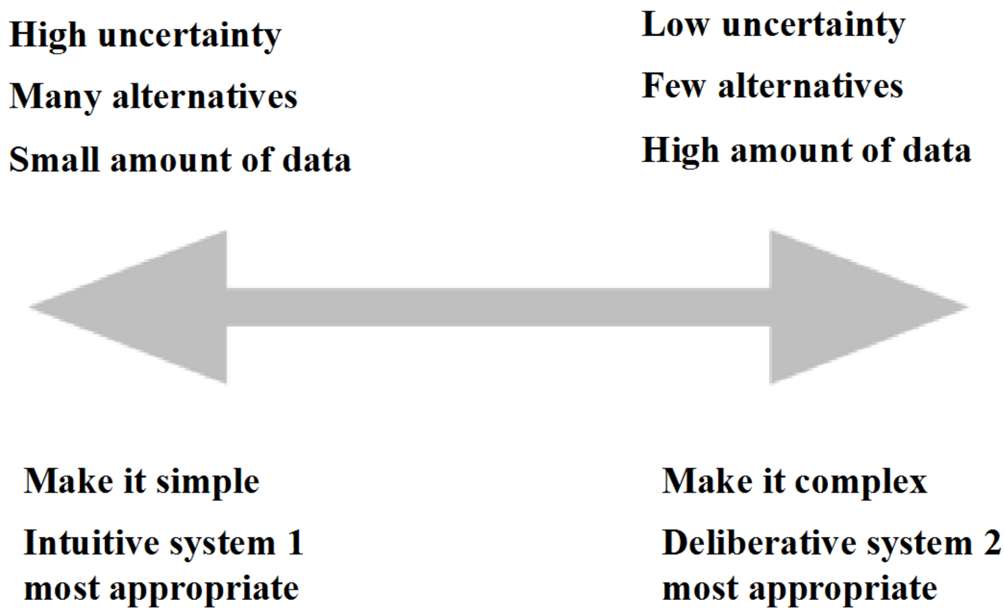


Figure 2.1: Dual-process thinking of decision-making; For decision-making under uncertainty when there is high ambiguity, deliberative thinking is of little value and the intuitive System 1 is most appropriate. For decision-making under risk, when there is low uncertainty, the deliberate System 2 is most appropriate. (figure taken from Gigerenzer, 2014).

Schiebener & Brand's (2015) description of the neuropsychological processes responsible for decision-making under risk is useful in describing the attributes of the deliberative System 2. The component cognitive processes outlined include executive function, working memory, numerical abilities and reasoning. Executive functioning and working memory are thought to allow for categorization of information relating to decision outcomes, the development and application of strategies and the integration of feedback. Numerical abilities, including knowledge about numbers and ratios allow the deduction and processing of outcome probabilities. While reasoning skills allow one to weigh up and deduce favourable outcomes among several alternatives (Schiebener & Brand 2015).

These cognitive abilities are thought to be involved in decision-making under risk as they are disrupted by dual task performance (Schiebener & Brand 2015). Dual task performance requires the participants to perform two tasks simultaneously; it follows the logic that if two tasks require the same processing resources when performed concurrently performance decrements will result. For example, using this method, Starcke, Pawlikowski, & Wolf, (2011) reported that high working memory load (2-back working memory task) impaired performance on the Game of Dice task (Brand, Fujiwara, Borsutzky, & Kalbe, 2005). Participants were found to adopt a suboptimal risky strategy, thus implicating working memory in the performance of decision-making under risk. In comparison, decision-making under uncertainty has been shown to be less susceptible to dual task working memory performance. For example Turnbull, Evans, Bunce, & Carzolio, (2005) report that increased working memory load (random number generation) did not impair performance of the Iowa Gambling Task (Bechara, Tranel, & Damasio, 2000). Thus it was concluded that decision-making under uncertainty may not require working memory resources to the same extent as decision-making under risk (Schiebener & Brand 2015). In addition to these deliberative processes Schiebener & Brand (2015) propose that for decision-making under risk the evaluation of options requires the processing of intuitive System 1, and for optimal outcomes to be deduced the integration of both systems are required.

There are a number of theories outlining how these systems are recruited or how they interact. The two main proposals are the default-interventionist approach or parallel processing (Evans, 2007). The default-interventionist approach suggests that the intuitive System 1 is the default mode of processing making initial judgments which get subsequently adjusted for by the deliberative System 2 (Newell et al., 2015; Cobos et al., 2003). The parallel processing account on the other hand proposes that these systems are occurring simultaneously (Newell et al., 2015). Both proposals provide inadequate accounts (Newell et al., 2015; Neys & Glumicic, 2008). For example, for System 2 to be brought on board appropriately as proposed by the default interventionist model, some of System 2 processes would need to be ongoing. Moreover, parallel processing of System 1 and System 2, would deem the slow computations of System 2 redundant and cognitively costly in situations where both modes of thinking produced the same solution (Newell et al., 2015).

2.2.2. Heuristics

For decision-making under uncertainty, it is proposed that the intuitive System 1 applies heuristic processing. Heuristics are mental short cuts or ‘rules of thumb’ that allow for quick and efficient decision-making (Gigerenzer & Gaissmaier, 2011). They operate by ignoring parts of the information available in a given setting and their simplicity means that they can be easily learnt and applied to novel situations. Heuristics are thought to rely on the ‘adaptive toolbox’ a term used to describe the collection of mental abilities that one has for constructing, selecting and applying heuristics in a given situation (Gigerenzer & Gaissmaier, 2011). This includes recognition memory, frequency monitoring, object tracking and an ability to imitate, as well as the components that heuristics are constructed from, including search, stopping and decision rules (Gigerenzer, 2014; Gigerenzer & Gaissmaier, 2011).

Gigerenzer & Gaissmaier (2011) put forward the idea that heuristics are evolutionarily adaptive, having evolved to meet the demands of an uncertain environment (Volz & Gigerenzer, 2012). The success of heuristic decision-making is, therefore, dependent on whether it fits a given situation. Indeed Gigerenzer’s notion of ‘ecological rationality’ describes that heuristic decision-making is neither positive or negative, but rather suited or not well suited to a given environment (Gigerenzer & Gaissmaier, 2011). Thus a person’s intelligence is reflected in assessing the suitability of a particular heuristic to a given environment (Volz & Gigerenzer, 2012). This is in contrast to the dominant view that the deliberative System 2 is superior, as it does not require the effort-accuracy trade off characteristic of heuristic processing (Kahneman, 2013).

Examples of common heuristics include the recognition-heuristic and the take-the-best-heuristic (for a review of these and others see Gigerenzer & Gaissmaier, 2011). The recognition heuristic proposes that when faced with a choice of two alternatives, one of which is familiar and the other which is not, the familiar option is given a higher preference (Goldstein & Gigerenzer, 2002). When the recognition heuristic cannot be applied, for example, if both choice options are familiar, a search for value clues is thought to occur. The take-the-best heuristic states that instead of systematically weighing up various indicators of value for the different choice options, a decision is based on one attribute only (Hardman

& Hardman, 2009). The take-the-best heuristic proposes that the decision options are searched according to the cue with the highest validity first, if one option has a positive attribute and the others do not, the search is stopped and the decision made (Hardman & Hardman, 2009).

2.2.3. Prospect Theory

An area of work that also views decision-making as involving the use of heuristics is Prospect Theory (Kahneman, 2013; Kahneman & Tversky, 1979). This theory was developed following the observation that individuals do not act as rational decision makers and fail to choose outcomes that maximize expected utility (as stipulated by Expected Utility Theory). This theory highlights the 'systematic errors' that occur in human decision-making due to the application of heuristics (Hardman & Hardman, 2009; Kahneman, 2013).

Prospect Theory states that there are two phases of decision-making, the editing phase and the subjective evaluation stage. In the editing phase, an internal representation of the decision is constructed. Information relating to the decision is encoded, transformed and simplified according to a number of heuristics. These processes include; framing potential gains and losses relative to a reference point, as well as simplifying the choice outcomes by rounding up or down and eliminating unwanted options (Kahneman, 2003; Newell et al., 2015). The subjective evaluation phase is undertaken on the edited information, and involves computing utility values for outcomes. The alternative with the highest utility is then chosen (Hardman & Hardman, 2009; Kahneman, 2013).

In Prospect Theory the way in which information is edited is critical to the outcome of the decision, and it is noted that application of heuristics at this stage bias decision-making. One observation is the influence of how a decision is framed in terms of gains and losses. In particular people tend to make risker decisions in relation to losses, in comparison to gains, which is known as loss aversion (Kahneman, 2013; Kahneman & Tversky, 1979). This theory is well regarded as one of the most prominent accounts of decision-making under risk (Newell et al., 2015), and has given rise to the development of a new discipline - behavioural economics (Hardman & Hardman, 2009). The theory however is lacking detailed psychological explanations for the concepts it proposes (Newell et al., 2015).

2.3. The Brain Regions Underlying Decision-making

The decision-making under risk and uncertainty involves a distributed network of brain regions including frontal, parietal, and limbic structures (**Figure 2.2**). There are three main frontal regions implicated, including the Orbitofrontal Cortex (OFC), Dorsolateral Prefrontal Cortex (DLPFC) and the Anterior Cingulate Cortex (ACC). Key subcortical regions include the amygdala, striatum (comprising the Nucleus Accumbens, Nucleus Caudate and Putamen) and the insula (Rosenbloom & Schmahmann, 2012; Starcke & Brand, 2012). In the next section the functions of these structures in relation to decision-making will be described. Following this, the development of these regions and their contribution to decision-making during the first and second decade of life will be examined.

2.3.1. OFC

Decision-making literature has paid particular attention to the OFC, a region located on the ventral surface of the prefrontal cortex (Rosenbloom & Schmahmann, 2012). This area has been implicated in stimulus reward learning and, as such, its function has been likened to a 'working memory for emotion' (Wallis, 2007). It is thought to aid decision-making by representing the reward values of different outcomes; information that is needed to guide behaviour (Wallis, 2007). Thus the OFC is often credited with intuitive, emotional aspects of decision-making (Starcke & Brand, 2012). Indeed, patients with OFC lesions present impaired decision-making despite retaining intact executive functioning (Rosenbloom & Schmahmann, 2012).

In particular these patients have been reported to perform poorly on the Cambridge Gambling Task (CGT; Rogers et al., 1999). On this task participants have to decide how many points to gamble on decisions with differing odds, patients with OFC damage were found to show generically risky decisions whereby they opt for high gambles regardless of the odds of winning (Clark, Bechara, Damasio, & Aitken, 2008). This observation led to the proposal that the

OFC may be responsible for biasing individuals towards safe options (Clark et al., 2008).

Similar results have also been reported in patients with OFC damage on the Iowa Gambling Task (Bechara, Damasio, & Tranel, 2005; Wallis, 2007). The Iowa Gambling Task requires participants to learn the reward contingencies of different decks of cards. Unlike healthy controls, patients with OFC lesions fail to learn advantageous strategies and persist in selecting risky high reward, high loss cards that have a low net gain (Bechara, Tranel, & Damasio, 2000). Moreover these patients do not show anticipatory skin conductance responses to risky cards, yet retain intact autonomic arousal for rewards and loses. These anticipatory physiological responses, known as somatic markers, are proposed as the mechanism by which the OFC may guide decision-making via hunches or gut feelings (Bechara et al., 2000; Starcke & Brand, 2012). However, this hypothesis has been criticized, for example Fellows & Farah (2005) report that the performance deficits of OFC patients may instead be due to impairments in reversal learning, as these patients do not show behavioural impairments if losses occurred when risky decks were first chosen (Wallis, 2007).

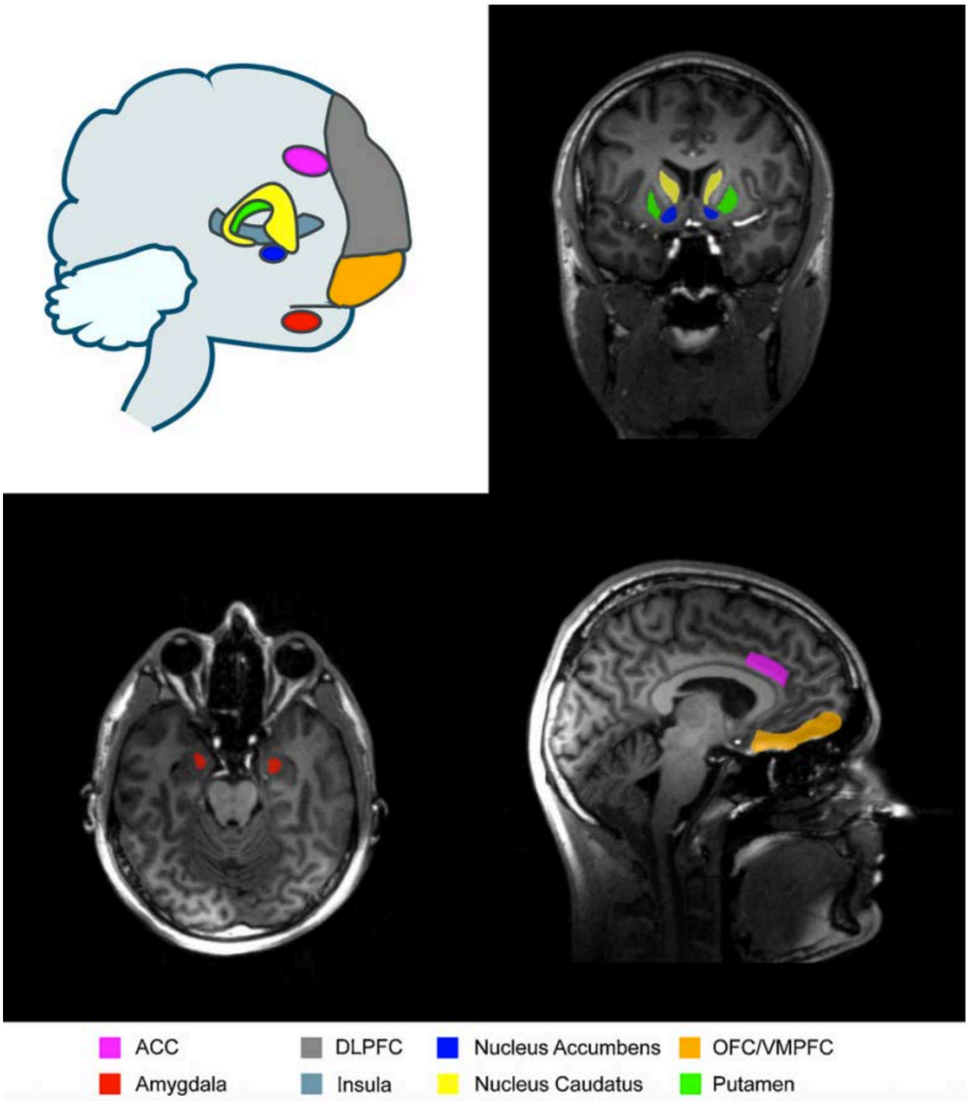


Figure 2.2: The anatomical location of brain regions implicated in decision-making. Pink = ACC; grey = DLPFC; orange = OFC; blue = Nucleus Accumbens; red = Amygdala; light blue= Insula; yellow = Nucleus Caudatus; green = Putamen (figure taken from Starcke & Brand, 2012).

2.3.2. ACC

The ACC, located in the medial frontal lobe, has been implicated in decision-making with a high degree of ambiguity. In particular decisions which present conflicting information (i.e. those which involve risk taking where there is a competing desire to win but fear of loss), or those that require selection between equally acceptable courses of action (Rosenbloom & Schmahmann, 2012). It has also been proposed that the ACC plays a role in monitoring response conflict, whereby one has to override concurrent competing responses (Krawczyk, 2002).

In support of this ACC activation has been reported in response to incongruent trials on the Stroop task (where there is conflict between word name and ink colour) (MacLeod & MacDonald, 2000) and in response to flanker images that present opposing responses to those associated with the target (Botvinick, Cohen, & Carter, 2004). The ACC is also thought to play a role in evaluating decision outcomes, particularly when errors are made (Botvinick et al., 2004). In support of this, ACC activation has been reported following aversive outcomes including pain (Rainville, 2002) and social rejection (Eisenberger, Lieberman, & Williams, 2003). Drawing these findings together, it has been concluded that the ACC may play an important role in guiding decision-making towards efficient strategies (Rosenbloom & Schmahmann, 2012).

2.3.3. DLPFC

The DLPFC is another frontal region thought to serve particular aspects of decision-making. This area has been repeatedly linked to working memory and executive functioning (Krawczyk, 2002), and patients with DLPFC lesions present 'dysexecutive syndrome', which manifests as impairments in planning, inhibitory control, cognitive flexibility and working memory (Krawczyk, 2002; Rosenbloom & Schmahmann, 2012). Many of the aforementioned abilities are thought to be cognitive requirements for successful decision-making as they allow for the manipulation and deliberation of information relating to outcomes, and are also responsible for maintaining decision goals (Krawczyk, 2002). Thus the DLPFC is often credited with rational, calculated aspects of decision-making (Starcke & Brand, 2012). For example, during moral decision-making, increased activation in the DLPFC is reported in response to impersonal moral decisions, thought to be more rational, when compared with personal dilemmas thought to be more emotive (Greene, Nystrom, Engell, & Darley, 2004).

There have also been suggestions of functional lateralisation within the DLPFC (Krawczyk, 2002), with some studies implicating the right DLPFC in risky decision-making. In particular, patients with damage to the right DLPFC have shown an increased tendency to opt for choices with larger potential rewards but larger potential loses in comparison to healthy controls, which was not shown in patients with predominantly left DLPFC damage (Clark, Manes, Antoun, Sahakian, & Robbins, 2003). Similar findings have been reported with Transcranial Magnetic Stimulation (TMS). The transient disruption of the right, but not left, DLPFC has been reported to induce increased risk taking (Knoch, Gianotti, & Pascual-Leone, 2006). These findings led to the suggestion that the right DLPFC may play a particular role in the inhibitory control of superficially desirable decision options (Knoch et al., 2006).

2.3.4. Subcortical Structures

In decision-making the amygdala, striatum and insula are regions typically attributed to the processing of gains and losses in decision-making (Starcke & Brand, 2012). The striatum has been implicated in the processing of hedonic reward value, in particular associated with the lure of gains. Indeed increased activation in this area has been reported following the presentation of primary rewards such as food and money (Starcke & Brand, 2012). The amygdala, on the other hand, is a structure commonly associated with the processing of threat. Thus in decision-making it is implicated in the fear of loss or avoidance of punishment (Weller, Levin, Shiv, & Bechara, 2009). Lastly, the insula is a structure proposed to be integral to the processing of risk. Patients with lesions to this area show an indifference to expected value of decision outcomes involving losses and gains (Weller et al., 2009). This observed 'emotional bluntness towards risk' led to the proposal that this region interprets information relating to gains and losses in risky decision-making (Weller et al., 2009).

2.3.5. The Development of Decision-making

Marked changes in decision-making occur during development, which are thought to be underpinned by the asymmetrical developmental trajectories of the different brain regions underlying decision-making (Blakemore & Robbins, 2012). These changes include increases in risk taking with the onset of puberty which peaks in adolescence (Defoe, Dubas, & Figner, 2015). As such, adolescents show non-optimal decision-making in emotional contexts (i.e. on the emotional variant of the Columbia Card Task), yet similar decision-making as adults in contexts involving deliberative rational choices (i.e. the cognitive variant of the

Columbia Card Task) (Figner, Mackinlay, Wilkening, & Weber, 2009). In line with this adolescents also show heightened reward sensitivity during this time. For example studies examining stimulus reward learning tasks across different age groups (Cohen et al., 2010) revealed that adolescents (aged 14-19) were the only group that were quicker and more accurate in their selections for items with high reward values in comparison to items with low reward values. Moreover studies also report a linear increase in inhibitory processes across the second decade of life (Blakemore & Robbins, 2012).

It has been proposed that these changes are due to a period of 'developmental immaturity' in brain regions underlying decision-making (Blakemore & Robbins, 2012). In particular during adolescence the dopaminergic reward system is hypersensitive, yet the regions underpinning cognitive control are not yet fully developed (Blakemore & Robbins, 2012), predisposing these individuals to elevated risk taking behaviour. Indeed functional neuroimaging studies have shown increased activation in the striatum in response to both high and low risk gambles during adolescence (Galvan, Hare, Parra, & Penn, 2006). Moreover when performing tasks that involve inhibition, such as the Stroop task adolescents (aged 18-19) have been reported to show reduced activation in cognitive control regions, such as the DLPFC and middle Cingulate, in comparison to young adults (aged 23-25) (Veroude, Jolles, Croiset, & Krabbendam, 2013). Moreover structural brain development has been shown to not cease until the mid twenties, especially in frontal regions, the corpus callosum and association tracts (Pujol, Vendrell, & Junqué, 1993). Together these findings highlight that age is an important factor in understanding decision-making.

2.4. The Application of tES to Decision-Making

Building on our knowledge of the neural correlates of decision-making, studies using non-invasive brain stimulation have explored whether manipulating activity in these regions influences, or can lead to improvements in decision-making (for a review see Levasseur-Moreau & Fecteau, 2012). Techniques referred to as tES have been applied to this effect. TES refers to a set of methods that alter neuronal excitability by modulating the spontaneous firing rate of neurons (Nitsche et al., 2003; Nitsche & Paulus, 2001; Nitsche & Paulus, 2000). They do so by delivery of weak electrical currents via electrodes attached to the scalp (**Figure 2.3**a). In the following section two of these techniques, tDCS and tRNS are outlined. The application of tES to modulate decision-making is then discussed, as well as issues relating to the application of these techniques outside of the laboratory.

2.4.1. TDCS

TDCS is the most widely applied tES method (Bestmann, de Berker, & Bonaiuto, 2015). The technique passes a small direct current between the two electrodes, the current flows from the positively charged anode to the negatively charged cathode (Tergau & Paulus, 2008) (**Figure 2.3**b). The electrodes are often referred to as the active and the reference; the active electrode delivers stimulation to the brain region of interest, while the reference electrode is placed over an area deemed to be of no interest (Kuo & Nitsche, 2012). When the active electrode is the anode, the stimulation type is referred to as anodal, when the active electrode is the cathode the stimulation type is referred to as cathodal (Tergau & Paulus, 2008).

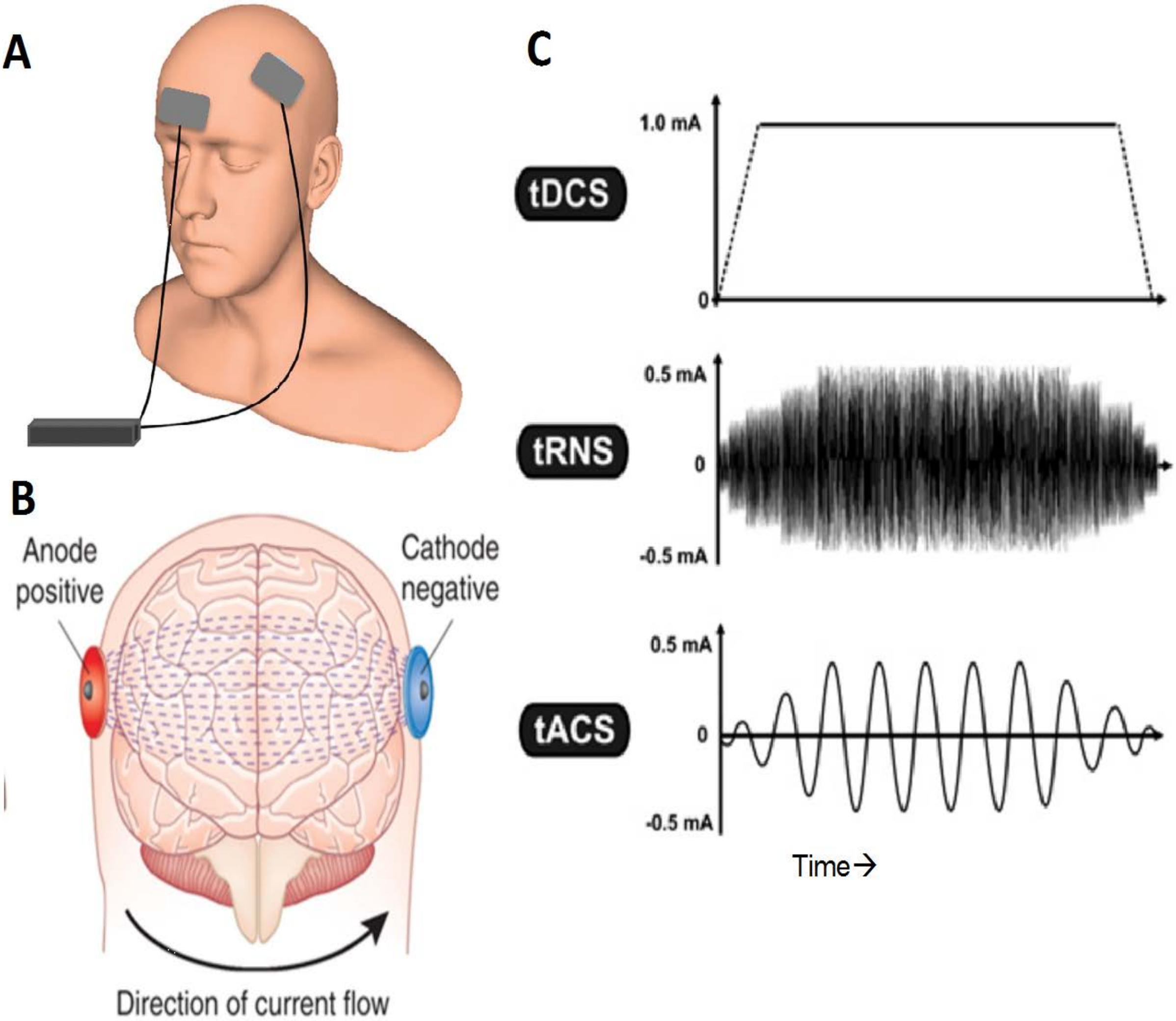


Figure 2.3: TES methods. A) TES delivers a small electrical current with a battery driven stimulator via electrodes attached to the scalp (figure taken from Dayan, Censor, Buch, & Sandrini, 2013) **B)** During tDCS a direct current flows from a positive anode electrode to a negative cathode electrode (figure taken from George & Aston-Jones, 2010). **C)** The waveform of different tES techniques; tDCS delivers a constant current, tRNS and tACS delivers an oscillating current. The horizontal axis represents time and the vertical axis stimulation intensity in milliamps (which can be adjusted by the researcher) (figure taken from Saiote, Polanía, Rosenberger, Paulus, & Antal, 2013)

The physiological basis of this technique is well documented through the study of motor cortex plasticity (for a summary see Stagg & Nitsche, 2011), and the effects have been shown to be polarity dependent. Work in this area has revealed anodal stimulation to exert an excitatory effect, and cathodal stimulation an inhibitory effect, via respective modulations in MEP amplitude, a global measure of corticospinal excitability (Nitsche & Paulus, 2001; Nitsche et al., 2003) (**Figure 2.4**a). These shifts in excitation and inhibition are thought to reflect sub threshold depolarization (anode) and hyperpolarization (cathode) of the neurons underlying the electrode. At a conceptual level, these changes in resting potentials make it more (anodal) or less (cathodal) likely that a neuron will produce an action potential (Bestmann et al., 2015; Kuo & Nitsche, 2012).

Pharmacological studies have allowed the physiological basis of the online effects, i.e. those that occur during stimulation, to be distinguished from the offline effects, i.e. those that persist after stimulation has ceased. The online effects of tDCS have been shown to result from modulations of membrane potentials, in particular by influencing the sodium and calcium ion channels (Stagg & Nitsche, 2011). For example the administration of drugs which block sodium and calcium channels abolish the online excitatory effects of anodal stimulation (Nitsche et al., 2003).

The offline effects of tDCS appear following stimulation protocols lasting 5 minutes. Stimulation durations of 5 minutes induce after effects that last for up to 15 minutes, while stimulation that lasts for 13 minutes induces after effects that persist for longer than one hour (Nitsche & Paulus, 2001; Nitsche et al., 2003). The offline after-effects of tDCS have been shown to arise from both modulations of membrane potentials, as well as changes at the synaptic level (Paulus et al., 2016). As seen with online effects, the after effects of tDCS are also abolished via the adminstration of drugs that block sodium and calcuim ion channels (Nitsche et al., 2003), implicating modulations in the membrane processes in the after-effects of tDCS. To explore the influence of synaptic processes studies administered N-methyl-D-aspartate (NMDA) antagonists, to inhibit this post-synaptic glutamate receptor. The online effects of tDCS were unchanged by blocking of the NMDA receptors, however the excitatory and inhibitory after-effects of tDCS were abolished (Liebetanz, Nitsche, Tergau, & Paulus, 2002; Nitsche et al., 2003). Therefore implicating the synaptic glutamatergic system in the offline that effects persist following the application of tDCS. There is some evidence that these offline effects may also arise from modifications of inhibitory GABAergic transmission, although this is less clear (Stagg & Nitsche, 2011). A notable study by Stagg et al (2009) examined the in-vivo neurotransmitter concentrations using MR spectroscopy of anodal and cathodal tDCS. Anodal was found to decrease the concentrations of inhibitory neurotransmitter GABA, while cathodal stimulation was shown to reduce both inhibitory neurotransmitter GABA and excitatory neurotransmitter glutamate. Lastly, work using paired pulse TMS protocols has further implicated changes in synaptic activity in the after effects of tDCS (Nitsche et al., 2005). In particular anodal tDCS has been reported to reduce intracortical inhibition and increase intracortical and I-wave facilitation (measures controlled by synaptic activity), these effects occur following, but not during, stimulation (Nitsche et al., 2005).

Together these findings suggest that the after-effects of tDCS arise from additional changes in synaptic processes, arising from Hebbian like Long Term Potentiation (LTP) and Long Term Depression (LTD) processes (Paulus et al., 2016; Stagg & Nitsche, 2011). Hebbian learning describes the changes that occur to neurons that fire in close succession that improve the efficiency by which one neuron causes the others to fire. The increase in NMDA activity associated with anodal tDCS is thought to lead to an increase in synaptic strength via LTP. The reduction in NMDA receptor activity and hyperpolarization of the post synaptic membrane following cathodal tDCS is thought to lead to a decrease in synaptic strength via LTD (Stagg & Nitsche, 2011).

2.4.2. TRNS

TRNS is the most novel of the tES approaches (Santarnecchi et al., 2015) (**Figure 2.4**c). Its potential application to cognitive neuromodulation has been demonstrated (Ambrus et al., 2011; Cappelletti et al., 2013; Romanska, Rezlescu, Susilo, Duchaine, & Banissy, 2015; Snowball et al., 2013) but at present is much less well developed than other approaches. TRNS applies an alternating current whereby the amplitude and frequency of oscillations are generated at random (**Figure 2.3**c). Frequencies from a spectrum of 0.1- 640 Hz can be selected, with narrower ranges routinely applied. The band 0.1-100Hz refers to low frequency tRNS (lf-tRNS) and 100-640 to high frequency tRNS (hf-tRNS) (Moreno-Duarte et al., 2014). Hf-tRNS have been shown to increase corticospinal excitability, as evidenced by modulation in the MEP amplitude, an increase which was not observed following lf-tRNS (Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). Although the mechanism of action is likely to differ (Paulus et al., 2016) the time course of MEP modulation is akin to that observed with anodal tDCS (Nitsche & Paulus, 2001). Indeed following hf-tRNS applied over the M1 for duration of ten minutes, sustained elevations in MEP amplitude after effects post stimulation were observed lasting ninety minutes (Terney et al., 2008) (**Figure 2.4**b). In contrast, the bidirectional nature of tRNS means that it does not have the polarity constraints of tDCS, and that these effects occur beneath both the active and reference electrode (Paulus, 2011).

The physiological mechanism of action by which tRNS exerts its effect is, at present, not clear (Paulus, 2011). One recent study by Chaieb, Antal, & Paulus (2015) explored the physiological basis of hf-tRNS. This revealed that excitatory after-effects arise partly from sodium channels since blocking the action of these channels via drugs have been found to reduce the efficacy of stimulation. Moreover, the after effects of tRNS were shown to be unaffected by blocking NMDA receptors, contrary to the synaptic modulation which underlies the after-effects of tDCS, suggesting that the two techniques rely on different mechanisms (Chaieb, Antal, & Paulus, 2015).

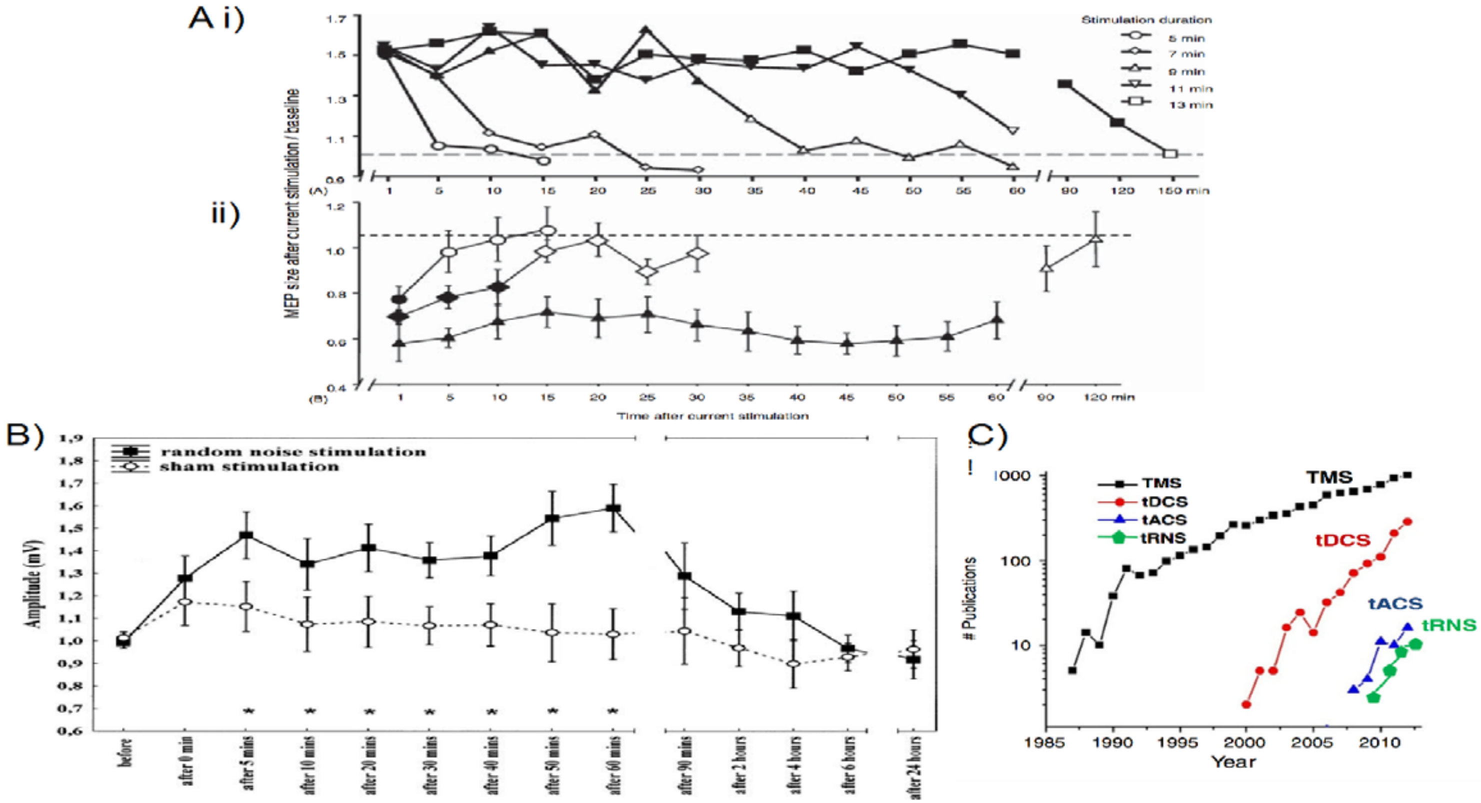


Figure 2.4: A) Figures taken from i) Nitsche & Paulus, 2001 and ii) Nitsche et al., 2003) depicting the time course of changes in MEP amplitude following M1/contralateral orbit tDCS at 1mA/ 0.029mA/cm^2. **(Ai)** Anodal tDCS resulted in increased MEP amplitude indicating heighted neuronal excitability. **(Aii)** Cathodal stimulation resulted in decreased MEP amplitude indicating reduced neuronal excitability. **B)** Figure taken from Terney et al., (2008) depicting the effect of hf-tRNS (applied with a M1/contralateral orbit montage for 10 minutes) on MEP amplitude. Excitatory after-effects of hf- tRNS were evident 5- 60 minutes post stimulation. Filled stimulation symbols indicate significant differences from baseline * Denotes significant differences in comparison to sham. **C)** The growth of brain stimulation research as evidenced by number of publications (search results from Medline database). Results are broken down by particular technique. (Figure taken from Santarnecchi et al., (2015).

2.4.3. The Neuromodulation of Decision-making

Much of the research that has applied tDCS with the goal of manipulating decision-making has applied stimulation to the DLPFC due to the accessibility of this brain region (Levasseur-Moreau & Fecteau, 2012). One attribute that has been the focus of much of this work is altering an individual's propensity for risk taking.

The seminal studies in this field are that of Fecteau, Knoch, et al., (2007) and Fecteau, Pascual-leone, et al., (2007) who revealed tDCS reduces risk-taking on tasks assessing decision-making under risk (Fecteau, Knoch, et al., 2007) and uncertainty (Fecteau, Pascual-leone, et al., 2007). Indeed, when reward and loss contingencies were explicit on the CGT, right anode and left cathode DLPFC tDCS caused participants to opt for more safe prospects, which was not the case following bilateral tDCS with reverse polarity (left anode and right cathode) and sham stimulation (Fecteau, Knoch, et al., 2007). When reward and loss contingencies were not explicit, performing the BART, bilateral tDCS over the DLPFC (irrespective of polarity) caused a decrease in risk taking in comparison to unilateral (with the anode over the right or left DLPFC and the cathode placed over the contralateral orbit) and sham stimulation (Fecteau, Pascual-leone, et al., 2007).

A number of subsequent studies have also reported changes to risk taking following DLPFC tDCS (Beeli et al., 2008; Boggio, Campanhã, et al., 2010; Boggio, Zaghi, et al., 2010; Cheng & Lee, 2016; Gorini, Lucchiari, Russell-Edu, & Pravettoni, 2014; Pripfl, Neumann, Köhler, & Lamm, 2013; Ye, Chen, Huang, Wang, & Luo, 2015). However, across these studies there is relative inconsistency in modulatory effects across the different tasks that are commonly used to assess decision-making, direction of polarity required for effect, characteristics of the sample group and parameters used for stimulation.

Following on from Fecteau, Pascual-leone, et al., (2007), a further study reported similar reductions in risk taking on the BART following bilateral DLPFC tDCS in a sample of healthy volunteers, and in those experiencing withdrawal from cocaine

(Gorini et al., 2014). This study showed that the effect can also be observed when stimulation was delivered prior to task performance, in addition to when stimulation is delivered during task performance as demonstrated by Fecteau, Pascual-leone, et al., (2007). However not all work has replicated these findings, with a number of studies reporting tDCS to have no effect on BART performance (Cheng & Lee, 2016; Weber, Messing, Rao, Detre, & Thompson-Schill, 2014). Such discrepancies in the literature have been attributed to divergent methodologies including a reduced number of trials (Cheng & Lee, 2016). These studies highlight that the effects of tDCS are likely to be fragile in respect to methodological parameters.

Later studies examining decision-making under risk, have reported similar reductions in risk taking on the CGT following right anodal and left cathodal DLPFC tDCS (Cheng & Lee, 2016) as initially presented by Fecteau, Knoch, et al., (2007). In this study, the influence of tDCS correlated with individual differences in impulsivity, with stimulation exerting a greater effect in those scoring highly on this trait (Cheng & Lee, 2016). There are also subsequent studies that have reported similar risk adverse decision-making when tDCS was applied with the reverse polarity (left anodal and right cathodal DLPFC), which was originally shown to have no effect in Fecteau, Knoch, et al (2007). Specifically, participants opted for more safe prospects on the CGT when receiving left anode and right cathode DLPFC tDCS (Boggio et al., 2010). In this study, the same stimulation was also shown to have an opposite effect in older adults (aged 55-70), resulting in increased risk taking behaviour (Boggio et al., 2010).

Other work has reported heterogeneous outcomes of DLPFC tDCS in clinical samples. Cocaine users, for example, show similar reductions in risk taking as demonstrated by Fecteau, Knoch, et al (2007) with right anodal left cathodal DLPFC tDCS, whereas stimulation with the reverse polarity was shown to increase risk taking behaviours in this population (Gorini et al., 2014). In contrast chronic marijuana smokers presented increased preference for high risk choices with right anodal and left cathodal DLPFC tDCS (Boggio, Zaghi et al., 2010). These findings indicate that the effects of tDCS may be additionally dependent on the characteristics of the sample group and have been attributed to alterations in underlying anatomical structure resulting in differing responses to stimulation (Boggio, Campanhã, et al., 2010; Boggio, Zaghi, et al., 2010; Gorini et al., 2014). There has however been other studies which have reported no effect of DLPFC stimulation on decision-making under risk tasks (Minati, Campanhã, Critchley, & Boggio, 2012).

In summary, these studies provide some evidence for the potential of tDCS applied to the DLPFC to affect risk taking, however, there are a number of discrepant findings within the literature. One important factor for my purposes and particularly in reference to applying the technique outside of the laboratory is in discerning the reproducibility of the original effects observed by Fecteau et al studies.

2.4.4. The Neuromodulation of Decision-making Outside of the Laboratory

An ability to modulate tendencies towards risk would have beneficial applications outside of the laboratory. At present the usefulness of tES in everyday life has been discussed, both in terms of application to clinical and healthy populations (Cohen Kadosh, 2014). One example application that has received much attention is the reduction of risky decision-making in those suffering from addiction disorders. At present there have been a number of small-scale studies to this effect showing differing degrees of success (Boggio, Sultani, Fecteau, & Merabet, 2008; Fecteau et al., 2014; Shahbabaie & Golesorkhi, 2014).

Considering other contexts, there has also been much speculation regarding the application of brain stimulation to improving performance in healthy populations, an area dubbed ‘neuro-doping’ (Davis, 2013). Within this, the potential application of tDCS has been extrapolated to the arena of sport, with interest in the possibility of enhancing abilities thought to underlie peak performance in athletes (Banissy & Muggleton, 2013; Cohen Kadosh, 2014; Reardon, 2016). For example recent studies have reported tDCS to modulate fatigue on an incremental cycling exercise test, with healthy participants who receive anodal tDCS to M1 (& cathodal over CZ) showing greater endurance in comparison to when receiving sham and cathodal stimulation (Vitor-Costa et al., 2015). Additionally, anodal tDCS over the temporal cortex has been reported to reduce heart rate and ratings of perceived exertion in response to a cycling endurance test in a sample of trained athletes (Okano et al., 2015). While the application of brain stimulation to sport is speculated to increase (Reardon, 2016), whether the theoretical leaps from laboratory to real world application become reality will in part depend on a number of issues being addressed by researchers in this area.

The first hurdle in translating these studies is one of replicability, especially in the context of greater methodological rigor. A number of limitations endemic in this field have been highlighted as potential challenges to the generalizability of research (Parkin et al., 2015; Walsh, 2013). For instance, many studies in this field lack the use of control tasks, which limit the conclusions that can be drawn regarding the specificity of processes being affected by stimulation. Furthermore, studies also often lack sufficient control sites for brain stimulation or use bilateral electrode montages, which have untested physiological effects (Parkin et al., 2015; Walsh, 2013, see chapter 4 and 5 on this).

Knowledge of how our laboratory proxies translate to real world decision-making is also currently limited. One study attempting to address this limitation is that of Beeli, Koeneke, Gasser, & Jancke (2008) who investigated the effects of tDCS on real world decisions during virtual reality driving simulation. Anodal DLPFC/ cathodal contralateral orbit tDCS was reported to lead to more careful driving styles when tested immediately after stimulation (Beeli et al., 2008). Despite this applied focus, even this study did not explore the question of whether their results remain post-immediate testing. Understanding how long the effects of the studies persist, as well as the intricacies of how they occur, are important factors in improving translation of these techniques. Other issues include exploring whether the effects generalize to diverse sample groups (Walsh, 2013), with initial indications suggesting that results may vary according to age (Boggio, Campanhã, et al., 2010) and gender (Chaieb, Antal, & Paulus, 2008).

2.5. Decision-Making in Sport

The ability to make optimal choices, to quickly and accurately select one course of action in a dynamic sporting environment, is essential for high quality performance in sport (Farrow & Raab, 2008). Indeed, decision-making abilities can differentiate levels of sporting expertise (Baker, Cote, & Abernethy, 2003), with top elite athletes often described as being able to 'read the play', basing their decisions on a seemingly intuitive ability to correctly predict a game's future (Farrow & Raab, 2008).

Sub optimal sporting performance has been linked to poor decision-making. For example, in basketball, decision-making errors leading to increase turnovers (a loss of possession of the ball) have been identified as a top predictor of match losses (Ibáñez et al., 2008). Previous work has also highlighted changes in risky decision-making as contributing to poor sporting performance (Jordet & Hartman, 2008; Paserman, 2007). In particular, reductions in risk taking have been linked to match losses of female tennis players during grand slam tennis tournaments (Paserman, 2007), and to performance decrements on football penalty shoot outs during international matches (Jordet & Hartman, 2008). Despite the importance of decision-making to sporting performance, these skills are often overlooked in coaching in comparison to training physical attributes of the athlete with the assumption that decision-making abilities will develop implicitly with practice of a sport (Farrow & Raab, 2008).

In order to drive progress in the field of decision-making and sport Bar-Eli et al., (2011) outlines the need to apply developments in psychological theories to the realm of sport. They note the 'impressive delay' in theory development in mainstream psychology and application to sports psychology (Bar-Eli et al., 2011). Nevertheless a number of key theories have been applied to increase understanding of decision-making in sport, which will be examined in the following section. This includes dual process thinking, heuristics and prospect theory. A further area of focus relating to understanding the abilities underlying optimal decision-making in those with high levels of sporting expertise will then be described.

2.5.1. Dual Process Thinking in Sport

There is a large emphasis on the intuitive System 1 in relation to decision-making in sport (Furley, Schweizer, & Bertrams, 2015). The idea that "what must be done, is simply done" when describing how elite athletes make choices highlights the perceived automaticity of the processes involved (Furley et al., 2015). Indeed athletes perform highly practiced procedural skills attributed to System 1 (Evans & Stanovich, 2013), processes that are interrupted by conscious self-focused attention of the deliberative System 2 (DeCaro, Thomas, Albert, & Beilock, 2011). In addition, almost all of the decisions undertaken during sport occur under time pressure that do not allow for the slow deliberations of System 2. Athletes have also been shown to adopt a number of heuristics that they then apply to their decision-making. These heuristics are characteristic of type 1 processing and discussed in more detail below (Raab, 2012).

Others have highlighted the over emphasis of intuitive processes in athletes' decision-making, instead proposing the use of both modes of thinking during sporting performance (Furley et al., 2015). In line with this, elite athletes have reported the use of System 2 to allow conscious monitoring and deliberation in the decision to modify overt behaviours. For example, Nyberg (2015) reports interviews of expert skiers, in which they describe explicit attentional monitoring (of rotational velocity) as a means to inform the decision to adjust positioning when attempting a trick (Nyberg, 2015). Interestingly, Breivik (2007) puts forward the idea that the key to expertise lies in counteracting automaticity, with even elite athletes relentlessly adapting and improving their techniques (Furley et al., 2015).

In addition, the processes of System 2 are thought to be essential in allowing an athlete to make appropriate decisions in the presence of conflict. Athletes with higher working memories (and therefore greater System 2 processing resources) make better decisions in the presence of choice conflict (Furley & Memmert, 2015). For example, Ice hockey players were presented with a tactical decision-making task, whereby either valid or invalid tactical instructions were given prior to each trial. When the information was valid, the situation did not require the reflections of System 2 and players with high and low working memories performed comparably. When the information was not valid, the players with high working memories showed an increased ability to adjust their decisions appropriately and make optimal choices. The authors concluded that this highlighted the usefulness of deliberative processing in responding to decision-making conflict in sport (Furley & Memmert, 2015).

A further role of type 2 processing in sporting decision-making is in applying and maintaining appropriate sets of behaviour where habitual responses need to be overcome (Furley et al., 2015). In sport, one example of this is when a previously decided tactic needs to be implemented, such as during a rugby center kick remembering to pass to a specific player. Together these findings suggest that the roles allocated to System 2 in decision-making in sport is to adjust the default processes of System 1 so that they are appropriate to the context (Furley et al., 2015). This perspective is in line with the default interventionist approach (Evans, 2007; Newell et al., 2015) described in section 1.21. In summary, the dual process theories can be successfully applied to decision-making in sport, it acts as a useful meta-theory allowing disparate lines of work to be organized under this framework.

2.5.2. Heuristics in Sport

It has been proposed that athletes apply heuristic strategies to allow for efficient processing of the dynamic sporting environment. Two examples of heuristics that have been examined in relation to decision-making in sport are 'take-the-first heuristic' and 'take-the-best heuristic' (Raab, 2012). In addition, gain and loss framing implicit to the sporting scenario has been proposed to influence players' decision-making (Jordet & Hartman, 2008).

The 'take-the-first heuristic' outlines that when decision options are generated in a sequential order, the earlier options tend to represent better choices. Application of this heuristic means that a person should choose the first solution that comes to mind (Gigerenzer & Gaissmaier, 2011). This has been shown in a sporting context. For example, when professional handball players watched video sequences of a match and were asked to list the potential moves they could perform, they opted more frequently for the first option generated. In addition the earlier options were (independently) rated as most appropriate and of better quality (Johnson & Raab, 2003; Raab & Johnson, 2007).

The ‘take-the-best’ heuristic is a rule describing how one choses from a number of alternate options. It outlines that one good reason is used to discriminate between alternatives, rather than weighing up different alternatives across various indicators of value. Cues are searched through in order of importance, when a chosen cue discriminates between the alternatives the search is stopped and the option with the highest value is chosen (Bennis & Pachur, 2006; Hardman & Hardman, 2009). This has been applied to a sporting context in terms of an athlete’s decision of whom to pass to in a game setting. There are a number of different cues that an athlete could base this decision on, such as the distance the other players to the goal, the number and proximity of defenders surrounding a player or the player’s recent performance. A player’s recent performance is an important cue in this decision which is ranked highly (Raab, 2012). The recent performance of an athlete is interpreted by team mates (and others) according to the ‘hot hand’ phenomena, this refers to the assumption that if a player has scored more than two times in recent matches then there is a higher likelihood they will score again compared to if they have scored only once (Gilovich, Vallone, & Tversky, 1985).

Prospect Theory (Kahneman & Tversky, 1979) highlights that heuristics are used to encode and simplify information relating to a decision. One example of a heuristic used in this process is the editing of information according to reference points, therefore how a decision is framed has been shown to influence the decision maker (Kahneman, 2013). In particular people are more risk seeking in relation to gains and more risk adverse in relation to loses which is known as the loss aversion (Kahneman, 2013). There is support for contextual features influencing decision-making in sport, and it has been shown that gain and loss framing implicit to the sporting situation influence players’ decisions. For instance, analysis from football penalty shootouts has revealed that the valence of a shot influences players’ success. When taking a shot that has a negative valence, i.e. a shot that if the player misses the team will instantly lose the match, players perform worse (62% success rate). This is in comparison to shots with positive valence, i.e. those that if the player scores the team will instantly produce a win (92% success rate) (Jordet & Hartman, 2008). In line with loss aversion, the performance decrements associated with playing to not lose were associated with increased avoidance behaviours in line with reduced risk taking, whereby players took less time to prepare shots and avoided eye contact with the keeper (Jordet & Hartman, 2008).

2.5.3. Attributes Linked to Optimal Decision-Making in Sport

A further line of research has examined the skills required for optimal decision-making in sport by exploring differences between expert and novice athletes. Two features that have been discussed in this context are pattern recognition and visual attention.

Pattern recognition refers to the superior memory processing that occurs with expertise. Experts are more efficiently able to recognize sequences and encode disparate elements to memory as ‘chunks’ (Farrow & Raab, 2008). Indeed it has been reported that elite players have enhanced abilities to recognize and recall sequences of play in their given sport in comparison to non elite players (Abernethy, Baker, & Côté, 2005). Interestingly these pattern recognition abilities have also been shown to generalize, to some extent, across sports. In particular, a study comparing basketball, netball and hockey, players reported elite players retain superior memory of sequences of different sports, in comparison to non elite players of the same sport (Abernethy, Baker, & Côté, 2005).

Differences in visual attention have also been noted to vary according to expertise. For example football players who make faster and more accurate decisions were found to fixate longer on players with the ball and attacking players, and less time fixating on the ball in comparison to players with less experience (Vaeyens, Lenoir, Williams, Mazyn, & Philippaerts, 2007). It is thought that differences in visual attention allow elite athletes to draw upon more appropriate environmental cues from which to base their decisions. Together, these abilities and the superior pattern recognition skills of elite athletes are thought to improve decision-making by reducing working memory demands and allowing for an increased ability for anticipation of other players. As such athletes with higher levels of expertise will expend more time and resources to choose and prepare appropriate responses (Farrow & Raab, 2008).

While an examination of expertise in sporting decision-making has proved informative, one criticism is that almost all of this work has examined differences between elite (usually undergraduate students participating in university sport teams) and non-elite athletes, rather than considering the spectrum of elite athletes. Within sports psychology there is a remarkably broad definition of elite athlete status, encompassing Olympic champions, to regional or university sports team players who have had as little as 2 years experience (Swann, Moran, & Piggott, 2015).

Swann et al., (2015) recently proposed a categorization system to distinguish across the spectrum of sporting expertise at an elite sporting level, defining a taxonomy from semi-elite, successful-elite, competitive-elite and world-class elite athletes. The world-class elite athlete category refers to those achieving the highest accolades for prolonged durations. In particular they have frequent appearances and sustained success in globally recognized competition. Athletes within the successful elite category also compete at the highest levels but have infrequent success. The competitive elite category describes those who play at a divisional or national level, and while they may have participated, have had no success at an international level. Those in the lowest category of the taxonomy are the semi elite players who may belong to talent development programs and had success at regional or university levels (Swann et al., 2015). In future research it is important to distinguish between these levels of elite athletes, in order to provide a more nuanced view of expertise and to allow insight into the abilities of top athletes.

2.6. Decision-Making Under Pressure In Sport

A further significant factor overlooked in much of the previous work on decision-making in sport is the context in which decisions are undertaken (Hepler, 2015). This is especially relevant for the elite athlete, as the context in which they perform is far from the usual laboratory settings of psychological experiments (Johnson, 2006). The next section considers the performance pressures that an athlete is exposed to and describes the handful of studies that have taken into account the impact of pressure on athletes' decision-making. Laboratory studies that have examined the influence of stress (increased cortisol) on the cognitive processes underlying decision-making will then be discussed, to highlight some of the ways athletes may be influenced during competition. Lastly the proposed mechanisms by which pressure may influence performance are examined.

2.6.1. Types of Performance Pressure in Sport

The elite athlete routinely undertakes impressive cognitive feats, this not only includes complex decision-making, but performed under conditions of intense pressure, limited time and restricted resources (Walsh, 2014). For example, imagine a situation where there is five minutes remaining for a goal to be scored. The goal will determine whether a team wins a competition title - an accolade a player may have dedicated their lives trying to achieve and upon which the fans, media, employers and sponsors will judge them. At this moment, players are battling with physical exhaustion while surrounded by crowds of noisy spectators. Such conditions are an innate part of the sporting experience, and for the elite athlete success is often shaped by their ability to cope or even thrive under these conditions (Bronson & Merryman, 2013). By definition, stress arises when the demands of a situation outweigh one's capacity (or perceived capacity) to respond (McGrath, 1970) and as described, at any one time a plethora of demands are placed on the athlete.

These demands can be broadly classed as mental or physical pressure (Anshel & Wells, 2000). Commonly cited sources of mental stress include the psychological impact of the desire to perform at one's best, often exacerbated by the importance of the competition, one's own expectations and the expectations of teammates, coaches, parents and the media. Other sources include the impact of errors, requirements for sustained attention in a dynamic environment, interpersonal conflicts and rivalry, as well as intimidation from the crowd. Sources of physical stress include sustained physical exertion, fatigue, injuries, dehydration and crowd noise (Anshel & Wells, 2000; Mellalieu, Neil, Hanton, & Fletcher, 2009). In addition to this, the decisions in question must be made often within fractions of seconds under the intense time pressure of competition (Johnson, 2006).

This ability to perform under pressure is integral to the elite athlete. Reports from elite coaches describe the technical and physical differences between elite as minimal, yet the distinguishing feature is one's ability to consistently make optional choices on the day under the pressure of competition (Thelwell, Harwood, & Greenlees, 2016). Indeed, in elite athletes when the pressure to perform is at its highest this has been noted to lead to performance decrements (Jordet & Hartman, 2008; Wells & Skowronski, 2012). One example is from analysis of Professional Golfing Association tournament scores (from 1983-2010) which revealed that professional golfers score worse on the 4th round – where the outcomes of the tournament is decided- in comparison to the 3rd round (Wells & Skowronski, 2012). Given such demanding environments, it is not uncommon for athletes to perform significantly below expectation despite high levels of motivation; this phenomenon has been termed 'choking' (Jackson, Beilcok & Kinrade, 2013).

2.6.2. The Influence of Pressure on Sport Specific Decision-Making

Such sources of pressure, as discussed above, are factors not captured in the majority of the laboratory experiments on decision-making (Walsh, 2014), and the intricacies of why, when and how different performance pressures influence athletes and their decision-making is still under question (Hepler, 2015; Johnson, 2006). A small number of studies that have explored decision-making under conditions of high pressure have operationalized pressure in a variety of ways. These tend to assess decision quality and reaction times in response to sport specific decision-making tasks (in comparison to examining the cognitive processes underlying decision-making).

Psychological performance pressures have been shown to significantly impair decision quality on sport specific decision-making tasks. Smith et al., (2016) examined the influence of mental fatigue (induced by performing the Stroop task for 30 minutes) on the ability to decide the best course of action following a video clip of a football match. Mental fatigue was found to reduce players' decision accuracy and response times. Further work by Kinrade, Jackson, & Ashford, (2015) found psychological performance pressure (operationalized as conditions of elevated social evaluation) to reduce the quality of basketball players' decision-making but only for highly complex game scenarios, which presented a large number of possible outcomes to the athlete. In this study, levels of self report rumination predicted decision-making accuracy decrements, suggesting that these may arise from consuming working memory resources (Kinrade et al., 2015).

However, one study that compared the effects of mental and physical performance pressures on the ability to generate sporting decision outcomes reported that neither mental nor physical pressure affected the accuracy of decision-making. Under conditions of mental pressure (performance of a dual subtraction task) athletes were slower to generate their first response and make their final decision. Physical pressure (exertion protocol at 70% of maximal capacity) was found to have no effect on athletes' responses (Hepler, 2015).

Other work examining the effects of physical exertion on decision-making abilities have reported mixed results, which vary according to the characteristics of the sample. One study has looked at how examining the influence of physical exertion on one's propensity for risk-taking reported that physical exertion (60% maximal exertion) increased risk taking in decision-making under uncertainty for male athletes but reduced risk taking for non elite female athletes (Pighin, Savadori, & Bonini, 2015). These findings are in line with the results of laboratory based studies that have examined how elevated cortisol levels affect decision-making (Lighthall et al., 2009, 2012; Preston, Buchanan, Stansfield, & Bechara, 2007). Other work has noted expertise influences the effects of physical pressure. In particular Schapschröer et al (2016), noted an inverted-U relationship of physical load and reaction times, with moderate exertion inducing a beneficial effect while intense exertion induces a detrimental effect on reaction times in the healthy controls. This was found to not extend to elite athletes who show a general facilitation in response time, measured on perceptual-cognitive tasks, under conditions of both moderate and intense physical pressure (Schapschröer, Lemez, Baker, & Schorer, 2016). This review is useful in highlighting that expertise is a factor when interpreting findings, especially as all the other studies discussed were undertaken using non-elite samples and may not generalize.

2.6.3. The Influence of Cortisol on Laboratory Decision-Making

Work that further highlights the importance of considering the high pressured context in which elite athletes compete are laboratory studies have shown that stress, in terms of elevated cortisol, has a significant impact on decision-making and its underlying cognitive processes. In these studies stress induction methods are employed. These include exposing the participant to physical challenges, social evaluative threats or cognitive demands. There are two widely used techniques. The Cold Pressor Test (Hines & Brown, 1932), whereby participants submerge their hands into ice cold water (0-3°C) for three minutes, and the Trier Social Stress Test (Kirschbaum, Pirke, & Hellhammer, 1993) where participants deliver a presentation in front of a despondent audience, and proceed to perform an arithmetic task under time pressure. These methods have been found to consistently elicit a stress response, which can be detected by measuring changes in the physiological (heart rate, pulse, electrodermal activity and blood pressure) and endocrine (cortisol via saliva sampling) systems (Starcke & Brand, 2012).

Using these protocols, it has been shown that stress influences decision-making under situations of risk and uncertainty, as well as some of the underlying psychological mechanisms (for a review see Starcke & Brand, 2012). Studies examining decision-making under uncertainty have reported a gender difference of the effect that stress has on risk taking. In particular Lighthall et al., (2009) reported that stress induced by the Cold Pressor Test made males more risk seeking and females more risk avoidant on the BART. In females, cortisol responses correlated with the shift to more conservative responses. Later work by Lighthall et al., (2012) repeated this study with neuroimaging; a gender-by-stress interaction was observed in the insula and the putamen whereby stress increased activity in these regions for males, but decreased it for females when participants were performing the task. Moreover, increased activation of the dorsal striatum was strongly associated with increased reward collection rate in stressed males but not in stressed females (Lighthall et al., 2012).

Similar effects of gender have been observed in the Iowa Gambling Task, a further measure of decision-making under uncertainty (Bechara, Damasio, Tranel, & Damasio, 1997). Following a stress induction procedure, participants (both males and females) were slower to learn task contingencies (i.e. to avoid the high risk high reward cards which have low overall net gains). In the latter half of the task, once task contingencies had been learnt, gender differences were noted such that, under stress, females had more explicit knowledge and showed advantageous performance by choosing decks that were less risky. Whereas under stress males had less explicit knowledge and showed poorer performance in that they chose decks that offered greater rewards at the cost of high losses (Preston et al., 2007)

It has also been noted that stress influences the processes that underlie decision-making under uncertainty, in particular feedback learning, i.e. the ability to make associations between decisions and their outcomes (Starcke & Brand, 2012). Using probabilistic reinforcement learning tasks, where participants are required to learn relationships between visual cues and feedback, it has been reported that stress enhances learning from positive feedback and reduces learning from negative feedback (Lighthall, Gorlick, Schoeke, 2013; Petzold, Plessow, Goschke, & Kirschbaum, 2008). Using a similar task, Cavanagh & Frank, (2010) reported replicable findings of improved learning from rewards and reduced learning from punishment, but only in participants with low trait level punishment sensitivity. The opposite pattern of results was evident in individuals with high trait level punishment sensitivity. Therefore, personality characteristics may be an additional factor that influences the relationship of stress on decision-making (Cavanagh & Frank, 2010).

Elevated cortisol levels have also been reported to affect decision-making under risk, where explicit information is available regarding the choice outcomes. Stress was found to decrease performance on the Game of Dice Task, causing participants (of both genders) to choose more high-risk disadvantageous options. Additionally a positive correlation was reported between cortisol levels and the number of non-optimal risky choices (Starcke, Wolf, Markowitsch, & Brand, 2008). In this task, the generation (calculating optimal choices) of optimal strategies is thought to rely on higher order executive functions. The authors suggest that stress may impair processes underlying task performance (Starcke et al., 2008), which is in line with work that has shown experimentally induced stress interferes with executive functions such as working memory (Schoofs, Preuß, & Wolf, 2008), and set shifting (McCormick, Lewis, Somley, & Kahan, 2007).

The influence of stress on decision-making under risk has been further explored by Porcelli & Delgado, (2009). In this experiment, participants gambled with explicit probabilities in either loss (where participants could only lose money) or gain domains (where participants could win money). Stress induced by the Cold Pressor Test made participants more likely to choose risky options on loss domain trials but less likely to choose risky options on gain domain trials. Therefore under stress the framing of decisions had a greater influence on the decision maker. The authors proposed that stress may cause a greater reliance of heuristic processing and a decrease in the adjustments from our automatic biases (Porcelli & Delgado, 2009; Starcke & Brand, 2012).

Further support for this explanation comes from studies of anchoring and adjustment. One strategy that is known to underlie estimating is to begin with information on what we do know (an anchor) and adjust until a plausible value is reached. Adjustments, however, are usually inefficient and estimates are strongly guided by our automatic anchors (Epley & Gilovich, 2001). A study by Kassam, Koslov, & Mendes, (2009) found that when under stress of receiving electric shocks, participants’ estimations showed less adjustment from anchor values.

In summary, it has been widely reported that elevated cortisol levels influence decision-making, and modulate one’s propensity for risk taking. Stress has also been reported to reduce executive functioning, alter the degree of learning from positive and negative feedback and cause inefficient adjustment from automatic processing. The direction of the effect that stress has on risky decision-making is not conclusive. However this is likely to be due to a myriad of factors influencing these effects such as gender, individual differences in punishment sensitivity and how a decision is framed. There is also large variation in the study of decision-making and stress. Methodologies differ according to how they induce stress, both in their timing (prior to task or on-going) and in their operationalization (physical or social evaluative) (Starcke & Brand, 2012). This body of research is useful in highlighting the importance of considering the influence of the stressful context of athletes’ decision-making, and provides a detailed examination of how such processes may be affected.

2.6.4. Theories of Performance Decrements Under Pressure

As highlighted during competition, athletes operate under psychological (e.g. desire to perform at ones best, high cognitive demands) and physical pressures (e.g. exhaustion, injury). There are three theoretical accounts proposed to explain how pressure may negatively impact performance. Performance pressure may a) divert focus away from a task (distraction account), b) increase the attention paid to a task and thereby disrupt the automaticity of performance (explicit-monitoring) or c) interfere via elevated arousal levels (the over-arousal account) (Beilock, 2011; Beilock & Gray, 2007).

The distraction account predicts that interferences to working memory and attention are responsible for performance decrements. In particular, pressure is thought to divert attention to irrelevant processes, such as worrying, that consume working memory resources and reduce those available for task execution. In support, Beilock, Kulp, & Holt, (2004) found that maths problems which placed high demands on working memory appeared to be selectively impaired by pressure (social evaluation and monetary incentives). This was not, however, the case for maths problems that placed low demands on working memory. Additionally, for tasks that place high demands on working memory, individuals with high working memory capacities were most affected by performance pressures (Beilock & Carr, 2005). It is thought that these individuals employ cognitive demanding strategies that fail when working memory resources are consumed, in comparison to individuals with low working memory capacities who rely instead on heuristic processing to a larger extent (Beilock, 2011).

An alternative account described by the explicit-monitoring theory proposes that pressure has the opposite effect on attention, causing an increase in self-monitoring processes. Focusing attention inward is thought to disrupt the automatic execution of tasks, in particular those tasks that require procedural skills that otherwise lie outside of conscious awareness (Beilock & Gray, 2007). Thus this explanation accounts for decrements on tasks that do not require working memory. In support, Gray (2004) reported that expert baseball players' performance on a batting task was impaired when undertaking a concurrent task which required them to attend to their swing (increased skill focused condition), but impairments did not result when athletes undertook a concurrent task of judging tone frequency (which consumed working memory resources). In this study, novice performers, whose batting skills were not automatized, showed the opposite pattern of performance decrements, which indicates that findings were not due to differences in attentional load in the two concurrent tasks (Gray, 2004; Beilock, 2011).

Together these theories suggest that the way in which a task utilizes attentional resources contributes to the mechanisms of pressure-induced performance decrements. Therefore in sport, pressure may influence the tasks athletes perform in different ways. It is possible that strategizing and tactical problem solving may be impaired due to the reductions in working memory resources, while a highly practiced motor skill, such as a golf swing, may be impaired because of disruption in the underlying automatic processes (DeCaro, Thomas, Albert, & Beilock, 2011 Beilock, 2011; Beilock & Gray, 2007). Moreover decision-making that taxes working memory, such as decision-making under risk may be impaired under pressure due to distraction. Whereas decision-making under uncertainty, which is more automatic, may be impaired due to increases in explicit monitoring (Beilock, 2011; Beilock & Gray, 2007; DeCaro et al., 2011).

The type of pressure is an additional factor found to affect the mechanisms underlying pressure induced performance decrements. Outcome pressures, arising from performance contingent incentives such as prizes, have been proposed to divert attention away from a task. Whereas, monitoring pressures, arising from being evaluated by others, is thought to increase the inward focusing of attention. In support, DeCaro, Thomas, Albert & Beilock (2011) revealed outcome pressure induced selective deficits on tasks that required working memory, while monitoring pressures induced impairments on tasks that were optimally performed in the absence of working memory (DeCaro et al., 2011). Although interesting, in the real world different types of performance pressures rarely act in isolation. In the sporting arena, for example, it is currently unknown how different types of pressures may interact with one another. Indeed, there are a number of possibilities; different pressures may act independently and in parallel, impairing both tasks reliant on working memory and automatic processing (Beilock & Gray, 2007). Alternatively the impact of one type of pressure may serve to lessen the influence of the other, or it may be that the type of pressure most salient to the individual at any given moment may take precedence (Beilock & Gray, 2007).

Following on from this, there have been interventions that have focused attempts on redirecting attention to mitigate the negative impacts of pressure. DeCaro et al., (2011) reported that the impairments of outcome pressure on working memory dependent tasks could be decreased with concurrent performance of a secondary explicit monitoring task. Thus when the performance situation distracts attention away from a task, a technique to redirect attention back proved beneficial. Alternatively when the performance situation makes individuals prone to focusing on explicit component processes of a procedural skill, interventions to mildly distract performers have reported positive effects. For instance mild distraction decreased the negative impacts of monitoring pressure on the information integration category learning (DeCaro et al., 2011). Moreover, instructing expert golfers to perform a putting task rapidly, limiting the opportunity for skill-focused explicit monitoring, increased performance (Beilock, Carr, MacMahon, & Starkes, 2002).

Finally the over- arousal account posits that performance decrements arise as a result of excessive elevations in arousal (Yu, 2015). The Yerkes-Dodson Model (Yerkes & Dodson, 1908) describes the optimal level of arousal for executing tasks. For simple or well-learned tasks the relationship between arousal and performance is thought to be linear, with performance increasing with arousal. However for more difficult tasks the relationship between arousal and performance is inverted, and increases in arousal are thought to result in detrimental performance (Yu, 2015). The mechanistic account by which increases in arousal interferes with cognition are less well formalized in comparison to distraction theories (Yu, 2015). A neuroimaging study reported that below optimal performance resulting from the pressure of high monetary rewards, activated the ventral midbrain, suggesting that excessive arousal may have its basis in the brain's reward networks (Mobbs et al., 2009).

2.7. Conclusion: Decision-Making and this Thesis

The data presented in the proceeding chapter has the translational goal of understanding and increasing insight into the decision-making of elite athletes. Firstly it builds on the work reviewed that has applied tDCS to modulate decision-making in order to explore the proposed application of neuromodulatory techniques to sport. It does so by addressing some of the issues that relate to translating these techniques from the laboratory to the real world, across three experimental chapters. In **Chapter 3**, the issue of replicability of initial findings in light of greater methodological rigor is examined with an attempted replication of a key study that found tDCS to modulate decision-making (Fecteau, Pascual-leone, et al., 2007). In particular. whether DLPFC tDCS can be used to reduce risk taking for decision-making under uncertainty is examined in an independent sample.

The following two chapters aim to examine the assumptions that underpin many studies in the cognitive neuromodulation field, that the physiological effects of these techniques remain despite divergent parameters being employed. In particular in **Chapter 4** whether the anodal-excitatory/ cathodal-inhibitory effects of tDCS administered using bilateral electrode montages (at 1mA & 2mA) will be investigated via the assessment of corticospinal excitability. In **Chapter 5** a similar approach is undertaken to discern the mechanistic basis of tRNS using parameters common in the application of this technique for cognitive neuromodulation. In particular, whether the excitatory effects of this technique remain when it is applied using bilateral montages and at durations of ten and twenty minutes.

Secondly, the work in this thesis addresses issues highlighted from examining decision-making in the sport literature, in particular that much of this work has ignored the pressure filled context in which athletes operate or has been undertaken using non elite athletes. In **Chapters 6, 7 and 8,** the influence that performance pressures have on decision-making is examined across three age groups spanning the developmental trajectory of elite sport. Three categories of decision-making abilities were investigated, including reactive perceptual decision-making, decision-making under risk, and under uncertainty. The influence of physical exhaustion (completion of a maximal exertion exercise protocol) on decision-making was examined in world class elite athletes (chapter 6) and in semi-elite athletes who are undergoing talent development training for possible Olympic competition in 4-8 years (chapter 7). In **Chapter 8** the influence of mental pressure (distracting dual working memory task) on decision-making is explored in the youngest athletes within the elite development training pathways referred to as elite- junior athletes. The overarching goal of this work is to assess how insights into decision-making can be applied in elite sporting environment.

3. Attempted Replication of Fecteau, Pascual-leone, et al., (2007) ‘Activation of Prefrontal Cortex by tDCS Reduces Appetite for Risk During Ambiguous Decision-Making’

3.1. Abstract

Background: TDCS has been shown to modulate risk-taking behaviours (for a review see Levasseur-Moreau & Fecteau, 2012). It’s real world application to decision-making outside of the laboratory (Beeli, Koeneke, Gasser, & Jancke, 2008; Fecteau, Fregni, Boggio, Camprodon, & Pascual-Leone, 2010) and it’s potential use as a training tool in athletes have been proposed (Banissy & Muggleton, 2013; Okano et al., 2015; Reardon, 2016). A seminal study in this area is that of Fecteau, Pascual-leone, et al., (2007) who revealed a decrease in risky decision-making on the BART following bilateral tDCS to the DLPFC. Subsequently, a number of heterogeneous findings within the field have been reported (eg. Cheng & Lee, 2016; Weber, Messing, Rao, Detre, & Thompson-Schill, 2014), possibly arising from an inconsistency in experimental design, stimulation parameters, behavioural assays and sample groups. Before exploring the application of this technique in the training of elite athletes, it is important to establish the reliability of these initial findings via direct replication.

Objective: The aim of this study was to replicate the methodology and findings of Fecteau, Pascual-leone, et al., (2007) in a new population sample. It was hypothesized that bilateral DLPFC tDCS would decrease risk-taking on the BART as reported in the original study. This study acts as an initial step in exploring the application of tDCS in decision-making training in sport.

Method: A double blind, between subject design was used. 48 healthy participants were randomly assigned to receive either a) bilateral DLPFC tDCS (anode F4/ cathode F3) (*replication condition*); b) bilateral parietal cortex tDCS (anode P4/ cathode P3) (*active control condition*); or c) no stimulation (*baseline condition*). Participants completed both the BART (*experimental task*) and Stroop task (*control task*). Methodological amendments were made to strengthen the design of the study. In particular, in Fecteau et al., (2007) the BART was undertaken during stimulation and the Stroop task undertaken post stimulation.

For both the control and experimental task to be subject to the same type of stimulation in the current study, both tasks were undertaken during tDCS. Additionally, the sample used in the current study was 60% larger, and double blinding was used. Other than this close replication of the Fecteau et al., (2007) methodology was adhered to, including stimulation parameters, methods of localisation, behavioual task parameters and reimbursement.

Results: The results of this study do not replicate Fecteau et al., (2007) original findings and there was no evidence for a reduction in risk taking on BART with DLPFC tDCS.

Conclusion: The results raise concerns regarding the effectiveness of tDCS as a modulator of risky decision-making and, in doing so, it's potential use as a training tool for elite athletes. As a consequence, in the next chapter, the physiological underpinnings of tDCS and its failure to modulate decision-making are investigated.

3.2. Introduction

TDCS, a method of altering neuronal excitability, has been used to induce changes in a wide spectrum of cognitive and motor behaviours for potential improvement or ‘neuroenhancement’ (Jacobson, Koslowsky, & Lavidor, 2012; Kuo & Nitsche, 2012). The ability to manipulate processes that underlie decision-making, such as risk taking, have been the focus of a number of studies (for a review see Levasseur-Moreau & Fecteau, 2012). The application of this methodology outside of the laboratory in modifying everyday decision-making has been proposed (Beeli et al., 2008; Fecteau et al., 2010), as has the potential use of tDCS in applied populations such as in the training of elite athletes (Banissy & Muggleton, 2013; Okano et al., 2015; Reardon, 2016).

TDCS involves passing a direct current between two electrodes (anode and cathode) placed on the scalp (Tergau & Paulus, 2008). Current models purport that anodal stimulation has an excitatory effect, and cathodal stimulation an inhibitory effect, on the neurons underlying the electrode (Nitsche & Paulus, 2001; Nitsche et al., 2003; Stagg & Nitsche, 2011; Tergau & Paulus, 2008). A common target for stimulation is the DLPFC, a region of the brain that has been repeatedly associated with risky decision-making in both healthy individuals (Krain, Wilson, Arbuckle, Castellanos, & Milham, 2006; Paulus, Rogalsky, Simmons, & Feinstein, 2003; Rao, Korczykowski, Pluta, Hoang, & Detre, 2008; Rogers et al., 1999) and patients with lesions to this area (Clark, Manes, Antoun, Sahakian, & Robbins, 2003; Manes et al., 2002). Studies have applied tDCS to the DLFPC and reported changes to risk-taking (Beeli et al., 2008; Boggio, Campanhã, et al., 2010; Boggio, Zaghi, et al., 2010; Cheng & Lee, 2016; Fecteau, Knoch, et al., 2007; Fecteau, Pascual-leone, et al., 2007; Gorini, Lucchiari, Russell-Edu, & Pravettoni, 2014; Pripfl, Neumann, Köhler, & Lamm, 2013; Ye, Chen, Huang, Wang, & Luo, 2015). At present, however, there is a relative inconsistency in the modulatory effects across different tasks used to assess risk, direction of polarity required for an effect, and characteristics of the sample group. These issues affect how well the findings can be generalized outside of the laboratory.

Initial seminal work by Fecteau and colleagues explored decision-making under uncertainty, where information about the probability of decision outcomes are unknown and required to be deduced by the participant via trial and error learning. In this study, bilateral tDCS to the DLPFC (irrespective of the direction of polarity) was shown to decrease risk-taking behaviours on the BART in comparison to those receiving unilateral anodal (with the cathodal electrode over contralateral orbit) or sham stimulation (Fecteau, Pascual-leone, et al., 2007). Similar findings were also reported by a later study in an independent sample of healthy participants, as well as in cocaine users experiencing withdrawal from the drug (Gorini et al., 2014). There are some inconsistent findings, however, with two further studies reporting no effect of DLPFC tDCS on BART performance (Cheng & Lee, 2016; Weber et al., 2014). At present these discrepancies have been attributed to differences in methodology, including task parameters (such as a reduced number of trials) (Cheng & Lee, 2016) or whether tDCS was delivered during (online) or after (offline) task performance (Weber et al., 2014).

Studies have also examined the effect of DLPFC tDCS in relation to decision-making under risk, where information about outcome probabilities are explicit. Similarly Fecteau, Knoch, et al., (2007) reported DLPFC tDCS to reduce risk taking on these types of tasks. In this case, however, the direction of polarity was important for inducing the effects and reduced risk taking resulted from right anodal / left cathodal DLPFC tDCS, which was not the case for those receiving stimulation with the reverse polarity or sham. A number of other studies have also reported a shift towards more cautious responding in decision-making under risk following right anodal / left cathodal DLPFC tDCS (Boggio, Zaghi, et al., 2010; Cheng & Lee, 2016; Gorini et al., 2014).

Again, not all work in this area is conclusive, and a number of other studies have shown no effect of tDCS on decision-making under risk (Fecteau et al., 2014; Minati, Campanhã, & Critchley, 2012). This includes a later study by the Fecteau group who reported a 5-day x 30-minute regime of right anodal / left cathodal DLPFC tDCS to have no effect on task performance on the Cambridge Risk Task (Fecteau et al., 2014). While other studies have found right anodal / left cathodal DLPFC tDCS to have the opposite effect and increase risk taking in older adults

(Boggio, Campanhã, et al., 2010) and chronic marijuana smokers (Boggio, Zaghi, et al., 2010).

While these studies provide some evidence for the potential of DLPFC tDCS to manipulate risk taking, there are a number of heterogeneous findings within the literature. Discrepant findings in these studies may reflect the low reproducibility of original findings and a reduced efficacy of DLPFC tDCS to modulate risky decision-making (Ioannidis et al., 2005; Vannorsdall et al., 2016).

In accordance with this, the claims made in many of these studies have come under criticism due to the lack of methodological rigor endemic to the field of cognitive neuroenhancement using TES approaches (Walsh, 2013). In a recent review the minimum conditions for executing a TES experiment were laid out in an attempt to progress the field and discern the true reliability and validity of reported effects. These included the importance of active control sites as opposed to sham conditions, as well as the use of control tasks to understand the specificity of given effects (Filmer, Dux, & Mattingley, 2014; Parkin et al., 2015). In the face of such diversity in findings, and concerns over lack of experimental practices leading to false positives, replication attempts are one of the best ways to clarify the reliability of DLPFC tDCS to reduce risk taking in healthy participants (Simons, 2014).

With this in mind, the goal of the current study was to perform a replication of one of the key findings in the cognitive neuroenhancement and decision-making literature. In light of the current literature it was decided that this was a necessary first step in discerning the efficacy of these techniques as a training tool in elite athletes. The study chosen for replication is Fecteau, Pascual-leone, et al., (2007) who showed decreased risk taking in a decision-making under uncertainty task (BART) during tDCS to the DLPFC. A decision-making under uncertainty task was chosen as this reflects the most common type of decision made in the real world (Schonberg, Fox, & Poldrack, 2011), while modulations in risk taking have been proposed to contribute to a performance failures in athletes (Jordet & Hartman, 2008; Paserman, 2007). Moreover, Fecteau, Pascual-leone, et al., (2007) represents an example of a strong methodological design compared to many other studies in this field, with the inclusion of both an active control stimulation condition and control task to determine whether the experimental effects were specific to both brain region and behavioral process.

In the current study therefore participants were allocated to one of three conditions. **A) The replication condition:** tDCS to DLPFC (right anodal/ left cathodal), a replication of the condition in Fecteau et al (2007) that showed the largest behavioral effect. **B) An active control condition**: tDCS to Parietal Cortex (PC) (right anodal/ left cathodal). **C) A baseline condition** where tDCS is not applied.

The experimental design adhered closely to the methodology of Fecteau, Pascual-leone, et al., (2007) (a comparison of methodological parameters are summarized in Table 3.1). Here a conceptual replication is undertaken as a number of amendments were made in order to strengthen the methodological design. In Fecteau, Pascual-leone, et al., (2007) the control task (Stroop) was undertaken before and after stimulation, while performance on the experimental task (BART) was tested during stimulation. In order for the experimental and control task to be subject to the same conditions, in the current study both tasks will be performed during stimulation. Also, in the current experiment double blinding was used, where both the experimenter and participant were unaware of the type of stimulation administered. Lastly, bilateral PC stimulation (right anodal /left cathodal) was chosen as the active control condition. Fecteau et al (2007) proposed that their results were due to the concurrent excitation and inhibition of opposing DLPFC hemispheres. Bilateral stimulation to an alternate region also implicated in decision-making will allow further specificity regarding the location of stimulation to be deduced (Studer et al., 2015).

A successful replication of Fecteau, Pascual-leone, et al., (2007) would reveal reduced risk taking on the BART in the replication condition (A) in comparison to the active control (B) and baseline condition (C), and no differences on performance of the control Stroop task. A successful replication would indicate high reproducibility of tDCS to reduce risk taking in healthy adults and the possibility for further application of this in the training of elite athletes.

3.3. Methods

3.3.1. Participants

Power analysis using G * Power 3.0 (http://www.gpower.hhu.de/en.html) indicated that to have 90% power to detect an effect the same size as Fecteau, Pascual-leone, et al., (2007) (d=.76), at least 45 participants would be needed in each replication attempt.

Forty-eight participants (24 female) aged between 18-37 (mean: 24.19) took part in the study. Participants within the DLPFC tDCS (n=16; mean age = 23; SD: 3.52; range 18-30), PC tDCS (n=16; mean age= 24; SD = 4.62; range: 19-38) and baseline condition (n=16; mean age = 24.40; SD = 2.61; range = 20-28) did not differ in terms of age ($F_{(2,45)}$= 0.778 p=0.465).

All participants were recruited via the Institute of Cognitive Neuroscience subject panel at UCL. Participants adhered to inclusion criteria for studies using non-invasive brain stimulation, including no metallic implants, previous history of neurological disorders, medication or substance abuse. All participants were native English speakers (English was their first and main language), had normal or corrected-to normal vision and were right handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Participants were naïve in respect to the precise experimental hypothesis and those in the stimulation conditions were not explicitly informed as to the type of stimulation they received until the end of the experiment. The study and consent procedures were approved by UCL ethical review board and were in accordance with the declaration of Helskini. Prior to inclusion written informed consent was obtained. Upon completion participants were reimbursed at a standard rate.

3.3.2. Experimental Protocol

The study employed a between-subject double-blind design, whereby participants were randomized by gender to one of three conditions (see **Figure 3.1**A). **The experimental replication condition** received anodal stimulation to the right and cathodal to the left DLFPC. This was chosen to replicate the condition which showed the largest behavioural effect in Fecteau, Pascual-leone, et al., (2007). **The active control condition** received anodal stimulation to the right and cathodal to the left PC. This direction of polarity was chosen to mirror that used in the DLPFC condition. The active control condition will allow the specificity of stimulation to the DLPFC to be discerned. **The baseline condition** did not receive stimulation. All participants completed both the BART and Stroop task, the order of which was counterbalanced in each group (taking gender into consideration). The main experimenter and participant were blinded according to stimulation condition. To achieve this, the experimenter applied electrodes to both the frontal and parietal regions that were attached to two separate devices (see **Figure 3.1**B). The main experimenter left the room briefly while a second experimenter, who was not blinded, began the appropriate stimulation and concealed the devices. The conditions were revealed to the main experimenter once all data were collected. Moreover, the participant was naïve to the precise hypotheses of the experiment until after the experiment when appropriate debriefing of participants were undertaken.

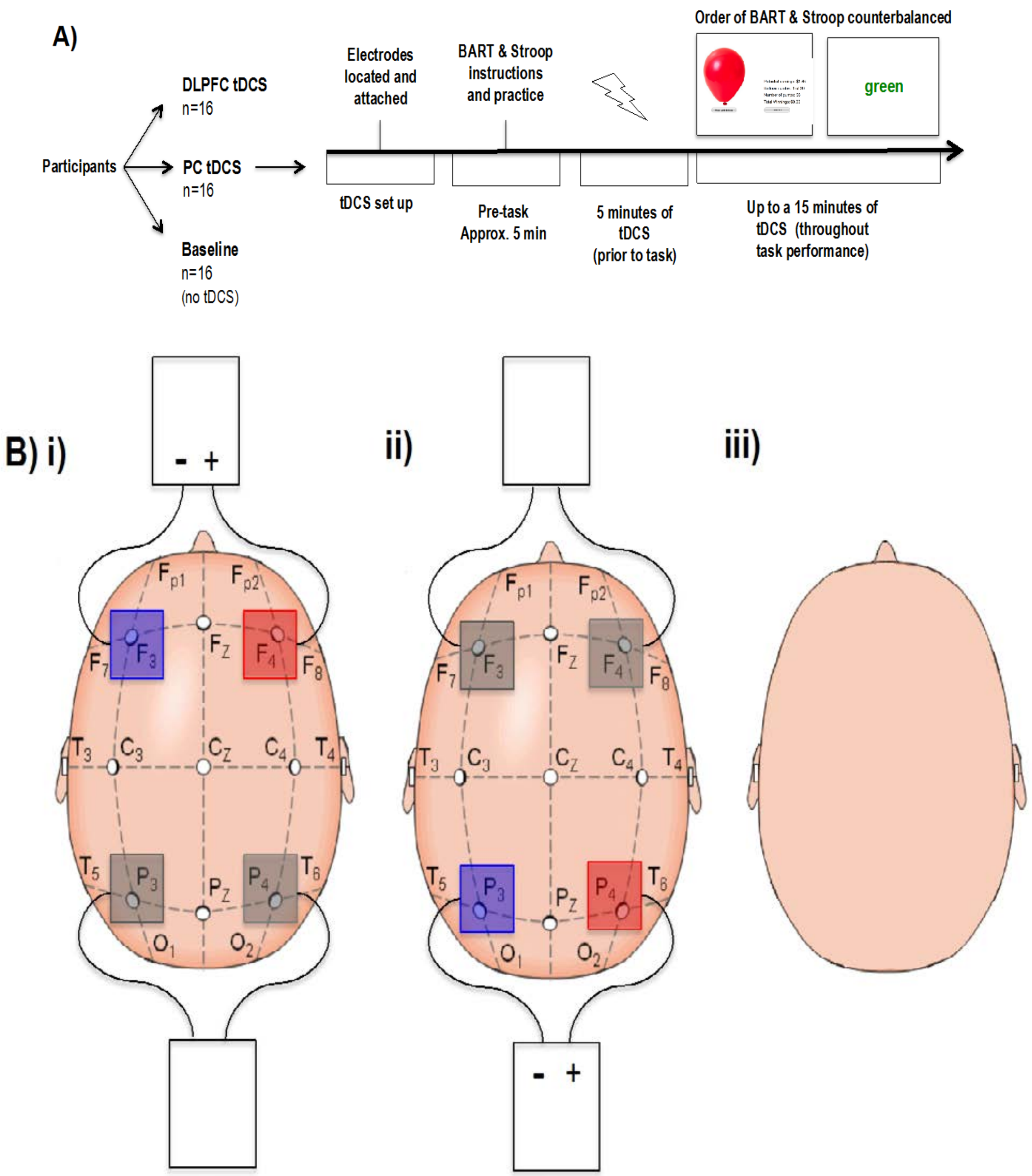


Figure 3.1 A) The experimental protocol; Participants were randomly assigned to one of three conditions, tDCS-DLPFC, tDCS-PC, baseline. Participants performed the BART and the Stroop task in a counterbalanced order. In the stimulation conditions, tDCS was delivered 5 minutes prior to task onset and then throughout task performance for a maximum of 20 minutes**. B)** Displays electrode placement and stimulation delivery for the three conditions **i)** DLPFC-tDCS, **ii)** PC-tDCS **iii)** Baseline. Red represent anode, blue represents cathode and grey represents an attached electrode with no stimulation delivered.

3.3.3. TDCS

tDCS was administered through a battery driven brain stimulator plus (Neuroconn, Germany), via standard sized rubber electrodes (5x7cm, 35cm^2). Stimulation was applied according to the parameters outlined in Fecteau, Pascual-leone, et al., (2007). In short, a constant current of 2mA was used, producing current densities of 0.057mA/cm^2. Stimulation began five minutes prior to the onset and continued throughout the course of task completion. The duration of stimulation was set to not exceed 20 minutes. This initial period of stimulation prior to task onset was chosen by Fecteau to reflect previous studies which have shown the excitability effects of tDCS to not be observed until 3-5 minutes into stimulation (Nitsche & Paulus, 2000). In keeping with previous work a 20 second fade-in fade-out period was used. These parameters did not exceed safety guidelines in healthy volunteers (Bikson, Datta, Elwassif, 2009).

The positioning of the electrodes was determined by the international 10-20 EEG system (Jasper, 1958), a method that has been shown to adequately target underlying structures (Herwig, Satrapi, & Schönfeldt-Lecuona, 2003), is standard in studies of neuromodulation (DaSilva, Volz, Bikson, & Fregni, 2011; Nitsche et al., 2008) and was used by Fecteau, Pascual-leone, et al., (2007). For the DLPFC condition, the centre of the anodal electrode placed over F4 (right DLPFC) and cathode over F3 (left DLPFC). For PC condition, the center of anode placed over P4 (right PC) and cathode over P3 (left PC). The electrodes were attached to the scalp with conductive paste and held in place with two rubber straps. This method differed from that used by Fecteau, Pascual-leone, et al., (2007) who applied electrodes via the saline soaked sponge method. Conductive paste was used to avoid problems of water leakiage in the saline soaked sponge method. To ensure double blinding all four electrodes (F3, F4, & P3, P4) connected to two separate devices were attached to the each participant in the stimulation conditions as shown in **Figure 3.1**b.

3.3.4. Decision-Making Tasks

3.3.4.1. BART

The BART (Lejuez et al., 2002) is a behavioural measure of risk taking under uncertainty. This task presents a number of computerized balloons that can be inflated to accrue money. If a balloon bursts before the money is transferred to a safe wallet, the winnings from the particular balloon are lost. This task has been described as a ‘strong naturalistic metaphor’ (Schonberg et al., 2011), the exhilaration of increased inflation in the context of the bursting elicits a strong affective response akin to the subjective experience of risk taking. As such the main dependent variable, the average adjusted number of pumps, has been shown to correlate with measures of real world risk taking. This includes frequency of substance use, smoking, stealing, risky sexual and delinquent behaviours, as well as self-report measures of risk related constructs such as sensation seeking and impulsivity in healthy adults and adolescences (Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Crowley, Raymond, Mikulich-Gilbertson, Thompson, & Lejuez, 2006; Lejuez, Aklin, Jones, et al., 2003; Lejuez, Aklin, Bornovalova, & Moolchan, 2005; Lejuez, Aklin, Zvolensky, & Pedulla, 2003).

The task initially presents a balloon on screen that is small in size (**Figure 3.2**). A button below the balloon with the text “pump the balloon” inflates the balloon when clicked. With each pump the balloon onscreen increases in size slightly and 5p is accumulated. Located to the left of the screen is an additional button labeled “Collect $$$”, this button allows the participant to transfer the money gained on the current balloon to their total winnings. Additionally on screen is the text “Potential Earnings” which displays the money collected on the current balloon and the “Total Winnings” outlining the collective amount of winnings from all previous balloons. After each pump participants are faced with the decision as to whether to continue inflating the balloon and risk explosion, or to stop pumping and transfer the money into their total winnings. When a balloon bursts, all the money accumulated on that balloon is lost, the partially inflated balloon disappears and the next balloon follows.

Each balloon has a unique randomly generated bursting point. The number of pumps that could be made before an explosion occurs ranges between 1-128, with the 'average' balloon bursting after 64 pumps. The computer program works by random number generation, initially between 1/128. If a 1 is drawn the balloon bursts, if not the number is removed and the algorithm continues. Therefore on the second pump, as one number will have been removed, the probability that the balloon would explode is 1/127. On the third pump, as two numbers will have been removed, the probability of bursting is 1/126, and so on. As a result, each pump is made in the context of increasing risk (increased probability of the balloon bursting). Moreover the relative reward gain decreases as the number of pumps increase, i.e. the second pump has a potential gain of 100% (from 5p to 10p) and the third a gain of 50% (from 10p to 15p). As a result some risk taking is necessary to obtain winnings, but excessive risk is associated with decreased returns, like behaviours in the real world participants must balance potential gains against possible losses.

Participants received written instructions to ensure consistency of task explanation across subjects as laid out by Lejuez et al., (2002). Importantly they were not given any specific information about the probability of explosion or the total amount of money possible to win. On this matter participants were instructed, "*it is your choice to determine how much to pump up the balloon, but be aware that at some point the balloon will explode. The explosion point varies across balloons, ranging from the first pump to enough pumps to make the balloon fill the entire computer screen."* (Lejuez et al., 2002).

In this version of the task there were 30 balloons in total. In contrast to the method presented in Lejuez et al., (2002) whereby participants received the amount of money accumulated on the task, the participant with the highest winnings received an additional cash prize of £30 payment.

The task was delivered via a laptop computer, with a 17-inch display screen, and was run via Inquisit software version 4.0.7.0 (Millisecond Software Seattle WA). Speakers or headphones were used to deliver sound effects from the task, including a slot machine pay off noise when money was transferred, as well as inflating and balloon bursting sounds.

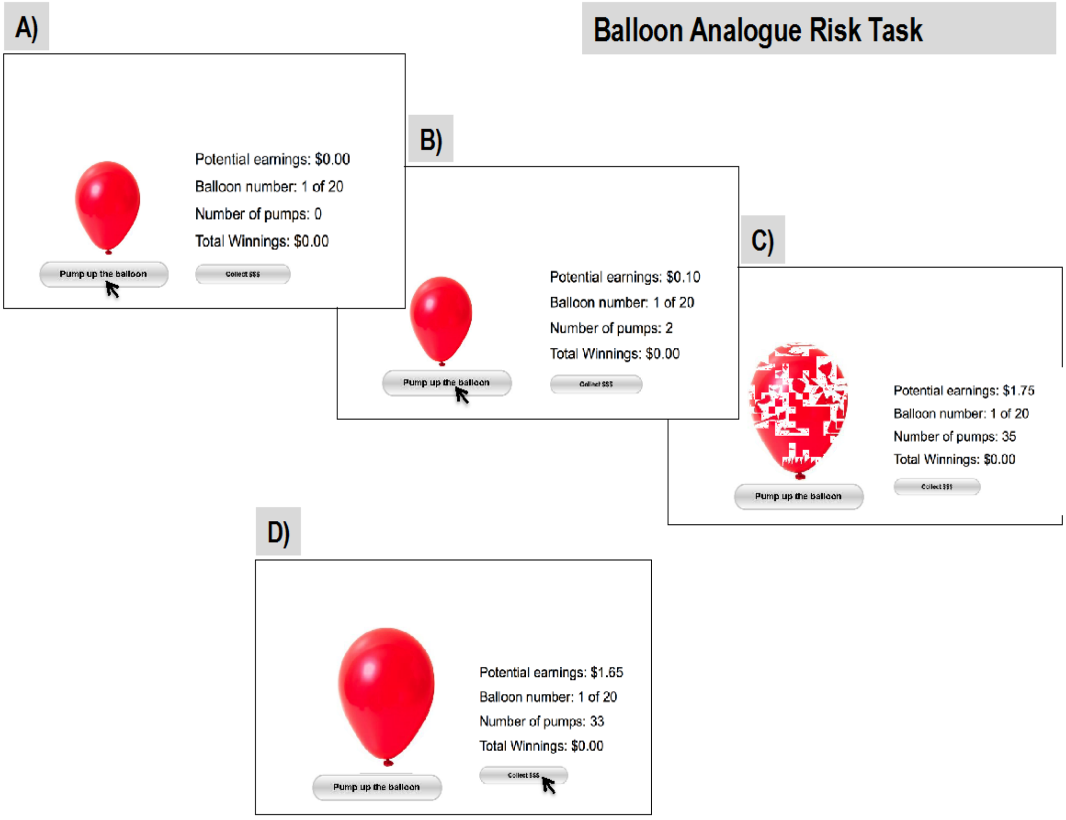


Figure 3.2: BART: **A)** Participants are required to inflate a balloon presented on screen and do so by selecting the pump up the balloon button with the mouse. **B)** With each pump 5p is earnt, which is added to the potential earnings. **C)** If the balloon bursts the potential earnings collected are lost and the next balloon appears. **D)** Participants have to decide the optimal point at which to bank the potential earnings and move these to their total winnings. They do so by clicking the collect button

3.3.4.2. Stroop Task

The Stroop task (Stroop., 1935) is a classic measure of interference, the additional processing required to override automatic responses. In this task participants were instructed to name the colour of items presented on screen. Colour words (red, blue, green and black) were presented in different colour text ink, thus the colour of the text was either congruent to the text (e.g. red written in red ink) or incongruent to the text (e.g. red written in blue, green or black ink). The Stroop interference effect refers to the increased amount of time it takes to name colours with incongruent text, compared to those with congruent text. This is because automatic access of word naming has to be overridden (Macleod, 1993).

The task had a total of 84 trials, the order of which were randomized (**Figure 3.3**). These consisted of 28 congruent trials and 28 incongruent trials, with each of the four colours being presented seven times. For the incongruent trials, each colour word was presented twice in each different colour (i.e. red presented in blue ink, green ink and black ink), and one of the colour-word pairing (randomly selected) was presented an additional time. There were also 28 control trials, which presented solid blocks of colour. Again each of the four colours were presented four times (the control trials were not used for the analysis of the task).

The task was self-paced, whereby the stimuli remained on screen until participants responded. Participants were required to identify the colour of the items via a button press; the d key for red, the f key for green, the j key for blue and the k key for black. When performing the task participants were instructed to keep the middle and fore fingers of their left hand over the d and f key and the middle and fore finger of their right hand over j and k key, to ensure prompt responses. Additionally participants were instructed to make their responses as quickly and accurately as possible. The task was run using a laptop computer with a 17inch screen via Inquisit software version 4.0.7.0 (Millisecond Software Seattle WA). Before commencing the task, participants undertook a short practice.

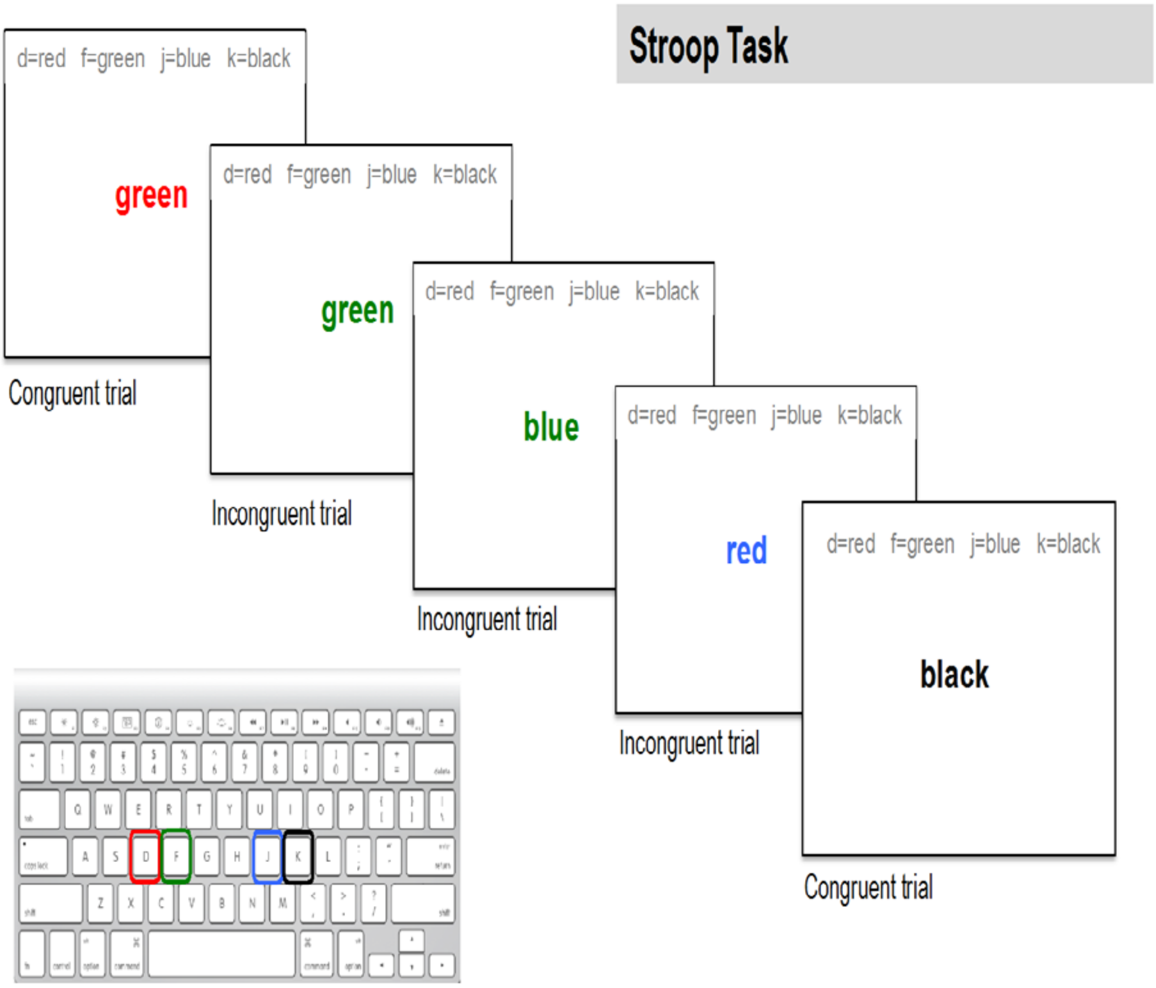


Figure 3.3: The Stroop task. The figure presents the trial types and required button presses. Participants are required to identify the colour of the word presented to them by a button press; d key for red, f key for green, j key for blue and the k key for black (highlighted on the keyboard). A congruent trial is when the ink colour is the same as the word (i.e. green written in green ink) an incongruent trial is when the ink colour is different to the word (i.e. green written in red ink).

3.3.5. Data Analysis

The analyses of these two tasks were undertaken in accordance with Fecteau, Pascual-leone, et al., (2007). The outcome variable for the BART was the average adjusted number of pumps, this is the number of times the participants pumped the balloon excluding the balloons that burst (calculated as: total adjusted number of pumps/number of non exploded balloons). The average adjusted number pumps are used to avoid the constraints of individual differences arising from the random point at which explosions occur (removing trials where the number of potential pumps were limited).

A mixed methods ANOVA was undertaken to compare the average adjusted pump count across the three experimental conditions (between subject factor: experimental condition: DLPFC-tDCS, PC-tDCS, baseline) broken down by time (within subjects factor of balloon number: 1-10, 11-20, 21-30). Post hoc comparisons were made using Bonferroni correction for multiple comparisons.

The outcome variable for the Stroop task was the interference effect. This is the difference in the time taken to identify the colour of a word written in a congruent colour compared to one written in an incongruent colour (calculated as: response times for incongruent trials minus response times for congruent trials). Response times for correct trials were used in the analysis. A One Way ANOVA was performed comparing the interference effect across the three experimental conditions (DLPFC- tDCS, PC-tDCS, baseline).

In the current replication both tasks were undertaken during stimulation (in a counterbalanced order). In comparison to Fecteau et al (2007) this meant that half the subjects in the stimulation conditions had undergone additional stimulation before commencing the BART. To ensure that this did not influence the results an additional analysis was undertaken. An independent samples t-tests was performed to compare the average adjusted pump count of those whom undertook the BART followed by the Stroop (BART first) with those who undertook the Stroop followed by the BART (BART second) in the DLPFC and PC tDCS conditions.

As there were a different proportion of male and female participants in the current study compared to Fecteau et al (2007) an additional analysis was undertaken to examine the influence of gender on the mean adjusted number of pumps. In particular a mixed methods ANOVA was performed this had a within factor of balloon number (balloon number 1-10, 11-20, 21-30), a between subject factor of experimental group (DLPFC-tDCS, PC-tDCS & baseline) and a between factor of gender (two levels: male; female). Post hoc comparisons were made using Bonferroni correction for multiple comparisons.

Table 3.1: Summary comparison of methodological parameters used in the current study & Fecteau, Pascual-leone, et al., (2007).

	Current study	**Fecteau, Pascual-leone, et al., (2007)**	**Details**
SAMPLE			
Number	48	30	Larger sample size in the current study.
Gender ratio	DLPFC tDCS: 50:50 Baseline condition: 50:50	DLPFC tDCS: 90:10 Baseline condition: 73:27	An equal ratio of males and females used in the current study to remove gender as a confounder.
Handedness	All right handed	Right (n=28) and left handed (n=2)	The sample of the current study included only right handed participants.
Age (mean)	24 years	21 years	
Recruitment source	Local University		
Heath status	Healthy		
STIMULATION			
Device	**NeuroConn Plus**	The device used developed by the research group	
Electrode attachment method	Electrode gel	Saline soaked sponges	Electrode gel used to avoid problems with water leakage.
Electrode size	$35cm^2$		Identical
Intensity / current density	$2mA/ 0.057mA/cm^2$		Identical
Location of electode: replication condition	Bilateral DLPFC: RH anode/ LH cathode	Bilateral DLPFC: RH anode/ LH cathode	Identical
Location of electrodes: active control condition	Bilateral PC: RH anode/ LH cathode	Unilateral DLPFC: DLPFC/ contralateral mastoid	An active control condition to examine whether behavioural effects were due to the concurrent excitation and inhibition of homotopic regions implicated in decision-making was included.
Duration	>20mins		As the Stroop task was undertaken during stimulation, half of the participants in the current study will have received 3 minutes more tDCS before

			commencing the BART. The effect of this was determined for in additional analysis.
Method of localizing	EEG 10-20 system		Identical
Baseline	No stimulation	Sham	Sham stimulation has come under criticism as a baseline as stimulation is still applied to the cortex albeit for 30 seconds.
Blinding	Single	Double	Both the experimenter and participant were unaware of experimental condition in the current experiment.
TASKS			
BART: Number of trials	30 balloons		Identical
BART: Reimbursement	Cash reward to the highest earner		Identical
Online/ Offline	BART: Online Stroop: Online	BART: Online Stroop: Offline	When comparing performance on different tasks it is important to subject them to the same type of stimulation.
Analysis	Repeated measures ANOVA		Identical

3.4. Results

The total time taken to complete the tasks did not differ across the three experimental conditions (DLPFC-tDCS, PC-tDCS, baseline) ($F_{(2,45)}=0.16$, $p=0.86$).

3.4.1. The Effect of tDCS on the BART

A repeated measures ANOVA was performed to examine the average adjusted number of pumps in the three conditions (DLPFC-tDCS, PC-tDCS & baseline) broken down by time (balloon number 1-10, 11-20, 21-30) (**Figure 3.4**). This revealed that there were no significant differences in the average adjusted number of pumps between the three experimental groups ($F_{(2,45)}=0.32$, $p=0.73$). There was a significant effect of balloon number of the adjusted number of pumps ($F_{(1.44,64.78)}=34.00$, $p<0.01$) and no significant interaction of experimental condition and balloon number ($F_{(2.88,64.78)}=1.34$, $p=0.27$). Post hoc pairwise comparisons revealed significant differences between all time categories, including balloons 1-10 and 11-20, between balloons 11-20 and 21-30, and between balloon 1-10 and 21-30 (All Bonferroni corrected, $p<0.01$; Figure 2.4). Therefore, tDCS to the DLPFC does not appear to affect decision-making behavior under uncertainty, as assessed by the adjusted number of pumps on the BART.

Task order effects: Independent t-tests revealed that there was no significant effect of task order on performance of the BART for either the DLPFC ($t_{(14)}=-0.97$, $p=0.35$) or PC ($t_{(14)}=-0.10$, $p=0.92$) condition. Therefore the average adjusted pump count was not influenced by additional tDCS received as a result of prior Stroop task performance, in either stimulation condition.

Gender effects: ANOVA analysis revealed that there were no significant effect of gender on the average adjusted number of pumps ($F_{(1,42)}=0.02$ $p=0.90$) and no significant effect of experimental group ($F_{(2,42)}=0.32$, $p=0.73$). As seen previously there was a significant effect of balloon number of the adjusted number of pumps ($F_{(1.39,58.38)}=32.97$, $p<0.01$). There were also no significant interactions of gender and the main effects, including balloon number and gender ($F_{(2,58.378)}=0.621$, p=0.484) or balloon number, gender and experimental group ($F_{(2,70,\ 58.38)}$=0.51, p=0.66).

3.4.2. The Effect of tDCS on the Stroop Task

All participants completed the task with a high level of accuracy (mean accuracy 96.30% correct). A one way ANOVA revealed no significant differences in the interference effect across the different experimental conditions ($F_{(2,47)}$=0.26, p=0.77; **Figure 3.5**)

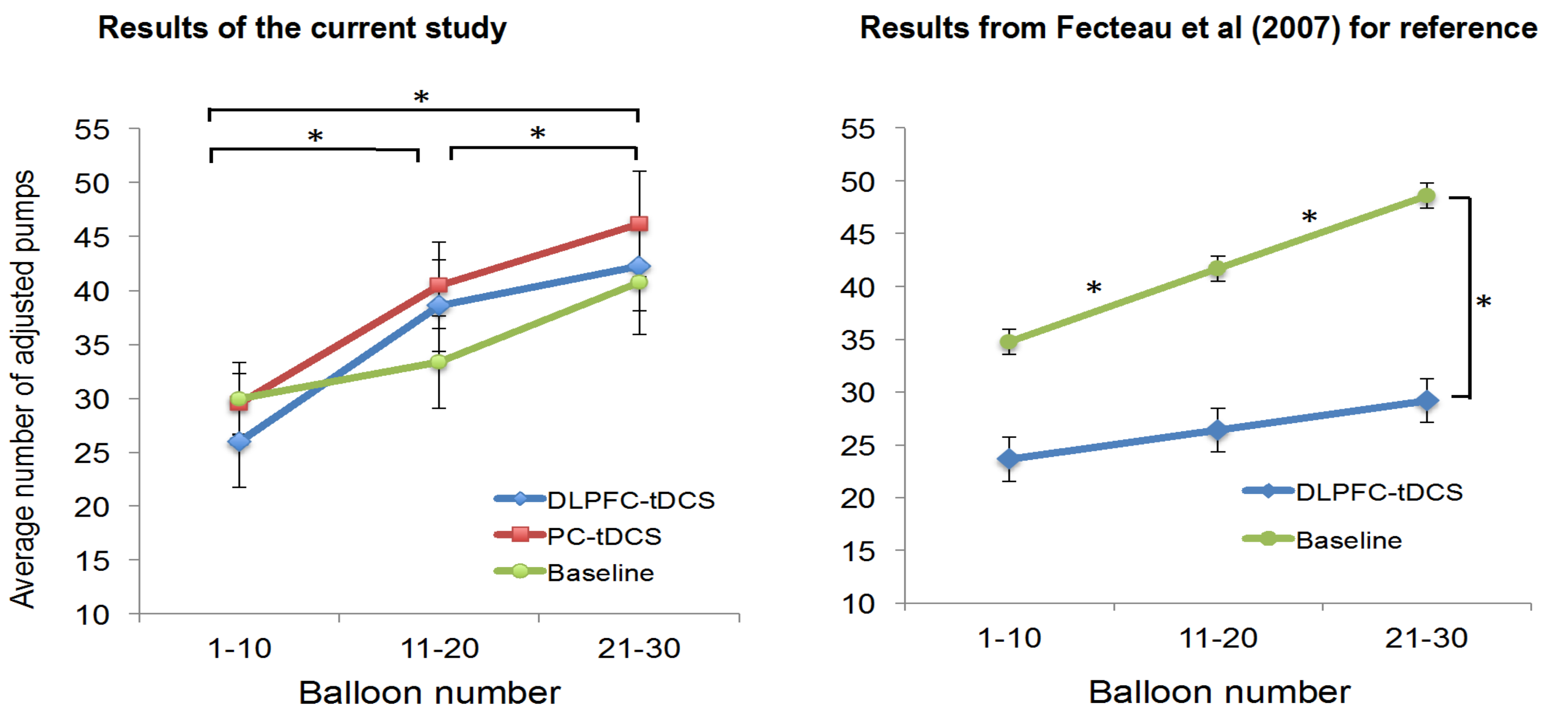


Figure 3.4: BART results; left; In the current study there were no significant differences in the average adjusted number of balloon pumps between conditions. There was a significant effect of balloon number and the average adjusted number of pumps significantly increased as the task progresses. **Right*:*** Fecteau, Pascual-leone, et al., (2007) showed a significant decrease in the average adjusted number of pumps following DLPFC tDCS. There was also a significant interaction of condition and time. In the baseline condition there were significant increases over time, which was not observed in those receiving DLPFC tDCS. * denotes a statistically significant difference at $p<0.05$. Error bars represent SEM.

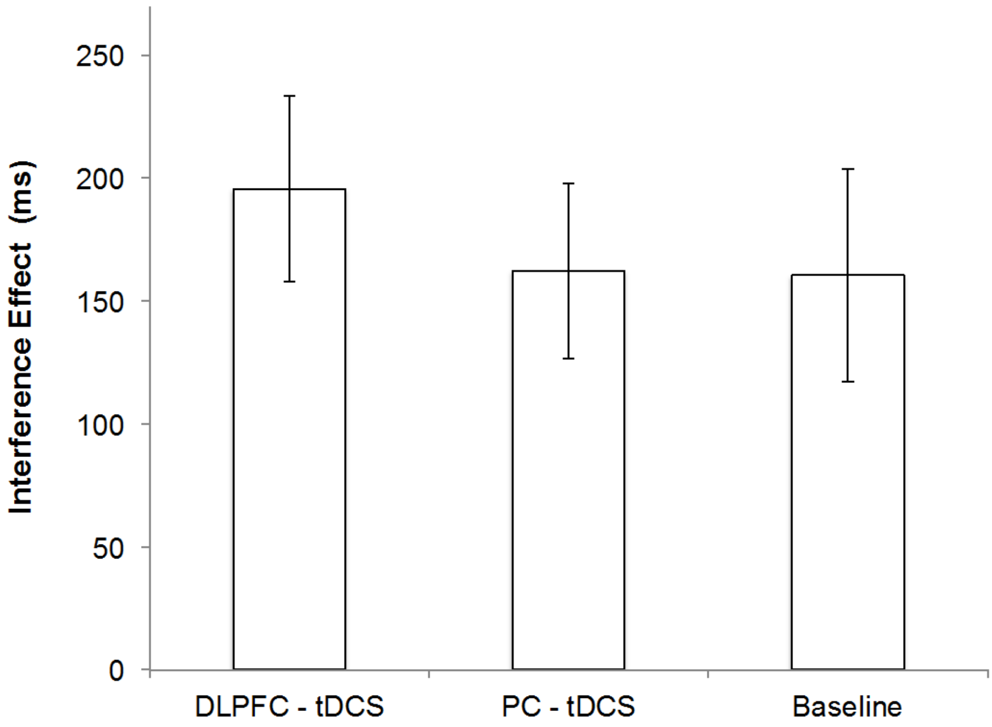


Figure 3.5: Stroop task results: In accordance with Fecteau, Pascual-leone, et al., (2007) there were no significant differences in the interference effect across experimental conditions**.** Interference effect was calculated as mean latency to incongruent words minus congruent words**.** Error bars represent SEM.

3.5. Discussion

The aim of the current study was to replicate the methodology of Fecteau, Pascual-leone, et al., (2007), in order to determine the reliability of tDCS as a tool to modify risky decision-making. Due to a number of subsequent discrepant findings (Cheng & Lee, 2016; Weber et al., 2014) a conceptual replication was thought necessary as an initial first step in exploring the potential application of tDCS in the training of athletes. The results of the current study reveal no significant reductions in risk taking behaviours following bilateral DLPFC tDCS analogous to those reported by Fecteau, Pascual-leone, et al., (2007) despite close adherence to the methodology of the original study. As such this non-replication result raises concerns over the effectiveness of tDCS as a modulator of decision-making under uncertainity and the potential for application outside the laboratory.

In particular, the results of the current study showed no effect of experimental condition (tDCS-DLPFC, tDCS-PC or Baseline) on the average adjusted number of balloon pumps, the main measure of risky decision-making within the BART. This is in direct contradiction to the findings of Fecteau, Pascual-leone, et al., (2007) who found that tDCS applied bilaterally to the DLPFC led to a reduction in the average adjusted number of balloon pumps. Specifically, in the baseline condition there were significant increases in the average adjusted number of pumps over time not observed in those receiving DLPFC tDCS. Fecteau, Pascual-leone, et al., (2007) claimed that these reductions in risky decision-making with bilateral DLPFC tDCS reflected the concurrent excitation and inhibition of alternate hemispheres. In the current study there was a main effect of time (but no time * condition interaction), indicating a general increase in the average adjusted number of balloon pumps as the participant progressed with the task. This effect is documented in a number of other studies (Lejuez, Aklin, Zvolensky, et al., 2003; Weber et al., 2014) and is thought to be typical of the learning that participants undergo when performing the task. In both the current study and Fecteau, Pascual-leone, et al., (2007), there were no effects of tDCS on performance of the Stroop task (as measured by the interference effect). The task was included in the study design as a control task to allow conclusions about the specificity of cognitive effects.

In addition to failing to replicate Fecteau, Pascual-leone, et al., (2007) the findings of the current study also stand in contrast to Gorini et al., (2014) who reported similar reductions in risk taking on the BART following DLPFC tDCS in healthy adults and participants experiencing withdrawal from cocaine. The results do, however, align with two further studies that also failed to find behavioural differences on BART performance with DLPFC tDCS. The first is Weber et al., (2014) who additionally used fMRI to assess changes in task performance induced by tDCS. In this study tDCS was applied offline prior to task and the task was modified to make it appropriate for fMRI analysis in that the balloons had a decreased average bursting point and no monetary rewards were awarded. An additional study by Cheng & Lee, (2016) also failed to replicate the finding of Fecteau, Pascual-leone, et al., (2007). This study reflected the original methodology more closely, however used a version of the BART that had a fewer number of balloons (20 instead of 30). This may have been pertinent to the replication attempt as differences in risk taking reported by Fecteau, Pascual-leone, et al., (2007) were largest in the last half of the task (Cheng & Lee, 2016). However this is not supported by the current study that used the same number of balloons and also failed to replicate initial findings. The current study adds to these two findings raising doubt about the reliability of the original results.

Indeed the absence of any consistent findings in our study is notable given the improvements made to the methodology used by Fecteau, Pascual-leone, et al., (2007). Stimulation parameters, including onset, current density and methods of localization were identical in the two studies, as were the behavioural tasks used as indices of decision-making under uncertainty and reimbursement approaches (comparison parameters are outlined in Table 3.1). What is more is that in the current study the sample size was larger than that used in Fecteau, Pascual-leone, et al., (2007) and a number of methodological improvements were implemented. These are outlined below and where appropriate their possible contribution to the discrepant findings are considered.

In the current study an apriori power analysis was undertaken to ensure the sample size was adequate to detect an effect of similar magnitude as reported by Fecteau, Pascual-leone, et al., (2007). The sample was 60% larger in the current study in comparison to Fecteau, Pascual-leone, et al., (2007) indicating that the failure to replicate in the current instance is unlikely to be a reflection of a lack of power. A further improvement in terms of the sample characteristics is that the current study consisted of an equal ratio of males and females that was the same across conditions (per condition: n=16, 8 males and 8 females). This was not the case for Fecteau et al (2007) whose sample was predominantly female (90% in the DLPFC-tDCS right anodal left cathodal condition and 73% in the baseline condition) and of different gender ratios across conditions. The difference between the two studies may be notable in light of work that has demonstrated gender differences in the cortical plasticity induced by tDCS (Kuo, Paulus & Nitsche et al 2006). Additional analysis also showed that there was no effect of gender on the results of the current study. Other than this, it is important to note the characteristics of these samples were similar in terms of demographic variables such as age (mean age, current study: 24 years; Fecteau: 21 years) and level of education (consisting of mainly undergraduate students).

A further improvement made to the Fecteau, Pascual-leone, et al., (2007) experimental methodology was in terms of timing of stimulation in relation to tasks. In Fecteau, Pascual-leone, et al., (2007) the onset of stimulation occurred 5 minutes prior to and throughout performance of the BART, whereas the Stroop task was performed pre and post stimulation. The physiological effects induced during tDCS are different from those arising following stimulation, and thus the two tasks were subjected to different types of stimulation (Stagg & Nitsche, 2011). In order to improve on this, the current study was designed in a way to avoid comparing the effects of online stimulation on the BART with the effects of offline stimulation on the Stroop task. In considering the short duration of the Stroop task (maximum 3 minutes), tDCS was administered for 5 minutes prior to tasks, and then continued throughout performance of both the BART and Stroop task, (with the order of these counterbalanced across participants). This meant the comparison of tDCS effects on the BART and Stroop was more valid in the current study.

In the context of this amendment, it did mean that in the current study half of the sample performed the BART following an additional approximately 3 minutes of stimulation, in comparison to Fecteau, Pascual-leone, et al., (2007). However attempts were made to minimize discrepancies across the two studies, as duration of stimulation is known to be an important factor for inducing the effects of tDCS (Fricke et al., 2011; Nitsche & Paulus, 2000; Nitsche et al., 2005). In both studies the total duration of tDCS did not exceed 20 minutes. In the current study all participants completed the tasks within this duration, apart from one participant who took a total 22 minutes from the onset of stimulation. For this participant the last two minutes of BART performance occurred with no stimulation. The results of the current study do not change when this participant was excluded from the analysis. Secondly additional analysis was undertaken to show that task order had no affect on performance of the BART in the stimulation conditions. Lastly double blinding was used in the current experiment whereby the experimenter and participant were unaware of the stimulation type, which was not the case for Fecteau, Pascual-leone, et al., (2007). Therefore in the current study there was improved control of confounding variables relating to experimenter expectation biases.

Given the current findings, in light of a larger sample size and a number of methodological improvements, there is room to suggest that the original findings of Fecteau, Pascual-leone, et al., (2007) may simply not be valid, and represent an example of a type 1 error. Type 1 errors, or false positives, result in the incorrect rejection of the null hypothesis. They can arise from a lack of methodological rigor and as a result of p value statistical approaches (i.e. with a p value of 0.05 – the accepted approach in psychology- there is at least 5% probability of a type 1 error) (Ioannidis et al., 2005). The prevalence of type 1 errors maybe further inflated as the published literature in a given field is likely to be an inaccurate representation of all the data collected due to the bias of journals and researchers to publish positive results (Rosenthal & Robert, 1979).

Replicability is the cornerstone of scientific research and as such independent verification of results in different laboratories important for a field to progress (Simons, 2014). While the findings of the current study relate to a specific measure of risk taking and method of applying tDCS**,** concerns of non-replicability have been widely discussed in the cognitive neuroenhancement literature (Horvath et al., 2015; Parkin et al., 2015; Riggall et al., 2015; Sahlem et al., 2015; Vannorsdall et al., 2016). In particular a recent study into researchers perspectives in this area (Riggall et al., 2015) highlight an overemphasis of positive results, non-reporting of negative findings, as well as weak methodological rigor as some of the main issues facing the application of TES techniques. Moreover, in a recent quantitative meta-analysis of the literature there was found to be no evidence of cognitive effects in healthy populations from single-session tDCS (Horvath et al., 2015), and thus the findings of the current study may not be entirely surprising. However it should be noted that the selection criteria of the aforementioned meta-analysis in question has been criticized (Price et al., 2015). It is important to have consistent replicable findings if one was to attempt application outside of the laboratory especially in samples groups whose time and access is limited like elite athletes.

3.6. Conclusion

In conclusion, the results of the current study failed to replicate findings from Fecteau, Pascual-leone, et al., (2007), and DLPFC tDCS was shown to have no effect on decision-making under uncertainty as assessed by BART performance. This work raises concerns about the effectiveness of DLPFC tDCS in modifying risk taking during decision-making under uncertainty. While the findings of the current study relate to one behavioural target and method of applying tDCS, they do echo a number of inconsistent results within the field (Cheng & Lee, 2016; Fecteau et al., 2014; Minati, Grisoli, et al., 2012; Weber et al., 2014) and draw attention to recent criticisms relating to the efficacy of single session tDCS in cognitive neuroenhancement (Horvath et al., 2015). Furthermore these results undermine the proposed progression towards applying tDCS to decision-making training in elite athletes. In the subsequent chapters the physiological underpinnings of tDCS and its failure in decision-making is explored, before returning to sport and decision-making.

4. Do the Physiological Effects of tDCS Transfer to Bilateral Montages at 1mA and 2mA

4.1. Abstract

Background: In this chapter the physiological basis of the failure to replicate Fecteau, Pascual-Leone et al., (2007) is explored. tDCS has been shown to induce polarity dependent shifts in cortical excitability, with anodal stimulation exerting an excitatory influence, and cathodal an inhibitory influence, on underlying neurons (Nitsche & Paulus, 2001; Nitsche et al., 2003). Our knowledge of these effects is based on work that applies stimulation of 1mA, with current densities of 0.029mA/cm^2, via the target electrode over M1 and the reference electrode over the contralateral orbit (known as a unilateral electrode montage; for a summary see Stagg & Nitsche, 2011). In Fecteau, Pascual-Leone et al. (2007), however, stimulation was applied using a bilateral electrode montage, where both electrodes are situated over the same cortical region on opposing hemispheres, at an intensity of 2mA and current densities of 0.057mA/cm^2. These divergent parameters are common among studies in the cognitive neuromodulation field, as is the assumption that the induced anodal-excitatory /cathodal-inhibitory effects remain unchanged. There are a number of reasons to question this assumption. Bilateral montages change the location, amount and depth of current flow through the cortex (Bestmann et al., 2015; Bikson et al., 2012; Datta et al., 2010; Datta, Elwassif, Battaglia, & Bikson, 2008; Miranda, Lomarev, & Hallett, 2006), and give rise to the possibility of inter-hemispheric interactions (Kimura, 1967). Moreover, research has shown that increasing cathodal stimulation intensity/current density from 1mA/0.029mA/cm^2 to 2mA/ 0.057mA/cm^2 induces excitatory effects (Batsikadze, Moliadze, Paulus, Kuo, & Nitsche, 2013). Empirically testing whether the anodal excitatory cathodal inhibitory effects of tDCS extend to bilateral montages and increased stimulation intensities will shed light on the validity of the physiological explanation of findings in Fecteau, Pascual-leone, et al., (2007). Moreover it will provide a necessary basis from which to interpret the tDCS and decision-making literature in light of potential application to elite athletes.

Objective: To assess the influence of electrode montage (unilateral and bilateral), and current intensities (1mA and 2mA) on the anodal and cathodal effects of tDCS.

Method: Anodal and cathodal tDCS was applied using either the traditional unilateral M1/ contralateral orbit montage at 1mA (experiment 1), or a bilateral electrode montage (left and right M1) at 1mA (experiment 2) or 2mA (experiment3). In each case stimulation was delivered for 10 minutes. Changes in cortical excitability were measured using MEP amplitude, at 5 minute intervals for 30 minutes post stimulation.

Results: In experiment 1, when tDCS was applied using the unilateral M1/contralateral orbit montage at 1mA, the classic effects of anodal-excitation/ cathodal-inhibition were found. Thus, unilateral anodal stimulation induced elevations in MEP amplitude, in comparison to cathodal stimulation that induced decreases in MEP amplitude. In experiments 2 & 3, when tDCS was applied with a bilateral electrode arrangement, these opposing polarity dependent shifts were not retained (for neither 1 nor 2mA) and there were no significant modulations of MEP amplitude.

Conclusion: These findings highlight that the anodal or cathodal nature of an electrode does not directly dictate its effect as either excitatory or inhibitory. As such, the physiological effects of tDCS should not be taken for granted, unless based on previous physiological work that has used similar parameters. These results also provide an explanation for the failure to replicate Fecteau, Pascual-Leone et al (2007), and raise concerns over the assumptions of anodal-excitation/cathodal-inhibition that underpin the rationale and justification of results in this study. Such concerns also extend to the wider literature, as many other studies in the decision-making and neuromodulation field have used similar stimulation parameters. Together, the results of chapters 3 and 4 suggest that the modulation of decision-making with tDCS is unreliable, and studies in this field lack an understanding of the physiological underpinning of their results. This undermines the original proposal of applying tDCS for decision-making training in elite athletes.

4.2. Introduction

A cornerstone of our understanding of the effects of tDCS on the human cortex is that it induces polarity dependent shifts in cortical excitability, with anodal stimulation exerting an excitatory effect and cathodal stimulation an inhibitory effect on the neuronal tissue underlying the electrodes (Nitsche & Paulus, 2001; Nitsche et al., 2003). The physiological basis of these effects has been widely explored through the study of motor cortex plasticity (for a summary see Stagg & Nitsche, 2011).

The classical studies of Nitsche & Paulus (2001) and Nitsche et al (2003), which originally demonstrated anodal-excitation/ cathodal-inhibition, examined modulation of the MEP amplitudes induced by single pulse TMS (see **Figure 2.4**a). MEPs are a global parameter of corticospinal excitability and changes in their amplitude are thought to reflect a sub-threshold depolarization (anodal) or hyperpolarization (cathodal) of resting membrane potentials (Tergau & Paulus, 2008). At a conceptual level, such modifications make it more (anodal) or less (cathodal) likely that stimulation of a neuron will produce an action potential (Bestmann et al., 2015; Kuo & Nitsche, 2012). The work that provided the groundwork of the anodal-excitatory/ cathodal inhibitory model of tDCS has applied stimulation using precise and consistent parameters. In particular, as studies aim to investigate anodal and cathodal effects in isolation, a unilateral electrode array is almost always applied. This is where the 'active' electrode, the one that is the focus of study, is placed over M1. The alternate 'reference' electrode is placed over the contralateral orbit, a region conceptualized as a dead spot unimportant to inducing effects. Other common reference positions are away from the head (e.g. the upper arm). In addition to this, almost all of this work has delivered tDCS at an intensity of 1mA and density of 0.029mA/cm^2. There is a much more limited understanding of the physiological effects of tDCS outside of these parameters (Lindenberg et al., 2016).

In line with the capacity to modulate neuronal excitability, tDCS has been widely applied to modify human brain function in healthy controls (Jacobson, Koslowsky, & Lavidor, 2012) and clinical populations (Flöel, 2014). These studies use the anodal-excitation/ cathodal-inhibition model of tDCS to guide the mechanistic rationale for application and to explain findings. The majority of studies within the field, however, have applied tDCS using parameters that differ from those used to induce the classical effects of anodal-excitation/ cathodal-inhibition, yet have assumed these effects remain. This is true for Fecteau, Pascual- Leone et al (2007) here instead using a unilateral montage at 1mA/ 0.029mA/cm^2, stimulation was applied bilaterally to the DLPFC at an increased intensity of 2mA/ 0.057mA/cm^2. The behavioural findings of reduced risk taking were proposed to arise from the concurrent excitation and inhibition of the opposing hemispheres, while the possible influence that modifying electrode positioning and stimulation intensity were not considered.

There are a number of reasons to suggest changes to electrode montage, from unilateral arrangement, used in studies of motor physiology, to bilateral arrangement, used in cognitive neuromodulatory studies, may influence the effects of tDCS. In particular the position of the return electrode governs the current flow throughout the cortex. Computational modeling studies have suggested that there is likely to be changes in the amount and depth of current entering the brain due to differences in interelectrode distances between the two montages (Bestmann et al., 2015; Bikson et al., 2012; Datta et al., 2010; Datta, Elwassif, Battaglia, & Bikson, 2008; Faria et al., 2012; Miranda, Lomarev, & Hallett, 2006). Moreover there is the possibility that inter-hemispheric interactions may occur with bilateral stimulation which might modify the effects of tDCS (Kimura, 1967).

In spite of this, there is some evidence that the anodal-excitatory/ cathodal-inhibitory effects of tDCS may be retained with bilateral electrode placement. This issue has been the focus of two previous studies. Mordillo-Mateos et al., (2012) reported bilateral anodal stimulation at 2 mA, (with a current density of 0.057mA/cm^2), delivered for 5 minutes, to cause an initial increase in MEP amplitude, and bilateral cathodal to cause an initial decrease in MEP amplitude, results that were not sustained for the second time point taken at 20 minutes. Moreover Kidgell et al., (2013) also reported anodal-excitatory and cathodal-inhibitory effects on MEP amplitude following bilateral motor cortex stimulation at

1mA, with a current density of 0.040mA/cm^2. In this case stimulation was delivered for 13 minutes. Despite these initial studies, further explorations are warranted, especially in the case of 2mA/ 0.057mA/cm^2 stimulation where duration is likely to be a further parameter that dictates the physiological effects (Nitsche & Paulus, 2001; Nitsche et al., 2003; Paulus, Antal & Nitsche., 2013).

When applying tDCS to modify cognitive functioning stimulation intensities of 2mA (current densities of 0.057mA/cm^2) are routinely used, predicated on the assumption that increasing stimulation intensities will enhance the efficacy of the anodal and cathodal effects. There is some evidence to support the assumption that increasing intensities enhances the effect of stimulation for intensities from 0.2mA-1mA (current densities of 0.005mA/cm^2 - 0.029mA/cm^2) (Nitsche & Paulus, 2000). However, when stimulating at intensities akin to those used in the cognitive neuromodulatory literature this linear relationship has been shown to break down. In particular, work by Batsikadze et al., (2013) revealed that when increasing stimulation intensity from 1mA/0.029mA/cm^2 to 2mA/0.057mA/cm^2 (using a unilateral electrode array) tDCS loses its opposing polarities and cathodal stimulation induces excitatory effects (for stimulation duration of 5 minutes). Moreover, Wiethoff, Hamada, & Rothwell, (2014) reported no cathodal inhibitory effects following tDCS delivered at 2mA (stimulation duration of 10 minutes) (Wiethoff et al., 2014). These findings are problematic for studies that have stimulated at 2mA and assumed anodal and cathodal polarity dependent shifts in cortical excitability.

The current study is motivated by concerns over the generalization of the anodal-excitatory/ cathodal-inhibitory model of tDCS. Findings from the physiological sciences have been extrapolated to all studies that employ tDCS, despite differences in stimulation protocols. Thus the aim of the study is to explore the effects of tDCS using parameters that have become standard in an increasing number of studies (Wiethoff et al., 2014) including those employed by Fecteau et al., (2007) - in particular, bilateral electrode montages with increased stimulation intensities. This will allow an examination of the underlying assumptions that guide the mechanistic rationale for application, and that are used to interpret findings cognitive neuromodulatory studies. In particular, the results will shed light on the validity of the physiological explanation provided for the results described in Fecteau et al., (2007) and form a basis from which to evaluate the wider tDCS and decision-making literature in light of potential application to elite athletes.

In order to investigate this, three experiments were performed, each of which assess the anodal and cathodal effects of tDCS protocols through the measurement of corticospinal excitability via modulation of MEP amplitude. In the first experiment, a replication of the parameters used in classical studies of motor physiology is performed. Unilateral-anodal and unilateral-cathodal tDCS was applied where electrodes were positioned with the target (e.g. in the unilateral anode condition this is the anodal electrode) over left M1 and reference over the contralateral orbit (e.g. in the unilateral anode condition this was the cathode) at 1mA. In the second experiment bilateral-anodal and bilateral-cathodal electrode montages at 1mA were studied, and in the third experiment these same montages at 2mA. In these bilateral stimulation conditions, electrodes were placed with the target over left M1 (e.g. in bilateral anode condition this was the anode) and reference over right M1 (e.g. in the bilateral anode condition this was the cathode). Modulations in MEP amplitude were assessed up to 30 minutes post stimulation, at 5-minute intervals.

4.3. Methods

4.3.1. Participants

4.3.1.1. Experiment 1 - Unilateral 1mA

Twelve subjects participated in experiment 1 (6 female, mean age = 20; age range 18-27), eight of whom undertook both unilateral-anodal and unilateral-cathodal conditions. The remaining four participants undertook either the unilateral-anodal or unilateral-cathodal condition and were excluded from the analysis.

4.3.1.2. Experiment 2 - Bilateral 1mA

Eleven subjects participated in experiment 2 (6 female, mean = age 21; age range 18-21). Nine subjects undertook both bilateral-anodal 1mA and bilateral-cathodal 1mA stimulation. Two subjects undertook either bilateral-anode 1mA or bilateral-cathodal 1mA stimulation and were excluded from the final analysis.

4.3.1.3. Experiment 3 - Bilateral 2mA

Eleven subjects undertook experiment 3 (6 female, mean age = 21; age range 18-21), nine of which undertook both bilateral-anodal 2mA and bilateral-cathodal 2mA stimulation. A further two subjects undertook either bilateral-anode or bilateral-cathodal stimulation and were excluded from the final analysis.

Upon expressing an interest in taking part in the study, participants were screened to determine their eligibility to participate in brain stimulation research (no history of acute or chronic medical, neurological or psychiatric diseases, not currently taking any medication and no problematic metallic implants). Those with any contraindications were not recruited. All participants were right hand dominant and in accordance with previous work (eg. Jo et al., 2009; Nilsson, Lebedev, & Lövdén, 2015) there was a wash out period of at least three days prior to the experiment during which participants must not have received brain stimulation. All participants gave their written informed consent and were financially compensated for their participation at a standard rate. The study and consent procedures were approved by UCL ethics committee in accordance the declaration of Helsinki.

4.3.2. Experimental Protocol

For each experiment a within subject design was used, participants were randomly assigned to anodal or cathodal stimulation conditions and the order of these session were counterbalanced across subjects. Each experimental session followed the same procedure, regardless of condition (**Figure 4.1**). Following consent procedures and study explanation, participants were seated in a chair with their hands resting on a pillow. Participants were instructed to keep their arms still but relaxed throughout the experiment. First, the site for TMS assessment was identified using single pulse TMS (the coil position that produced the largest MEP amplitude in the FDI muscle) and marked with a pen. The coil orientation was also identified by drawing a line on the scalp that outlined the contour of the coil, these marks were used to ensure consistency in the placement throughout the experiment. In experiments 2 and 3, the motor hotspot was also located on alternate hemisphere, which was used to ensure precise placement of the bilateral tDCS electrode.

Once the site for TMS assessment was located, the TMS intensity was adjusted to elicit MEPs with peak-to-peak amplitudes of approximately 1mV, and baseline MEPs were then recorded. Following this, tDCS was administered for 10 minutes, the placement of the electrodes and intensity were determined according to condition. Immediately after stimulation the electrodes were removed and the participant’s scalp briefly cleaned. MEPs were then recorded at five-minute intervals for thirty minutes post stimulation (5, 10, 15, 20, 25, 30 minutes post). In all experiments, a single-blind design was used where participants did not know what type of stimulation (anodal or cathodal) they were receiving, at the end of the experiment the participant was appropriately debriefed and paid for their participation.

4.3.3. TDCS

tDCS was delivered by a battery-driven constant current stimulator (Neuroconn, Germany) via a standard pair of rubber conductive electrodes (5x7cm, surface area of 35cm^2 each). The electrodes were attached to the scalp with conductive paste and held in place with two rubber straps. This method was used to ensure precise stimulation of the intended region and avoid the potential problems of water leakage with the saline soaked sponge method. In all conditions, stimulation was applied for 10 minutes, with a 15 second phase in / phase out period. The stimulation parameters employed did not exceed safety limits (Bikson, Datta, & Elwassif, 2009). Two types of electrode montage, unilateral and bilateral, were examined across the three experiments (**Figure 4.1**).

4.3.3.1. Experiment 1- Unilateral 1mA

In experiment 1, tDCS was applied using a unilateral montage. Here, the active electrode was fixed over left M1, with the centre of the electrode positioned over the site identified for TMS assessment. The reference electrode was placed horizontally over the right contralateral orbit. For unilateral-anodal stimulation the anode was placed over left M1 and the cathode over the contralateral orbit. For unilateral-cathodal stimulation the cathode was placed over left M1 and the anode over the contralateral orbit. Unilateral stimulation was delivered at 1mA, creating a current density of 0.029mA/cm^2.

4.3.3.2. Experiment 2- Bilateral 1mA

In experiment 2, tDCS was applied using a bilateral montage where the active electrode was fixed over left M1 and the reference electrode over right M1. For bilateral-anodal stimulation the anode was positioned over left M1 and cathodal over right M1 and for bilateral-cathodal stimulation the electrode polarity was reversed. In each case electrodes were centered over the motor hotspot identified by TMS. Stimulation was delivered at 1mA creating a current density of 0.029mA/cm^2.

4.3.3.3. Experiment 3- Bilateral 2mA

In experiment 3 stimulation was applied using the same electrode montage as described in experiment 2, but with an increased current of 2mA to create a current density of 0.057mA/cm^2.

4.3.4. Measurement of Motor Cortex Excitability

In all experiments, to detect changes in corticospinal excitability, MEPs elicited by single pulse TMS were recorded in the right First Dorsal Interosseous muscle (FDI).

TMS was delivered to the left M1 using a Magstim Rapid 200 Stimulator (Magstim Company, Whitland, Dyfed, Uk) and a 70 mm figure of eight shaped coil. The coil was held tangentially over the scalp positioned laterally at 45° from the midline, such that the current flowed in a posterior anterior direction in the brain. The optimum stimulus location, marked as the site for TMS assessment, was defined as the region that consistently elicited the largest MEP. This was determined by first identifying the C3 position of the EEG 10-20 grid (Jasper, 1958), and then moving the coil in 0.5 cm steps around the region to locate the motor ‘hotspot’. All TMS safety guidelines were adhered to (Rossi, Hallett, Rossini, & Pascual-Leone, 2009). In the bilateral tDCS conditions the same procedure was also implemented to locate the motor hotspot on the right hemisphere, using the EEG 10-20 C4 position (Jasper, 1958) as an initial starting point. This was used to guide placement of the bilateral reference electrode.

Surface electromyography (EMG) was recorded with disposable adhesive disc electrodes (Ag-AgCl) placed in a belly tendon montage on the right hand. To ensure good surface contact and reduce skin resistance, a standard skin preparation procedure of cleaning and abrading was performed at each electrode site. Peak-to-peak MEP amplitude was acquired with a sampling rate of 3kHz via an automatic acquisition system (Brainsight, Rogue Research, Montréal, Québec, Canada). The TMS intensity was adjusted per subject to elicit a MEP with amplitudes of approximately 1mV, the intensity was recorded and then used throughout the testing session. An MEP height of 1mV was used as this is moderate amplitude that allows for possible enhancements or reductions without ceiling or floor effects (Wiethoff, Hamada, & Rothwell, 2014). Fifteen consecutive MEPs where collected as baseline measurements prior to tDCS. Post tDCS, blocks of 10 consecutive MEPs were recorded at each timepoint. Similar paradigms of identifying and measuring MEP amplitude have been used by several experiments in this field (for example by, Batsikadze et al., 2013; Nitsche & Paulus, 2000; Nitsche et al., 2003).

4.3.5. Data Analysis

For evaluation of corticospinal excitability, the peak-to-peak amplitude of MEPs was measured in the 15-50 ms window after the TMS trigger. This was carried out automatically using BrainSight 3.10b software (Brainsight, Rogue Research, Montréal, Québec, Canada). The mean peak-to-peak amplitudes were calculated for each time point per subject. These included the first 10 (post stimulation) or 15 (baseline) consecutive MEPs that were recorded. Trials with more than 15 microvolts background EMG activity for 100ms pre-stimulation were discarded. The mean peak-to-peak amplitudes recorded post stimulation were then normalized to baseline and expressed as the ratio of MEP amplitude obtained after tDCS compared to the MEP amplitude obtained before tDCS (amplitude after/ amplitude before).

In order to assess the opposing anodal and cathodal polarity dependent shifts in cortical excitability, repeated measures ANOVA were undertaken for each experiment (using normalized values), with two within subject factors, polarity (2 levels: anodal, cathodal) and time (6 levels: 5, 10, 15, 20,25, 30 minutes). Post hoc comparisons were undertaken using paired t-tests. Additionally, in order to determine whether there were significant shifts from baseline, paired t-tests (one-tailed) were undertaken for each stimulation type (using the un-normalized values). The t-tests were not corrected for multiple comparisons as this is equivalent to Fishers LSD correction which is used as standard use in studies in this field (Batsikadze et al., 2013; Kidgell, Goodwill, Frazer, & Daly, 2013; Moliadze, Antal, & Paulus, 2010; Nitsche et al., 2003; Nitsche & Paulus, 2001)

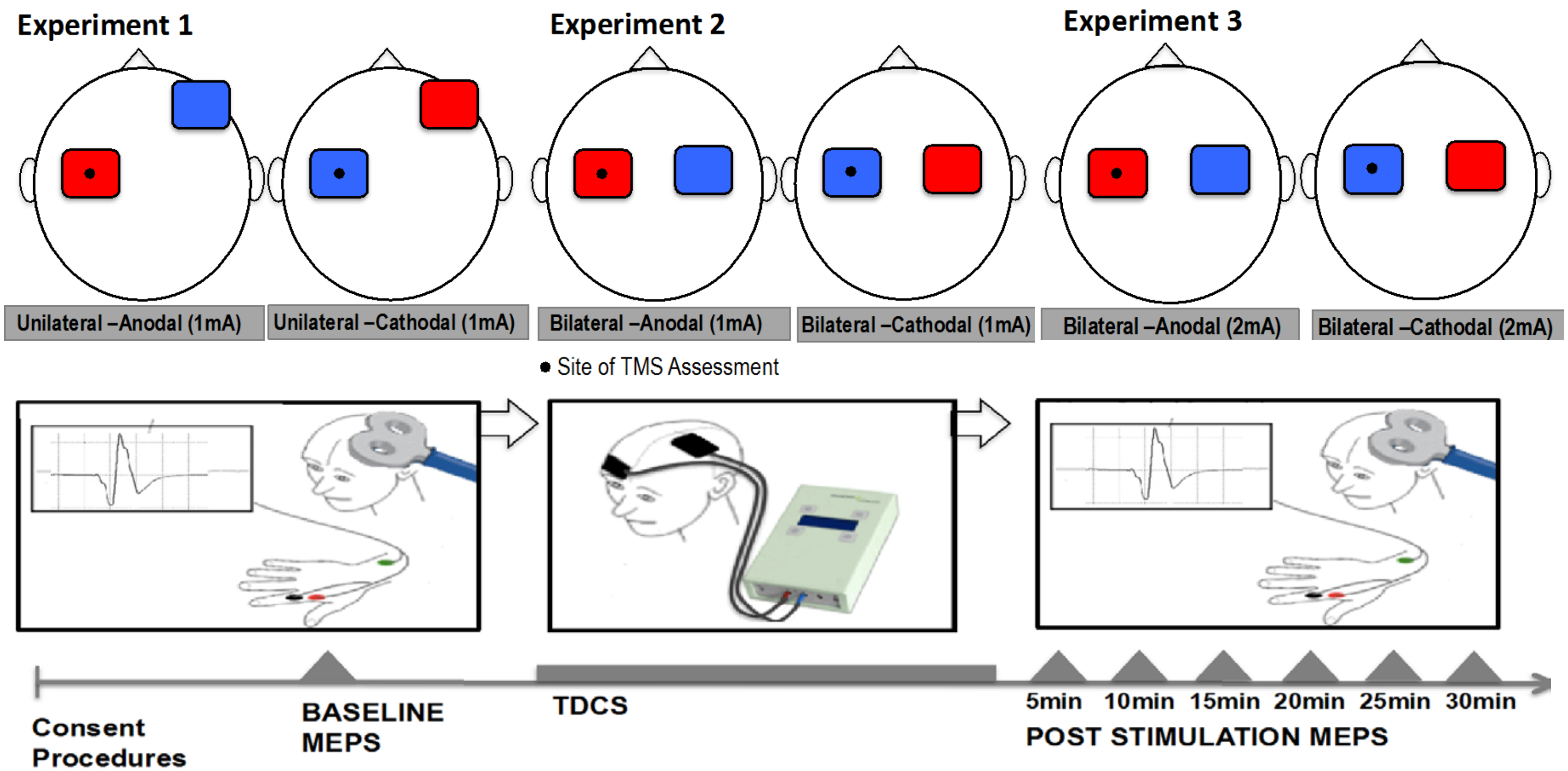


Figure 4.1:**Top image;** The tDCS parameters used in each experimental condition. **Bottom image;** The experimental protocol: The motor hotspot was identified and the TMS threshold intensity was adjusted per subject to give a peak-to-peak amplitude of approximately 1mA. 15 baseline MEPs of the right FDI muscle were recorded. tDCS was then applied for 10 minutes. Post stimulation MEPs were recorded to determine changes in corticospinal excitability, 10 measurements were taken at 5-minute intervals for half an hour.

4.4. Results

4.4.1. Experiment 1 - Unilateral 1mA

A repeated measures ANOVA revealed a significant effect of polarity ($F_{(1,7)}$=22.03, p<0.01), a non significant effect of time ($F_{(5,35)}$=1.47, p=0.22), and no significant interaction of time and polarity ($F_{(5,35)}$=0.46, p=0.80). Post hoc paired t-tests revealed that unilateral-anodal stimulation induced an increase in MEP amplitude in comparison to unilateral-cathodal stimulation at each timepoint post stimulation; 5 minutes ($t_{(7)}$=4.12 p<0.01); 10 minutes ($t_{(7)}$=3.41 p<0.01); 15 minutes ($t_{(7)}$=2.30 p<0.05); 20 minutes ($t_{(7)}$= 3.78 p<0.01); 25 minutes ($t_{(7)}$=3.70 p<0.01) and 30 minute ($t_{(7)}$=5.88 p<0.01) (**Figure 4.2**).

Paired t-tests comparing baseline (i.e. unadjusted) MEP amplitude values to each timepoint post stimulation revealed that, for unilateral anodal stimulation, MEP amplitude values were significantly higher than baseline at all timepoints post-stimulation stimulation. This includes at 5 minutes ($t_{(7)}$=-5.12 p<0.01) 10 minutes ($t_{(7)}$=-3.65, p<0.01), 15 minutes ($t_{(7)}$=-2.54, p<0.05), 20 minutes ($t_{(7)}$=-3.87, p<0.01), 25 minutes ($t_{(7)}$=-3.58, p<0.01) and 30 minutes ($t_{(7)}$=-3.10, p<0.01) post stimulation. These results suggest that corticospinal excitability is increased by unilateral anodal stimulation of M1, which is consistent with previous studies.

For unilateral cathodal stimulation, MEP amplitude was significantly lower than baseline at 5 minutes ($t_{(7)}$=2.62, p<0.05), 10 minutes ($t_{(7)}$=3.04 p<0.01), 20 minutes ($t_{(7)}$=1.80, p<0.05) and 25 minutes ($t_{(7)}$=1.90, p<0.05). These results suggest that, in accordance with previous studies, corticospinal excitability is reduced by unilateral cathodal stimulation of M1.

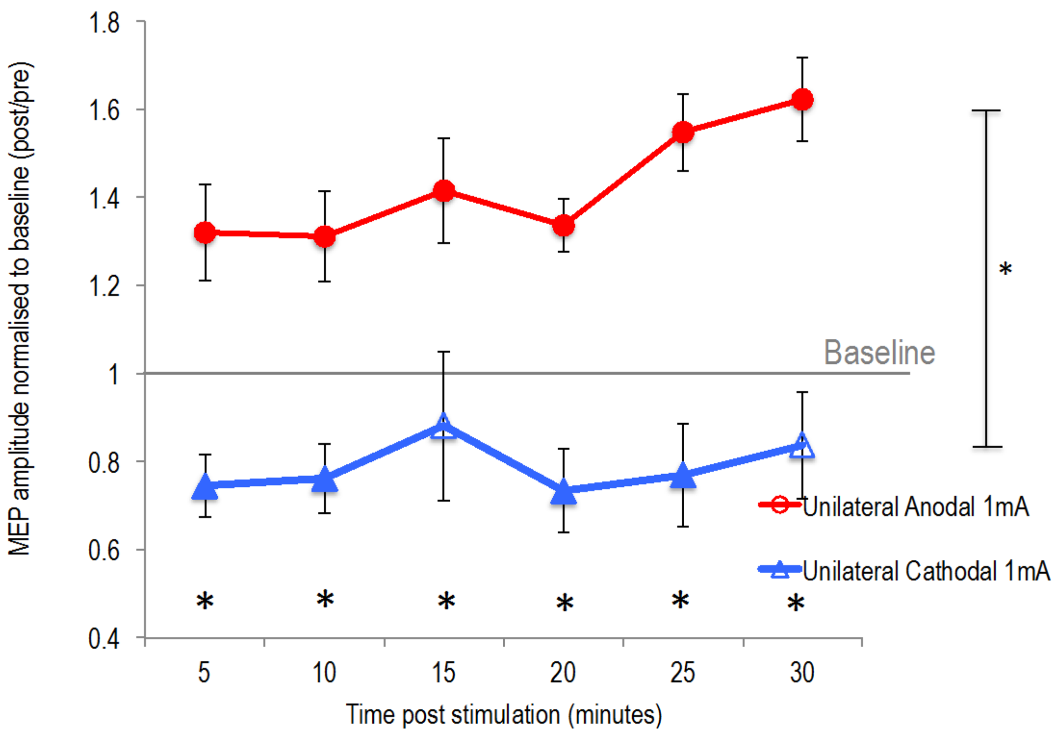


Figure 4.2: Results for experiment 1- unilateral 1mA; Timecourse of normalised MEP amplitude following 10 minutes of unilateral-anodal (anode left M1/ cathode right contralateral orbit) and unilateral-cathodal stimulation (cathode left M1/ anode right contralateral orbit) at 1mA intensity. Unilateral-anodal stimulation induced elevations in the MEP amplitude in comparison to unilateral-cathodal stimulation at each time point. There were also significant shifts in comparison to baseline for unilateral-anodal at all timepoints. There were significant shifts in comparison to baseline for the unilateral-cathodal stimulation at 5, 10, 20 and 25 minutes post stimulation. * denotes significant differences of MEP amplitudes between unilateral-anodal compared to unilateral-cathodal at each time point. Solid circles = timepoints which were significantly different from baseline. Red line= anodal; blue line = cathodal.

4.4.2. Experiment 2- Bilateral 1mA

One dataset, which was 3 SD above the mean, was excluded from analysis. Repeated measures ANOVA analysis revealed no significant effect of stimulation polarity ($F_{(1,7)}=0.11$, $p=0.75$), no effect of time ($F_{(5,35)}= 1.24$, $p=0.31$), and no significant interaction of stimulation polarity * time ($F_{(5,35)}=1.53$, $p=0.21$) on MEP amplitude (**Figure 4.3**). Therefore, the opposing anodal and cathode polarity dependent shifts in MEP amplitude described above were not retained following bilateral stimulation at 1mA.

Paired t-tests comparing baseline (i.e. unadjusted) MEP amplitude values to each those collected post stimulation revealed, no significant differences between baseline values at any timepoint post stimulation following bilateral-anodal or bilateral-cathodal stimulation at 1mA. Therefore there were no changes in MEP amplitude as a result of bilateral 1mA tDCS.

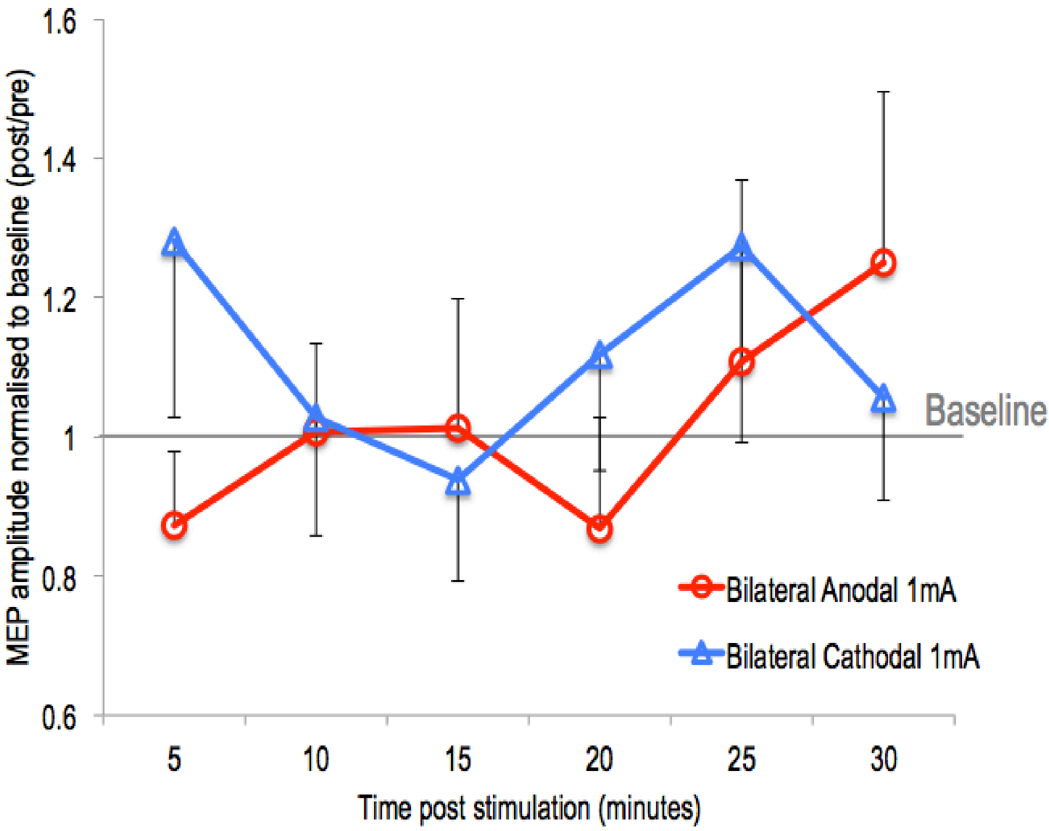


Figure 4.3: Results for experiment 2- bilateral 1mA*:* Timecourse of normalized MEP amplitudes following 10 minutes of 1mA bilateral-anodal (anode left M1/ cathode right M1) and bilateral-cathodal stimulation (cathode left M1/ anode right M1). There was no significant effect of stimulation polarity on MEP amplitude, indicating that the opposing anodal and cathode polarity dependent shifts in corticospinal excitability were not retained. Error bars represent SEM; red line= anodal; blue line= cathodal

4.4.3. Experiment 3- Bilateral 2mA

A repeated measures ANOVA revealed no significant effect of stimulation polarity ($F_{(1,8)}$=0.17 p=0.30), no effect of time ($F_{(5,40)}$=0.61, p=0.69), and no interaction of stimulation polarity and time ($F_{(5,40)}$=0.44, p=0.81) on MEP amplitude. The opposing anodal and cathodal polarity dependent shifts in MEP amplitude were therefore not retained when stimulation is applied using bilateral montages at 2mA (**Figure 4.4**).

Paired t-test comparing post stimulation values to baseline, revealed a significant difference at 15 minutes ($t_{(8)}$= -2.38, $p<0.05$). There were no other significant excitatory or inhibitory shifts from baseline for any timepoint post stimulation following bilateral-anodal or bilateral-cathodal stimulation at 2mA.

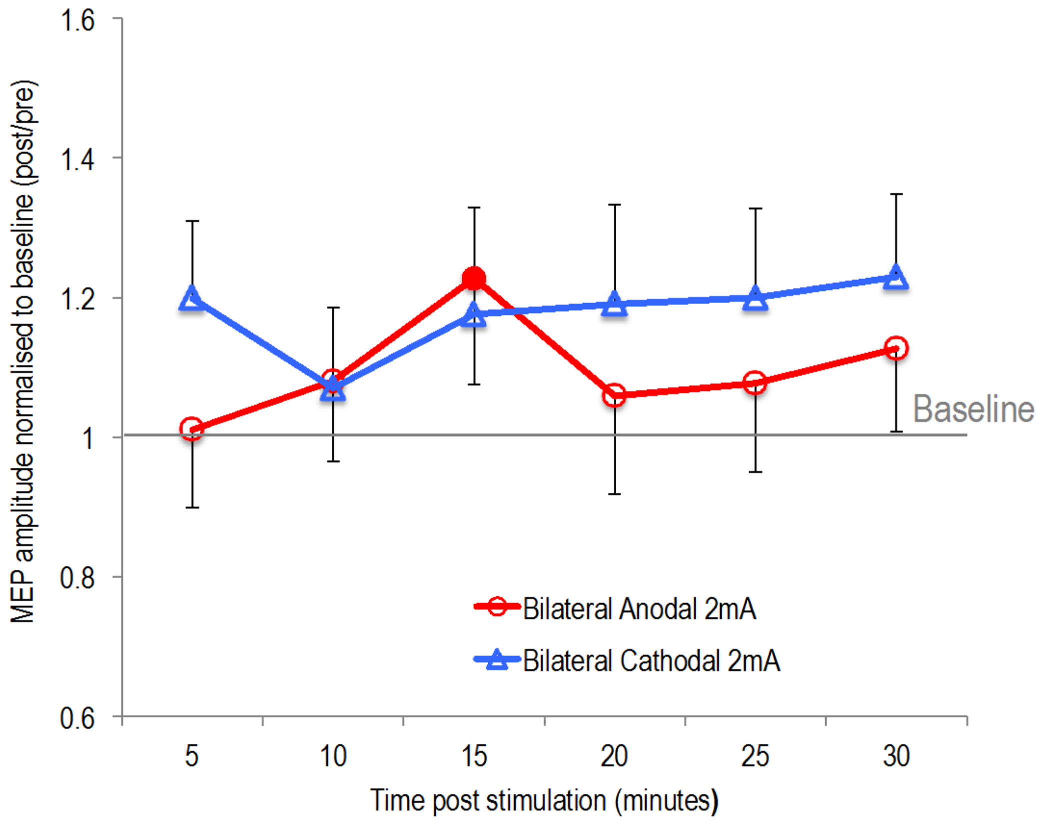


Figure 4.4: Results for experiment 3 – bilateral 2mA: Timecourse of normalized MEP amplitude following 10 minutes of 2mA bilateral-anodal (anode left M1/ cathode right M1) and bilateral-cathodal stimulation (cathode left M1/ anode right M1). There were no significant effects of stimulation polarity on MEP amplitude. Indicating that the opposing anodal and cathode polarity dependent shifts in coritcospinal excitability were not retained following bilateral stimulation at 2mA. Error bars represent standard error of the mean. Red line= anodal; blue line= cathodal.

4.5. Discussion

The aim of the current study was to examine whether anodal-excitatory/ cathodal-inhibitory effects of tDCS extend to protocols applying stimulation using bilateral electrode montages at intensities of 1 and 2mA. Experiment 1 replicated the parameters used in classical studies of motor physiology (e.g. Batsikadze et al., 2013; Moliadze et al., 2010; Nitsche & Paulus, 2001; Nitsche et al., 2003; Stagg & Nitsche, 2011) on which our knowledge of the effects of tDCS is based and delivered stimulation with a unilateral electrode array (M1/ contralateral orbit) at 1mA intensity (and densities of 0.029mA/cm^2). The results showed that unilateral-anodal and unilateral-cathodal stimulation induced polarity dependent shifts in corticospinal excitability (as evidence by respective elevations and diminutions in MEP amplitude) these were significantly different both from one another, and from baseline. The results of experiment 2 and 3 showed that when departing from this typical unilateral arrangement, these polarity dependent shifts in cortical excitability were not induced. In particular, anodal and cathodal stimulation delivered via bilateral electrode montages (left and right M1) at 1mA (experiment 2) and at 2mA (experiment 3) did not induce significantly opposing effects on MEP amplitudes, nor did these protocols induce changes to the MEP amplitude in comparison to baseline values.

The bilateral stimulation parameters were chosen for investigation due to their use in the Fecteau, Pascual-leone, et al., (2007) study, and in an increasing number of cognitive, behavioral and clinical studies including the majority of the neuromodulatory decision-making literature (Boggio, Campanhã, et al., 2010; Boggio, Zaghi, et al., 2010; Cheng & Lee, 2016; Fecteau et al., 2014; Fecteau, Knoch, et al., 2007; Gorini et al., 2014; Minati et al., 2012; Weber et al., 2014; Ye et al., 2015). These studies have based their understanding of the effects of tDCS on work using unilateral electrode positioning, assuming that the effects are consistent despite differing parameters. The findings from the current study do not support this premise and raise concerns over the assumptions of polarity dependent shifts in excitation and inhibition underlying studies that stimulate bilaterally at 1mA/0.029mA/cm^2 or 2mA/0.057mA/cm^2 (e.g: Fecteau et al, 2007a, 2007b; Hecht et al 2010; Boggio et al 2009, 2010a 2010b; Chi et al 2010; Cohen

Kadosh et al 2010). In particular, Fecteau, Pascual-leone, et al., (2007) reported decreased risk taking during bilateral tDCS (2mA/ 0.057mA/cm^2) over the DLPFC, regardless of whether the anodal electrode was placed over the left and cathodal over right DLFPC, or vice versa. It was claimed that these results were a result of the concurrent excitation and inhibition of alternate hemispheres, based on the assumption that anodal is exerting an excitatory and cathodal an inhibitory influence. In addition to failing to replicate the behavioural findings of Fecteau, Pascual-leone, et al., (2007) (chapter 3), the results of the current study does not support the physiological evidence underpinning this explanation.

In support of the importance of electrode positioning on determining the effects of tDCS, the initial use of unilateral electrode montages came from one of the earliest studies in the tDCS field. Nitsche & Paulus (2000) explored five different electrode arrays when assessing the rapid induced effect of weak DC stimulation (stimulation applied for 4 seconds at 1mA/ producing current densities of 0.029mA/cm^2). It was only the unilateral M1/ contralateral orbit arrangement that produced significant excitability changes (as measured by MEPs), while for other electrode placements including bilateral M1 no effects of stimulation were evident. As the most robust arrangement the unilateral array persisted as convention in future studies exploring the physiology of tDCS.

There have been two previous studies that have similarly examined the after-effects of bilateral tDCS of motor cortex corticospinal excitability. Mordillo-Mateos et al., (2012), reported bilateral anodal stimulation at 2 mA (current density 0.057mA/cm^2) to cause an initial increase in MEP amplitude, and bilateral cathodal to cause an initial decrease in MEP amplitude, results that were not sustained for the second time point taken at 20 minutes. While these findings are not in line with the current study that found no such shifts in corticospinal excitability following bilateral tDCS of 2mA, Mordillo-Mateos et al., (2012) did report the effects of bilateral electrode montages to be less robust in comparison to the unilateral stimulation condition. It is difficult to make direct comparisons due to differences in the stimulation protocol used, for example Mordillo-Mateos et al., (2012) stimulated for 5 minutes, while in the current study stimulation was applied for 10 minutes (a duration closer to those used in cognitive enhancement studies). Comparing the current study to Mordillo-Mateos et al., (2012), it may be that stimulation duration interacts with montage and intensity, making assumptions of transferability between studies more different again.

An additional study by Kidgell, Goodwill, Frazer, & Daly, (2013) examined the after-effects of bilateral tDCS delivered at 1mA with current densities of 0.04mA/cm^2 (stimulation was applied with smaller electrodes that used in the current study). Stimulation was delivered for durations of 13 minutes. The study reported excitatory effects of anodal stimulation and inhibitory effects of cathodal stimulation on MEP amplitude, findings which differ to the current study. In the current study current densities of 0.029mA/cm^2 (1mA experiment 2) and 0.057mA/cm^2 (2mA experiment 3) were explored, and in comparing these two studies it may be with bilateral montages there is a critical intensity needed for corticospinal modulations to occur.

With unilateral electrode arrays, there have been reports that at increased intensities cathodal stimulation loses its opposing polarity and no longer exerts inhibitory effects. A study by Batsikadze et al., (2013) revealed that at 2mA, with a current density of 0.057mA/cm^2, cathodal stimulation delivered at 20 minutes induced excitatory after effects of stimulation. While Wiethoff et al., (2014) reported 10 minutes of cathodal stimulation delivered at 2mA/ 0.057mA/cm^2 to not produce any excitatory shifts from baseline. The findings of the current study show that for bilateral electrode array at 2mA/ 0.057mA/cm^2 cathodal stimulation (10 minutes) similarly does not produce inhibitory effects.

When comparing the current study to others in the field, it is important to acknowledge the many factors that may influence the effects of tDCS, including duration, montage and intensity, and these may interact with each other, making assumptions of transferability between studies more different again. This reiterates one of the key messages of the study, that the excitatory or inhibitory effects of tDCS should not be taken for granted unless based on previous physiological research that has used the same parameters.

There have been two studies which have examined the effects of electrode montage using fMRI, these have reported differences in the effects induced when tDCS was applied using bilateral in comparison to unilateral montages. Sehm, Kipping, Schäfer, Villringer, & Ragert, (2013) assessed functional connectivity analysis across and within M1, and found that tDCS applied with both bilateral and unilateral montages resulted in decreased interhemispheric functional connectivity during stimulation, yet bilateral tDCS was unique in that it increased intracortical functional connectivity within the stimulated M1 after stimulation. Additionally Lindenberg et al., (2016) revealed that bilateral stimulation exerted widespread bihemspheric changes to functional connectivity to regions including those outside of the motor and supplementary motor areas. In comparison unilateral stimulation exerted effects more locally within the primary and secondary motor cortices. This is in keeping with the results of the current study which show a greater influence of unilateral stimulation on the motor cortices.

There are a number of reasons that have been proposed to account for why bilateral electrode arrays may produce differing after-effects than unilateral montages. These include differences in, the amount of current reaching the cortex, the position (location and depth) of current flow (Faria, Hallett, & Miranda, 2011), and the possibility of interhemispheric interactions from concurrent stimulation of monosynpatically connected brain regions (Kimura, 1967). Recent computational studies have noted inter-electrode distance as an important factor in determining efficacy of tDCS (Faria, Hallett, & Miranda, 2011). Due to the increased conductivity of the scalp and cerebral spinal fluid relative to the skull and brain, a large portion of the applied current has been calculated to flow through these tissues rather than reaching the brain. Studies have calculated that electrodes which are further apart on the scalp are optimal, with 60% of current calculated to reach the brain when the electrodes are more than 20cm apart, as compared to 35% when electrodes are at a distance of 8cm (Faria et al., 2011). For unilateral montages there are larger inter-electrode distances compared to bilateral arrangements, thus with unilateral arrangements the amount of current entering the brain relative to that shunted across the scalp maybe higher. The absence of significant modulations in cortical excitability from bilateral montages may simply arise from less stimulation reaching the cortex.

Inter-electrode distance has also been calculated to influence the position of maximum current density within the brain and depth of current flow which may also contribute to differences in the effects produced with unilateral and bilateral electrode montages (Bikson, Datta, Rahman, & Scaturro, 2010; Faria, Hallett, Miranda, et al., 2011). When electrodes are placed closer together, which is the case for bilateral montages in comparison to unilateral montages, the maximum current density is shifted between the two electrodes and depth of current flow more superficial (i.e. the magnitude of current density decreases more rapidly with depth) (Faria, Hallett, Miranda, et al., 2011). It may be that, in order to produce shifts in the corticospinal neurons that contribute to the MEP, sufficient depth of stimulation is needed which does not occur with bilateral application. In addition to changes in the depth of current flow, changing the position of the 'return' electrode will influence the location of current flow through the brain. The unilateral montage, with the reference electrode placed over the contralateral orbit, directs the current in an anterior orientation, in comparison to the bilateral montage where the reference electrode guides the current in a more lateral orientation towards the alternate hemisphere (Kidgell, Goodwill, et al., 2013).

A further difference proposed between the unilateral and bilateral electrode montages is the issue of possible interactions between two brain regions that have monosynaptic connections. Previous work has hypothesized that the prominently inhibitory transcallosal connections between the motor cortices may act to enhance the excitatory and inhibitory effects of bilateral stimulation (Fusco et al., 2013; Mordillo-mateos et al., 2012). According to this line of thought the cathode electrode over the contralateral M1 may lead to a decrease in transcallosal inhibition, accentuating the anodal effects of the 'active' electrode. And the opposite is expected for the anode electrode placed over the alternate M1, acting to increase transcallosal inhibition and further inhibiting the action of the 'active' cathodal electrode (Fusco et al., 2013; Sehm et al., 2013). This explanation is not supported by the current data, and such push-pull accounts of tDCS function have been criticized as highly over simplistic (Bestmann, de Berker, Bonaiuto, 2015b).

On a wider note the current study highlights the premature acceptance present in the cognitive tDCS literature that anodal electrode is always excitatory and cathodal inhibitory, highlighting a failure to consider the importance of stimulation parameters in producing the effects of tDCS. When considering the tDCS and decision-making literature, stimulation has been applied using bilateral montages (at 1 and 2mA) in all but one of the studies to date (Beeli, Koeneke, Gasser, & Jancke, 2008), yet all these studies used the assumption of anodal-excitation/ cathodal-inhibition to guide both study design and to explain the effects. Stimulation is applied to brain regions thought to be responsible for behaviour, with the anodal electrode being placed where increased excitation is hypothesized as beneficial, or the cathodal where increased inhibition is desired (Bestmann et al., 2015a). In the case of Fecteau, Pascual-leone, et al., (2007) the DLPFC was chosen as the site of stimulation due to its role in the estimations of risk-taking during decision-making. In this study the assumption of anodal-excitation/ cathodal- inhibition producing concurrent excitation and inhibition of bilateral DLPFC was used to explain the behavioural findings of reduced risk taking. This explanation is not supported by results of the current study, examining the physiological effects of the type of stimulation applied in Fecteau, Pascual-leone, et al., (2007) (bilateral montage 2mA) does however offer an explanation for the non-replication findings in the previous chapter. Importantly these concerns are not unique to Fecteau, Pascual-leone, et al., (2007) and extend to the wider decision-making and tDCS literature.

In order for tDCS to be utilized to it’s full potential, the lesson to be learnt from the current study is that inferences about the effects of tDCS should only be made between studies that have used similar stimulation parameters. That being said it is important to note that the physiology in studies of cognitive neuromodulation should always be interpreted cautiously. Electrode positioning is an inherently difficult issue as the effects of montages other than those applied to the motor cortex can only be inferred indirectly. Although it is likely that the underlying mechanism are similar it is not clear to what extent these findings translate to other areas of the cortex, especially as poor correlations between visual and motor thresholds have been reported (Stewart, Walsh, & Rothwell, 2001).

Together, the results of the current study, the non- replication finding from the previous chapter and the broader context of a number of inconsistent findings within the decision-making and tDCS literature, question the validity of tDCS as a tool for modulating decision-making. As such the original proposal of applying tDCS to the training of elite athletes is undermined.

4.6. Conclusion

In sum, the findings of the current study show that the polarity dependent shifts in cortical excitability induced by unilateral electrode montages (experiment 1), were not evident using bilateral electrode montages and stimulating at either 1mA (experiment 2) or 2mA (experiment 3). This highlights that the effects of tDCS should not be taken for granted in the literature unless based on previous physiological work that has used similar parameters.

These findings provide an explanation for the non-replication of Fecteau, Pascual-leone, et al., (2007) in Chapter 3, where tDCS was found to have no effect on risky decision-making. Moreover they raise important concerns regarding the physiological assumptions of anodal-excitation/ cathodal- inhibition that underpin the rationale and justification of results in this study. Bilateral montages are common in studies of cognitive neuromodulation and therefore these concerns extend to the wider decision-making and tDCS literature. In combination, the results of Chapters 3 and 4 undermine the reliability of tDCS as a modulator of decision-making, and highlight that many studies in this field lack a physiological understanding of their effects. As such the proposal to apply tDCS to decision-making in elite athletes is not supported. In the following chapter the efficacy of a novel neuromodulatory method, tRNS, is assessed as possible alternative for decision-making training in elite athletes.

5. Do the Physiological Effects of tRNS Transfer to Bilateral Montages and Increased Durations?

5.1. Abstract

Background: Previous chapters reported the modulation of decision-making by tDCS to be unreliable, with studies in this area lacking an understanding of their physiological effects. These findings undermined tDCS as a potential candiate for application in elite athletes. Instead, in the current chapter the eligibiltiy of an emerging neuromodulatory technique, hf-tRNS, is explored. hf-tRNS induces elevations in cortical excitability, via application of an alternating current at random frequencies (between 101-640 Hz). Born out of the tDCS literature, our knowledge of these effects is based on work that applied stimulation for 10 minutes applied with unilateral electrode montages (target over the M1 and reference over the contralateral orbit) (Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). There are a small number of studies that have applied hf-tRNS for cognitive neuromodulation. Many of these studies have applied stimulation with parameters which differ from those used to produce the effects of increased excitation, in particular increased durations (20 minutes) and bilateral electrode montages. Taking lessons from the previous chapter, here the underlying physiology of tRNS is explored. Assessing the validity of the assumptions of excitation underpinning work in this field is an efficient way of establishing confidence in tRNS as a potential candidate for application in elite athletes. Moreover it will provide increased knowledge of the effects of this technique that may help guide subsequent application if this path is chosen.

Objective: To assess the influence of electrode montage (unilateral and bilateral) and stimulation durations (10 and 20 minutes) on the physiological effects of hf-tRNS.

Method: In experiment 1, the effects of hf-tRNS applied using traditional parameters unilateral electrode montage (M1/contralateral orbit montage) and bilateral montages (left and right M1) were examined. Stimulation was applied for the standard duration of 10 minutes. In experiment 2, hf-tRNS was applied for 20 minutes (using the traditional M1/contralateral orbit montage). Changes to

cortical excitability were measured using MEP amplitude, at 5 minute intervals for up to 30 minutes post stimulation.

Results: In experiment 1, there was a significant effect of electrode montage (unilateral or bilateral) of hf-tRNS on MEP amplitudes. hf-tRNS delivered with unilateral montages was found to increase MEP amplitudes in comparison to baseline, indicative of induced elevations in cortical excitation. This was not the case for hf-tRNS delivered with bilateral montages. In experiment 2, there was a significant effect of stimulation duration on MEP amplitude, there were no significant modulations of MEP amplitudes, pre and post stimulation. In both cases there is the assumption in the literature that despite changing these parameters the effects of stimulation are identical.

Conclusion: These findings highlight that the neuroplastic - inducing mechanisms that underpin hf-tRNS are time dependent and sensitive to electrode montage. Again, the findings highlight the importance for the cognitive neuromodulatory literature to not extrapolate the effects of these techniques beyond those that have been tested physiologically. The results of this chapter undermine the physiological assumption of excitation that is used to guide methodological design and interpret effects in many prior studies using this technique; therefore there is reduced confidence in tRNS as a candidate for application outside the laboratory. Together the findings of chapter 3, 4 and 5 led to the conculsion that tES are not robust enough to proceed with in investigations in elite athletes at this time. In the following chapter behavioural work with elite athletes is pursued in order to address the original goal of exploring decision-making in elite sport.

5.2. Introduction

One initial aim of the thesis was to explore the potential application of tES as a tool for improving decision-making in elite athletes. Findings from the previous chapters revealed the application of tDCS to decision-making to be unreliable, with studies in this field lacking an understanding of their physiological effects. In the preceeding chapter tRNS, a novel neuromodulatory approach is explored as a possible alternative.

TRNS applies alternating currents, at random frequencies, via electrodes placed on the scalp. The amplitude and frequency of oscillations are generated at random, within a range set by the experimenter. Frequencies from a spectrum of 0.1-640 Hz can be selected, with narrower bands within this range routinely applied, namely 0.1-100Hz for low frequency tRNS (lf-tRNS), or 100-640 for high frequency tRNS (hf-tRNS) (Moreno-Duarte et al., 2014). Using standard stimulation parameters (electrode position, intensity and duration) imported from the direct current literature, hf- tRNS has been shown to increase corticospinal excitability (Chaieb, Antal, & Paulus, 2015; Chaieb, Paulus, & Antal, 2011; Inukai et al., 2016; Moliadze, Antal, & Paulus, 2010b; Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). The classical study revealing the excitatory effects of hf-tRNS was Terney et al., (2008) who applied hf-tRNS using an M1/contralateral orbit montage for a duration of ten minutes. Here sustained elevations in MEP amplitude lasting up to ninety minutes post stimulation were demonstrated (see **Figure 2.4**b).

While still in its infancy, the adoption of tRNS as a tool for cognitive neuromodulation is evident (**Figure 2.1**c). As with tDCS, work in this field has applied tRNS to modify cognitive functions by attempting to manipulate excitation in regions underpinning these abilities. tRNS is often chosen for its bidirectional current which means it does not have the polarity constraints of tDCS. In healthy participants, tRNS has been reported to facilitate motor (Terney et al., 2008) and perceptual learning (Fertonani, Pirulli, & Miniussi, 2011), to enhance abilities in mental arithmetic (Snowball et al., 2013), numerosity (Cappelletti et al., 2013) and face perception (Romanska, Rezlescu, Susilo, Duchaine, & Banissy, 2015). Modifications to political beliefs have also been reported (Chawke & Kanai, 2015), as well as decrements on a probabilistic classification task (Ambrus et al., 2011). There are also initial investigations in its clinical utility to treat tinnitus symptoms (Vanneste, Fregni, & De Ridder, 2013), and schizophrenia (Palm, Hasan, Keeser, Falkai, & Padberg, 2013). In reviewing this literature, it is evident that the parameters used in the application of tRNS have deviated from which the original effects of increased motor cortex excitability were induced (Terney et al., 2008), as seen previously with tDCS. Yet the assumption of corticospinal excitation has guided the methodological design and interpretation of findings in these studies. Two such parameters of divergence are duration of stimulation and electrode montage. In light of findings from the previous chapter it seems important to examine these core assumptions in order to evaluate the technique's potential.

Adapted from the tDCS literature durations of 10 minutes were used to establish the physiological effects of tRNS on the motor cortex (Terney et al., 2008). The standard duration employed by cognitive neuromodulatory studies of tRNS however is one twice this length of twenty minutes. Previous studies have shown that duration is an important factor for determining the after-effects of brain stimulation. With tDCS there is a minimal length of stimulation needed to induce after-effects (at 1mA this is 3 minutes) (Nitsche & Paulus, 2000), and a linear relationship between the length of application (5-13 minutes) and duration of after effects (Nitsche & Paulus, 2001; Nitsche et al., 2003). However, this relationship does not extend indefinitely and in unpublished work by Paulus, Antal & Nitsche, (2013) it has been reported that increasing anodal stimulation from 13 to 26 minutes, changes the induced effect from excitation to inhibition. Moreover, similar results have been reported for theta burst stimulation (TBS), when the duration of the TBS protocol is doubled there is a reversal of the effects from cortical excitation to inhibition (Gamboa, Antal, Moliadze, & Paulus, 2010). The influence that stimulation duration has on the effects of tRNS is less well characterized. There has been one published study that has investigated stimulation duration with hf-tRNS, this focused upon the minimum duration needed to induce after-effects (Chaieb et al., 2011). Induced elevations in corticospinal excitability were reported following 5 and 6 minutes yet after-effects were short lived compared to those induced after 10 minutes of stimulation. Despite tRNS commonly being applied for durations of 20 minutes, work documenting its effects for durations exceeding 10 minutes is lacking.

Electrode placement is a further parameter of divergence. The physiological effects of hf-tRNS have been explored using the traditional unilateral montage with electrodes placed over the motor cortex (M1) and contralateral orbit (Chaieb et al., 2015, 2011; Inukai et al., 2016; Terney et al., 2008). Despite this bilateral electrode arrays, where electrodes are placed on the same region over opposing hemispheres, are commonly used in studies applying hf-tRNS to modulate cognition. Target sites are similar to those used with tDCS including the left and right PC (Cappelletti et al., 2013), and left and right DLFPC (Chawke & Kanai, 2015; Snowball et al., 2013). The influence of electrode montage on the effects of tRNS has been investigated by one study which explored extra-cephalic montages, whereby one electrode is placed off the skull (Moliadze, Antal, & Paulus, 2010a). The shifts in cortical excitability induced when hf-tRNS was applied using a unilateral montage were not present when stimulation was applied using a M1/contralateral upper arm montage. If nothing else, this finding shows that the effects of hf-tRNS are dependent on electrode placement, which in itself is problematic for the assumption that hf-tRNS applied with unilateral and bilateral montages will produce identical effects. Moreover, in light of the findings from the previous chapter whereby the effects of tDCS did not translate to bilateral montages, further investigations on this topic are warranted, especially before behavioural replication of findings using hf-tRNS are attempted.

The current study is motivated by concerns over the assumption that the effects of hf-tRNS, as demonstrated by studies of motor physiology, apply to all work employing this technique despite differing stimulation parameters. An assumption implicitly imported from the tDCS literature and one which has been undermined by work in Chapter 3. In order to investigate this the current study explores the underlying physiological effects of tRNS using parameters commonly applied in studies of cognitive neuromodulation, namely bilateral electrode placement and increased durations (20 minutes). Assessing the validity of the assumptions underpinning work in this field is an efficient way of establishing confidence in tRNS as a potential candidate for application in elite athletes (in comparison to performing behavioural replications for example). Moreover given that hf-tRNS is an emerging technique, increased knowledge of the effects will be useful to help guide the subsequent application of the technique, if this path is chosen.

In order to investigate this, two experiments were performed, each of which assess the effects of hf-tRNS protocols through the measurement of corticospinal excitability via modulation of MEP amplitude. In the first experiment to examine the influence of electrode montage, the effects of unilateral (left M1/right contralateral orbit) and bilateral (left M1/ right M1) electrode montages are examined. Unilateral electrode montages replicate the parameters used in classical studies of motor physiology (Chaieb, Antal, & Paulus, 2015; Chaieb, Paulus, & Antal, 2011; Inukai et al., 2016; Terney, Chaieb, Moliadze, Antal, & Paulus, 2008) while bilateral placements were chosen due to their use in a number of studies of neuroenhancement to date (e.g. Cappelletti et al., 2013; Popescu et al., 2016; Romanska et al., 2015; Vanneste et al., 2013). In each case 10 minutes of stimulation were delivered. In the second experiment the influence of stimulation duration is investigated. Using a unilateral electrode montage, hf-tRNS is applied for 20 minutes, a duration common place in studies of cognitive neuroenhancement (e.g. Cappelletti et al., 2013; Chawke & Kanai, 2015; Palm et al., 2013; Popescu et al., 2016; Romanska et al., 2015; Vanneste et al., 2013). These effects will be compared to the unilateral condition in experiment 1 which applies stimulation for 10 minutes, this represents the duration that is used in classical studies of motor physiology.

5.3. Methods

5.3.1. Participants

5.3.1.1. Experiment 1: Electrode Montage

There were ten datasets collected in the unilateral-tRNS (10mins) condition and eight datasets collected in the bilateral-tRNS (10mins) condition. One participant was was excluded from the bilateral-tRNS condition due to experimenter error. Therefore a total of seventeen participants took part in the experiment (10 female, mean age: 21 age range 19-25).

5.3.1.2. Experiment 2: Duration

Ten participants took part in the unilateral-tRNS 20 minutes condition (5 female; mean age 20; age range 19-23). Two of these participants were later excluded due to experimental error. These data was compared to the unilateral-tRNS 10 minutes condition collected in experiment 1.

Upon expressing an interest in participating, subjects were screened to determine their eligibility to take part in brain stimulation research (no history of acute or chronic medical, neurological or psychiatric diseases, not currently taking any medication and no problematic metallic implants). Those with any contraindications were not recruited. All participants were right hand dominant as indicated by the Edinburgh Handedness Inventory (Oldfield, 1971). In accordance with previous work there was a wash out period of at 3 days where participants must not have taken part in brain stimulation research for this duration to avoid carry over effects (Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). All participants gave written informed consent and were financially compensated at the standard rate for cognitive neuroscience studies. The study and consent procedures were approved by UCL ethics committee in accordance with the declaration of Helskini.

5.3.2. Experimental Protocol

A between subjects design was used. In experiment 1 the participants were randomized by gender to one of two conditions (unilateral or bilateral tRNS). In experiment 1 & 2 each condition followed a similar procedure (**Figure 5.1**). Following consent and study explanation, participants were seated in a chair, with their hands resting on a pillow. Surface EMG electrodes were attached to the right hand, following a skin abrasive procedure. The site for TMS assessment was identified, i.e. the coil location which produced the largest MEP amplitude in the right hand. Once located, this was marked, as was the coil orientation used to produce it, in order to ensure consistency of placement. The TMS intensity was adjusted to elicit MEPs with peak-to-peak amplitudes of approximately 1mV, which was used throughout the study. 15 MEP baseline measurement were recorded. Following this hf-tRNS was adminstered, the precise stimulation parameters depended on experimental condition (**Figure 5.1**). Immediately following hf-tRNS, electrodes were removed and the scalp was cleaned. Post stimulation 10 MEPs were recorded at five- minute intervals for a duration of thirty minutes (5,10,15,20,25,30 minutes post stimulation). While participants knew what type of stimulation they were receiving, they were not made of aware of the precise experimental hypothesis until after the experiment, when they were appropiately debriefed and paid at the standard rate for participation.

5.3.3. TRNS

TRNS was delivered by a battery-driven constant current stimulator (Neuroconn, Germany) and administered via a standard pair of rubber conductive electrodes (size 5x7 cm, surface area of 35cm^2). The electrode size replicated that used by cognitive neuromodulatory studies in this field, but differed from those used in Terney, Chaieb, Moliadze, Antal, & Paulus, (2008) - where the stimulation electrode over the M1 was 4x4 cm and the reference electrode over the contralateral orbit was 6x14 cm. To avoid potential problems of water leakage with the saline soaked sponge method (Woods et al., 2016) the electrodes were attached to the scalp with conductive paste and held in place with two rubber straps.

In all conditions high frequency random noise was selected with alternating currents randomly selected from 101-640 Hz and an offset of 0. The current intensity was 1mA peak-to peak, with each sample being drawn from a normal distribution with mean 0 μA, and with 99% of all generated amplitude values lying between −500 μA and +500 μA. A 20 second fade in/ fade out period was used. Two different electrode montages were examined in experiment 1, and an extended duration was examined in experiment 2.

5.3.3.1. Experiment 1: Electrode Montage

hf-tRNS was applied using either a unilateral montage or bilateral montage. In the unilateral montage condition, one electrode was fixed over the left M1, the other was placed horizontally over the right contralateral orbit. This montage was used to replicate the electrode positioning used in previous work of motor physiology. For the bilateral montage the electrodes were placed over the left and right M1. M1 electrodes were located with the center of the electrode positioned over the site for TMS assessment. In both conditions stimulation was delievered for a duration of ten minutes.

5.3.3.2. Experiment 2: Duration

In experiment two, hf-tRNS was applied using a unilateral montage, where the electrodes were fixed over the left M1 (placed over the site located for TMS assessment), and over the right contralateral orbit. In this experiment stimulation was delivered for 20 minutes. This was compared to the unilateral condition of experiment 1 that delivered stimulation for 10 minutes.

5.3.4. Measurement of Motor Cortex Excitability

To detect changes in the corticospinal excitability, MEPs elicted by single pulse TMS were recorded in the FDI muscle. This method is described in detail Section 4.3.4. In short TMS was delivered to the left M1 (using a Magstim Rapid 200 Stimulator (Magstim Company, Whitland, Dyfed, UK), at a site identified as the 'motor hotspot' the location which elicited the largest MEP amplitude. The intenisty of the TMS stimulus was adjusted to elicit an MEP of approximately 1

MV. The intensity was recorded and then used throughout the testing session. An MEP amplitude of 1mA was used as this is moderate amplitude that allows for possible enhancements or reductions without ceiling or floor effects (Wiethoff, Hamada, & Rothwell, 2014). Surface EMG was used to measure changes in the right FDI hand muscles, via disposable adhesive disc electrodes (Ag-AgCl) which were placed in a belly tendon montage. Peak-to-peak MEP amplitude were recorded with a sampling rate of 3kHz using an automatic acquisition system (Brainsight, Rogue Research, Montréal, Québec, Canada). Fifteen consecutive MEPs where collected as baseline measurements prior to hf-tRNS. Post hf-tRNS blocks of 10 consecutive MEPs were recorded at each timepoint.

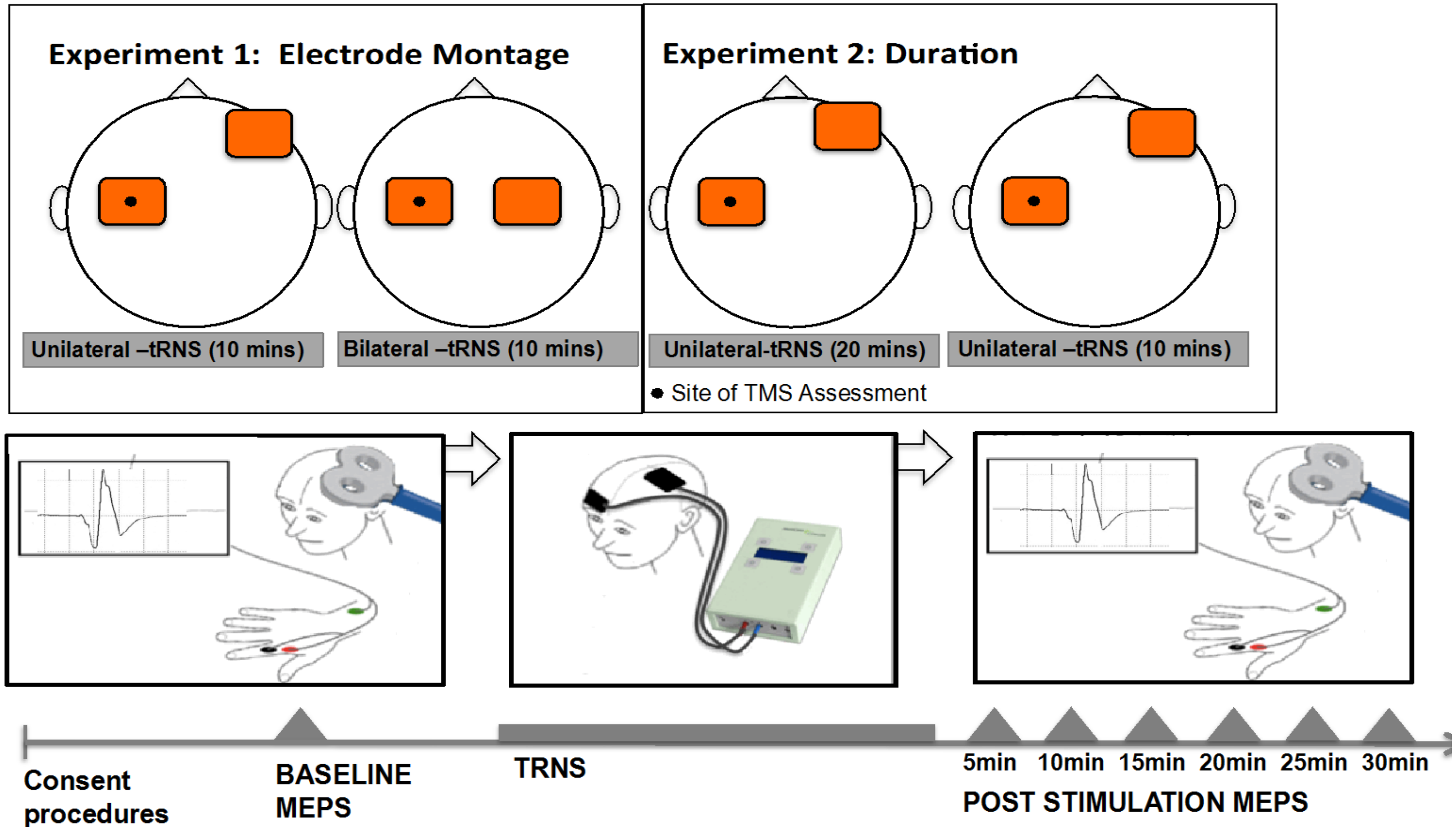


Figure 5.1: Top image: The tRNS parameters used in each experimental condition. **Bottom image**: The experimental procedure: The motor hotspot was identified and TMS threshold intensity was adjusted per subject to give a peak-to-peak amplitude of approx 1mA. 15 baseline MEPs of the right FDI muscle were recorded. tRNS was applied, the parameters used were determined by experimental condition. Post stimulation MEPs were recorded to determine changes in corticospinal excitability, 10 measurements were taken at 5-minute intervals for half an hour

5.3.5. Data Analysis

For evaluation of corticospinal excitability, the peak-to-peak amplitude of MEPs was measured in the 15-50ms window after the TMS trigger. This was carried out automatically using BrainSight 3.10b software (Brainsight, Rogue Research, Montréal, Québec, Canada). The mean peak-to-peak amplitudes were calculated for each time point per subject. These included the first 10 (post stimulation) or 15 (baseline) consecutive MEPs that were recorded. Trials with more than 15 microvolts background EMG activity for 100ms pre-stimulation were discarded. The mean peak-to-peak amplitudes recorded post stimulation were then normalized to baseline and expressed as the ratio of MEP amplitude obtained after tDCS compared to the MEP amplitude obtained before tDCS (amplitude after/ amplitude before).

5.3.5.1. Experiment 1: Electrode Montage

In order to assess the influence of electrode montage, the shifts in cortical excitability induced by hf-tRNS with unilateral and bilateral electrode montages were compared. A mixed model ANOVA was undertaken on normalized MEP amplitudes, this had a between subject factor of montage (2 levels: unilateral, bilateral electrode placement) and a within subject factor of time (6 levels: 5,10,15,20,25,30 minutes). The Machley's test of Sphericity was performed and Greenhouse Geisser correction applied where necessary. Post hoc comparisons were undertaken using independent samples t-tests (one sample). Additionally, in order to determine whether there were significant shifts from baseline, paired t-tests (one sample) were undertaken for each stimulation condition (using un- normalized values). The t-tests were not corrected for multiple comparisons as this is equivalent to Fishers LSD correction which is standard use in studies in this field (Batsikadze et al., 2013; Kidgell, Goodwill, Frazer, & Daly, 2013; Moliadze, Antal, & Paulus, 2010; Nitsche et al., 2003; Nitsche & Paulus, 2001).

5.3.5.2. Experiment 2: Duration

In order to assess the influence of stimulation duration, the shifts in cortical excitability induced by hf-tRNS applied for 10 and 20 minutes were compared. As described in experiment 1, a mixed model ANOVA were undertaken on normalized MEP amplitudes. This had a between subject factor of stimulation duration (2 levels: 10 or 20 minutes) and within factor of time post stimulation (6 levels: 5,10,15,20,25,30 minutes). As described previously, post hoc tests were undertaken using independent samples t-tests. In order to determine whether there were significant shifts from baseline, paired t-tests were undertaken for each stimulation type (using un- normalized values). The t-tests were not corrected for multiple comparisons as this is equivalent to Fishers LSD which is standard use in similar studies.

5.4. Results

5.4.1. Experiment 1:Electrode Montage

The ANOVA analysis revealed a significant effect of electrode montage ($F_{(1,15)}$=6.23, $p<0.05$), no significant effect of timepoint post stimulation ($F_{(5,75)}$=0.95, p=0.46), and no significant interaction of time and polarity ($F_{(5,75)}$=0.58, p=0.72) (Figure 4.3).

Post hoc independent samples t-tests revealed that there were significant differences in MEP amplitudes following unilateral and bilateral stimulation at 5 ($t_{(15)}$=2.37, $p<0.05$), 15 ($t_{(15)}$=2.84, $p<0.01$) 25 ($t_{(15)}$=2.13, $p<0.05$) 30 ($t_{(15)}$=2.04, $p<0.05$) minutes post stimulation.

Paired t-tests comparing baseline (i.e. unadjusted) MEP amplitude values to each timepoint post stimulation revealed that, for unilateral hf-tRNS MEP amplitude was significantly higher than baseline at timepoints 5 ($t_{(9)}$=-2.05, $p<0.05$), 10 ($t_{(9)}$=-1.95, $p<0.05$), 15 ($t_{(9)}$=-2.84, $p<0.01$), 20 ($t_{(9)}$=-2.08, $p<0.05$) and 30 ($t_{(9)}$=-1.98, $p<0.05$) minutes post stimulation. These results suggest that, in accordance with previous studies, corticospinal excitability is increased by unilateral hf-tRNS to the M1.

For bilateral hf-tRNS, paired t-tests revealed that MEP amplitudes did not significantly differ from baseline at the majority of timepoint post stimulation. At 25 minutes post stimulation there was a significant decrease in MEP amplitude in relation to baseline ($t_{(6)}$=2.05, $p<0.05$).

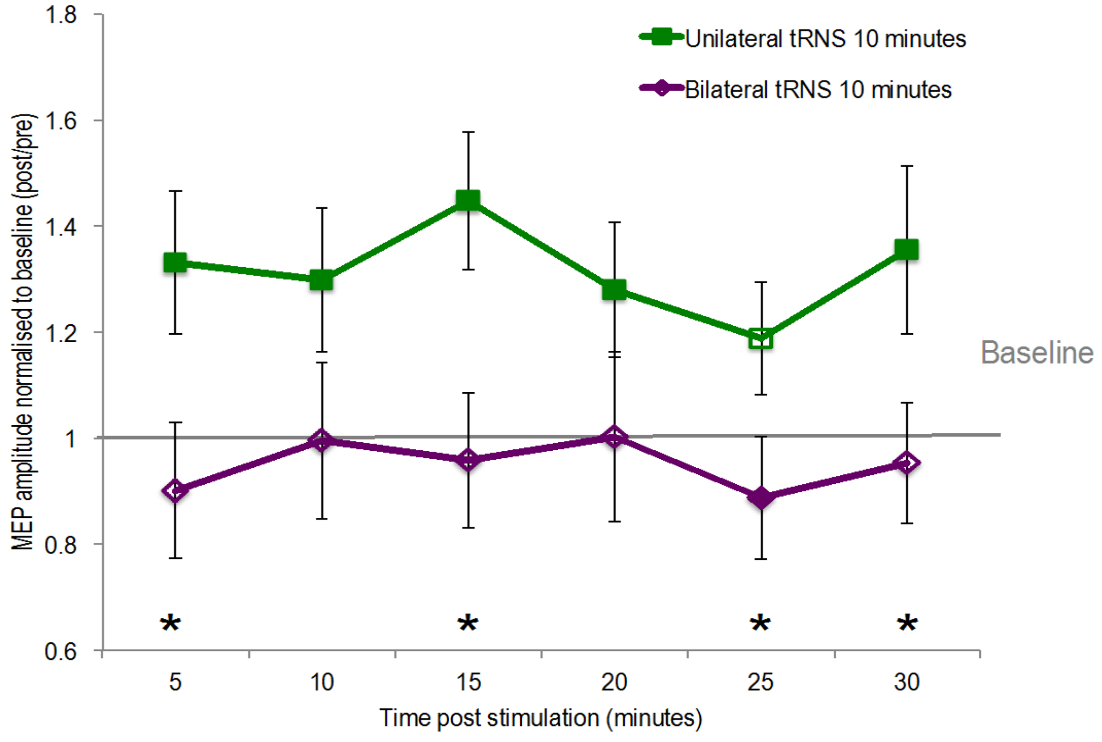


Figure 5.2: Results for experiment 1- electrode montage: Timecourse of normalised MEP amplitude following 10 minutes of hf-tRNS applied with unilateral (left M1/ right contralateral orbit montage; green line) and bilateral (left M1/ right M1; purple line) electrode montages. Electrode montage had a significant effect on normalised MEP amplitude. * denotes significant differences between the after effects of unilateral and bilateral electrode montages at a particular timepoint ($p<0.05$). MEPs amplitudes were significantly larger relative to baseline (indicated by solid circles) at 5, 10,15,20 and 30 minutes post stimulation for unilateral montages, which was not the case for bilateral montages.

5.4.2. Experiment 2: Duration

The ANOVA analysis revealed a significant effect of stimulation duration ($F_{(1,16)}$=5.50, p<0.05), no significant effect of timepoint post stimulation ($F_{(5,80)}$=1.20, p=0.32) and a no significant interaction of stimulation duration and time post stimulation ($F_{(5,80)}$=0.50, p=0.98) (Figure 4.4).

Post hoc independent samples t-test revealed there were significant differences in MEP amplitudes 10 and 20 minutes of tRNS, at 5 minutes ($t_{(16)}$=1.97, p<0.05), 10 ($t_{(16)}$=2.02, p<0.05), 15 ($t_{(16)}$=2.31, p<0.05), 20 ($t_{(16)}$=2.24, p<0.05), 25 minutes ($t_{(16)}$=1.85, p<0.05) and 30 ($t_{(16)}$=1.81, p<0.05) minutes post stimulation.

Paired t-tests comparing baseline (i.e. unadjusted) MEP amplitude values to each timepoint post stimulation revealed that, following 20 minutes of hf-tRNS, MEP amplitudes did not significantly differ from baseline at any of the timepoints. This was not the case for hf-tRNS delivered for 10 minutes, for which the data is presented in experiment 1.

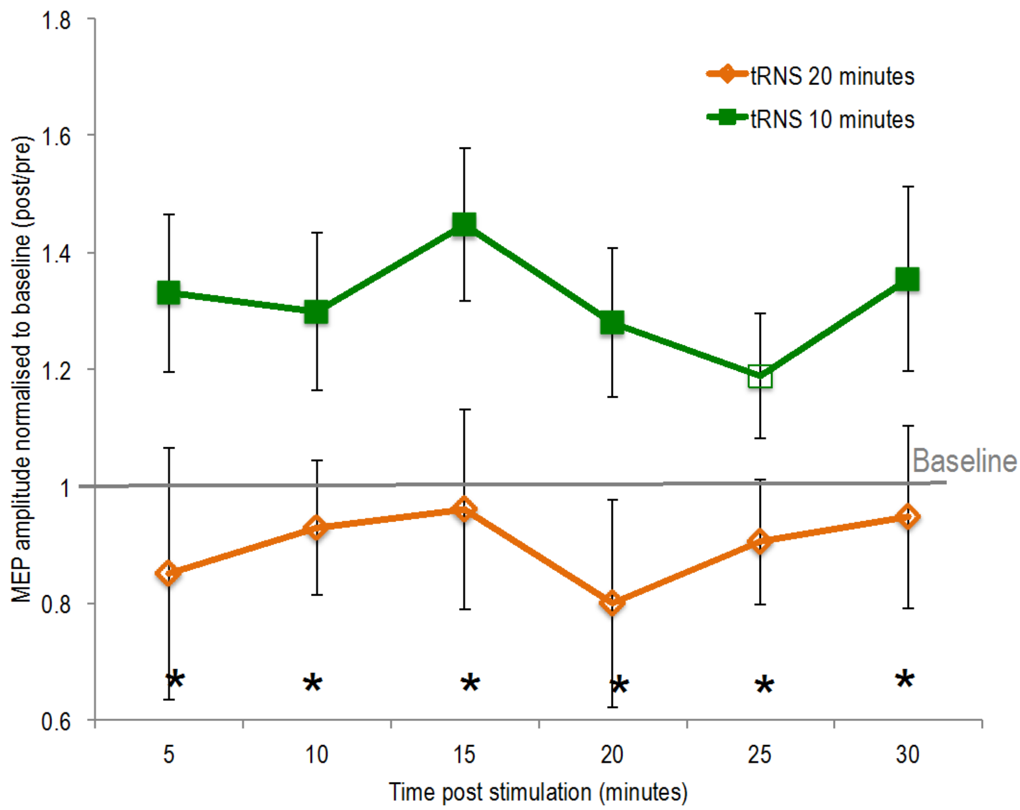


Figure 5.3: Results for experiment 2- duration: Timecourse of normalised MEP amplitude following 10 (green) and 20 minutes (orange) of hf-tRNS applied with a unilateral montage (left M1/ right contralateral orbit montage). Stimulation duration had a significant effect on normalised MEP amplitudes and 10 minutes of tRNS induced elevations in the MEP amplitude in comparison to 20 minutes of tRNS at all timepoints post stimulation. *Denotes a significant difference between the after effects of 10 and 20 minutes of hf-tRNS at a particular timepoint. Hf-tRNS delivered for 20 minutes did not induce significant shifts in MEP amplitudes relative to baseline.

5.5. Discussion

In order to establish confidence in hf-tRNS as a potential candidate for application in elite athletes, it was necessary to investigate the influence of stimulation parameters, electrode montage (experiment 1) and duration (experiment 2), on the after effects of tRNS. Findings from the current study demonstrate that the assumptions of increased corticospinal excitation were not evident for bilateral electrode montages (experiment 1) and increased stimulation durations of 20 minutes (experiment 2), parameters that are routine in the application of tRNS for cognitive enhancement. These findings raise concerns regarding the physiological assumptions that underpin the rationale for application in many studies applying this technique.

The findings from experiment 1 reveal that electrode montage influences the effects of hf-tRNS. In particular, hf-tRNS delivered via a unilateral montage were shown to significantly differ from those induced via bilateral montage for the majority of timepoints post stimulation. Using parameters similar to those which have established the physiological effects of tRNS, namely unilateral montages for 10 minutes, a replication of increased corticospinal excitability (as evidenced by elevations in MEP amplitude in comparison to baseline) was observed (Chaieb, Paulus, & Antal, 2011; Inukai et al., 2016; Moliadze, Antal, & Paulus, 2010; Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). In these studies the excitatory after-effects were observed using an active electrode (over M1) of 4x4cm and reference electrode of 6x14cm. Computational modeling (Faria, Hallett, & Miranda, 2012) and experimental work (Bastani & Jaberzadeh, 2013) suggest smaller electrodes produce more focal, effective and localized neuronal modulation than larger ones. In the current study both electrodes were sized 5x7 (35 cm^2) to replicate conditions in studies of cognitive neuromodulation (e.g. Cappelletti et al., 2013; Chawke & Kanai, 2015; Palm, Hasan, Keeser, Falkai, & Padberg, 2013; Popescu et al., 2016), the observation that increases in corticospinal excitability extends to this electrode size is useful.

When stimulation was delivered via bilateral electrode montages (for durations of 10 minutes) there were no significant elevations in MEP amplitudes in comparison to baseline, for the majority of timepoints post stimulation. The findings that bilateral M1 montages are less effective at inducing elevations in corticospinal excitability replicates those from the previous chapter which applied tDCS, as well as those from a number of other studies that have demonstrated the importance of the positioning of the return electrode in inducing the effects TES (Moliadze et al., 2010; Mordillo-Mateos et al., 2012; Nitsche & Paulus, 2000). There are now two alternate electrode montages explored in the tRNS literature, other than the conventional M1/contralateral orbit montage. The other is M1/contralateral upper arm, which has additionally been shown to not be effective at inducing increases in corticospinal excitation (Moliadze et al., 2010). The explanation proposed as to why electrode montage may be a crucial factor in inducing shifts in corticospinal excitability, is that this changes the spatial locality and depth of current flow, as well as the degree to which current may be shunted across the cortex (Bestmann, de Berker, & Bonaiuto, 2015; Bikson, Rahman, & Datta, 2012; Datta et al., 2010; Faria et al., 2012; Miranda, Faria, & Hallett, 2009). Moreover with bilateral montages there is the possibility of interactions with regions that are monosynaptically connected (Kimura, 1967).

Experiment 2 examined the influence of increased stimulation duration on the effects of hf-tRNS. The findings demonstrate duration of stimulation to influence the after-effects of hf-tRNS, in particular hf-tRNS delivered for 10 minutes produced significantly elevated corticospinal excitability in comparison to that delivered at all timepoints measured. Moreover there were no significant changes in MEP amplitude following 20 minutes of tRNS, in comparison to baseline, at any timepoint post stimulation. Therefore the classical effects of increased corticospinal excitation were not observed using stimulation with a duration of 20 minutes.

Previous work has shown that durations of five minutes of hf-tRNS stimulation are necessary to induce elevations in corticospinal excitability. Stimulation for 5 minutes induced a significant increase in MEP amplitude at one timepoint – 10 minutes post stimulation only (Chaieb et al., 2011). With 10 minutes of hf-tRNS these after-effects are much more robust (Terney et al., 2008). The results of the current study show that at longer durations of 20 minutes, this linear relationship of duration of stimulation and magnitude of after effects breaks down and hf-tRNS becomes less effective at increasing cortical excitability. As tRNS is a novel technique its mechanism of action is not yet well defined (possible mechanisms are outlined by Antal & Herrmann, 2016), the results of the current study suggest however that this mechanism is time dependent. The reason for the reduction in MEP amplitude at longer durations is not clear, although with other neuromodulatory techniques, namely anodal tDCS (Paulus, Antal & Nitsche, 2013), TBS and TMS (Gamboa, Antal, Moliadze, & Paulus, 2010), longer stimulation durations have been reported to change the induced effects on cortical excitability from excitation to inhibition. These findings indicate that there are neuronal inhibitory mechanisms that have a delayed onset when exposed to excitatory protocols, and similar mechanisms may be at play with tRNS.

Together these findings illustrate the importance of stimulation parameters, duration and electrode montage in the application of hf-tRNS, which has implications for studies of cognitive neuromodulation. Stimulation durations of 20 minutes (e.g. Cappelletti et al., 2013; Chawke & Kanai, 2015; Palm, Hasan, Keeser, Falkai, & Padberg, 2013; Popescu et al., 2016; Romanska, Rezlescu, Susilo, Duchaine, & Banissy, 2015; Vanneste, Fregni, & De Ridder, 2013) and bilateral electrode placement (e.g. Cappelletti et al., 2013; Popescu et al., 2016; Romanska et al., 2015; Vanneste et al., 2013) are common in the application of tRNS to produce cognitive enhancement. The use of tRNS in such studies is predicated on the assumption of increased cortical excitation, in particular this premise is used to guide study design and interpret effects. For example tRNS is often chosen to induce shifts in cortical excitation that are comparable, if not enhanced, and without polarity constraints of tDCS (Inukai et al., 2016; Paulus, Nitsche, & Antal, 2016). The results here highlight that neither a duration of 20 minutes nor bilateral placements are adequate for this goal. Moreover the principle of increased corticospinal excitation is applied in the interpretation of results and while the findings of the current study do not dispute the behavioural effects, they do question the validity of the physiological explanations based on increased cortical excitation. Notably the application of tRNS is in it infancy in comparison to the other neuromodulatory techniques (Paulus et al., 2016), however in order for the field to progress in a way that is useful to understanding underlying neural mechanisms (and not just inducing behavioural effects) it is important for tRNS to be applied using parameters for which the physiological effects have been observed.

The reliability of behavioural findings induced by tES, as well as an understanding of why these effects occur, have been highlighted as issues that need to be addressed in order to assess the use of these techniques outside of the laboratory (Parkin et al., 2015; Walsh, 2013). As seen in the tDCS literature, the findings from the current study undermine the physiological assumptions that guide work that has applied tRNS for cognitive neuromodulation. As such the use of tRNS as a possible candidate for application in elite athletes is undermined. Together the findings from chapter 2, 3 and 4 suggest that, despite the potential suggested and a small number of studies highlighting tES as a tool to modulate abilities underlying performance in athletes (Alves et al., 2013; Banissy & Muggleton, 2013; Okano et al., 2015; Reardon, 2016), these techniques are not robust enough to continue with use in elite-athletes at this time. As a result behavioural work in elite athletes is pursued in the following chapters.

5.6. Conclusion

In conclusion, the findings of the current study show that duration of stimulation and electrode montage are important factors in determining the excitatory effects of hf-tRNS. The assumptions of corticospinal excitation may not extend to stimulation parameters that are common in the application of this technique, namely bilateral montages and 20 minutes of stimulation. Yet studies applying tRNS have used the assumption of corticospinal excitation to guide methodological design and interpret effects. The results of this chapter highlight that any understanding of the physiological underpinning of behavioural effects is lacking, therefore there is reduced confidence in tRNS as a candidate for application outside of the laboratory. Together the findings from chapter 3, 4 and 5 highlight that the behavioural findings, and physiological understanding of the results of studies employing tES for cognitive neuromodulation are not robust enough to continue with application to elite athletes at this time.

6. Decision-making Under Physical Pressure in Elite Athletes

6.1. Abstract

Background: The cognitive skills required during sport are highly demanding; accurate decisions based on the processing of dynamic environments are made in a fraction of a second (Walsh, 2014). Optimal decision-making abilities are crucial for success in sporting competition (Bar-Eli, Plessner, & Raab, 2011; Kaya, 2014). Moreover, for the elite athlete, decision-making occurs under conditions of intense mental and physical pressure (Anshel & Wells, 2000), yet much of the work in this area has largely ignored the highly stressful context in which athletes operate (Hepler, 2015). A number of studies have shown that conditions of elevated pressure influence athletes decision quality (Kinrade, Jackson, & Ashford, 2015; Smith et al., 2016), response times (Hepler, 2015; Smith et al., 2016), as well as risk-taking (Pighin, Savadori, & Bonini, 2015). However almost all of this work has been undertaken in non-elite athletes and participants that do not routinely operate under conditions of high stress. Thus, there is very little known about the influence of pressure on decision-making in elite athletes.

Objective: A key aim of this chapter was to examine how to apply and develop psychological insights useful to elite sport. The current study investigated the influence of physical performance pressure on decision-making in a sample of world-class elite athletes. This allowed an examination of whether findings from previous work in non-elite athletes extend to those who routinely operate under conditions of high stress. How this work could be applied to improve insight and understanding of decision-making among sport professionals is examined.

Method: 23 elite athletes, classified as ‘world-class’ and ‘successful-elite’ (Swann et al., 2015), took part in the study. These athletes compete and have frequent success at an international level, and include 6 Olympic medal winners. Tasks relating to three categories of decision-making were undertaken under conditions of low and high physical pressure. Decision-making under risk was measured with performance on the CGT (Rogers et al., 1999), decision-making

under uncertainty with the BART (Lejuez et al., 2002), and fast reactive responses and interference with the Stroop task (Stroop, 1935). Performance pressures of physical exhaustion were induced via an exercise protocol consisting of intervals of maximal exertion undertaken on a watt bike.

Results: At a group level, under physical pressure elite athletes were faster to respond to control trials on the Stroop task and to simple probabilistic choices on the CGT. Physical pressure was also found to increase risk-taking for decisions where probability outcomes were explicit (on the CGT), but did not affect risk-taking when probability outcomes were unknown (on the BART). There were no significant correlations in the degree to which individuals' responses changed under pressure across the three tasks, suggesting that individual elite athletes did not show consistent responses to physical pressure across measures of decision-making. When assessing the applicability of results based on group averages to individual athletes, none of the sample showed an 'average' response (within 1SD of the mean) to pressure across all three decision-making tasks.

Conclusion: There are three points of conclusion. First, an immediate scientific point that highlights a failure of transfer evidence reported from non-elite athletes to elite athletes in the area of decision-making under pressure. Second, a practical conclusion with respect to the application of this work to the elite sporting environment, which highlights the limitations of statistical approaches based on group averages and thus the beneficial use of individualized profiling in feedback sessions. Third, the application of this work in a sports setting is described, in particular the development and implementation of a decision-making taxonomy as a framework to conceptualize and communicate psychological skills among elite sporting professionals

6.2. Introduction

Optimal decision-making is a crucial component of successful performance in sporting competition (Bar-Eli, Plessner, & Raab, 2011; Kaya, 2014). A significant factor often overlooked in previous work in this area is the context in which decisions are made (Hepler, 2015). In particular, elite athletes routinely operate under a diverse array of mental and physical pressure. Commonly cited sources of acute stress include physical exhaustion, crowd noise and physical injury, as well as the psychological impact of errors, negative feedback from the crowd, coaches and teammates, interpersonal conflict, rivalry and the pressure to obtain highly valued awards (Anshel & Wells, 2000; Mellalieu, Neil, Hanton, & Fletcher, 2009). Given such a demanding environment, it is not uncommon for athletes to perform significantly below expectation despite high levels of motivation, a phenomenon termed 'choking' (Beilock & Gray, 2007). Indeed, reduced performance when pressure is at its greatest has been shown even at an elite level. For instance, analysis of European Championship football penalty shootouts (from 1976-2004) revealed significant differences in performance under high versus low pressure. Players perform worse (62% success rate) for penalty shots which would cost the team winning the game (high pressure) when compared to penalty shots which would secure the team the win (lower pressure, 92% success rate) (Jordet & Hartman, 2008). Similarly, analysis of Professional Golfing Association tournaments scores (from 1983-2010) showed that professional golfers played worse on the final round, when pressure is at its highest, compared to the penultimate round of a tournament (Wells & Skowronski, 2012).

There are a handful of studies that have explored decision-making in the sporting domain under conditions of high pressure. These studies tend to examine non-elite athlete's decision quality and reaction times to sport specific decision-making tasks (rather than the cognitive processes underlying decision-making such as risk-taking). In these studies performance pressure is operationalized in a variety of ways that fall into broad categories of psychological and physical. Psychological performance pressure has been shown to impair task performance in non-elite athletes. For example (conditions of elevated social evaluation) was reported to negatively impact the decision quality of novice basketball players but only in highly complex game scenarios (Kinrade et al., 2015). Moreover, mental exhaustion (induced by performance of the Stroop task for 30 minutes) was shown to impair decision accuracy and response times of non elite athletes on a football specific decision-making task (Smith et al., 2016). Hepler (2015) compared mental and physical pressure in non elite athletes and found that the time taken to generate decision outcomes was longer under conditions of mental stress (performance on a dual subtraction task), while conditions of physical exertion had no effect.

Other studies have focused on the physical performance pressure of intense physical exertion. A recent review paper examined the influence of physical load on perceptual- cognitive tasks in athletes of differing levels of expertise. This revealed that the inverted-U relationship between physical exertion and reaction times established in non-athletic samples - with moderate exertion inducing a facilitatory effect while high intensity exertion inducing a detrimental effect on reaction times – did not extend to expert athletes. Expert athletes were found to show a general facilitation in response time measures under conditions of both moderate and intense physical pressure, and were more positively affected than novice athletes. (Schapschröer, Lemez, Baker, & Schorer, 2016). While, the review had a broad inclusion criterion of an expert athlete including all those competing at a national level, it importantly highlighted athletic expertise as an important factor in determining the influence of physical pressure on indicators of performance.

There have been two studies to date that examined the influence of physical pressure on risk-taking both undertaken in non elite athletes. One found physical exertion to increase risk taking on the BART in a sample of male adolescent athletes (Black et al., 2012). The other reported physical exertion to induce an increase in risk taking in male and decrease in risk-taking in female athletes on the BART (Pighin et al., 2015).

These results are similar to that found in laboratory studies that have examined the precise influence that stress (operationalized as elevated cortisol levels) has on decision-making (for a review see Starcke & Brand, 2012). The majority of these studies report increased risk-taking under conditions of elevated stress for both decisions made under uncertainty, (similar to those reported previously) (Lighthall et al., 2009; Preston, Buchanan, Stansfield, & Bechara, 2007; van den Bos, Harteveld, & Stoop, 2009), and also for decisions made under risk where probability outcomes are known (Pabst, Schoofs, Pawlikowski, Brand, & Wolf, 2013; Starcke, Wolf, Markowitsch, & Brand, 2008). In line with Pighin et al., (2015) a number have additionally reported an interaction with gender, where males show increased risk-taking, while females show decreased risk-taking, under conditions of acute stress (Lighthall et al., 2009, 2012; Preston et al., 2007). Possible mechanisms proposed to explain modulations to risk taking include the detrimental influence of cortisol on higher order cognitive processes that supports decision-making such as inhibition (Starcke, Wiesen, Trotzke, & Brand, 2016) and working memory (Schoofs, Preuß, & Wolf, 2008). It is thought that this results in a loss of top-down control and increased stimulus-driven behaviours (Buckert, Schwieren, Kudielka, & Fiebach, 2014b). Moreover increased cortisol has been proposed to alter reward and loss processing possibly leading to increased dopaminergic signaling in the striatum (Buckert et al., 2014b; Starcke & Brand, 2012).

Due to the difficulties of access to elite populations, most of the research examining decision-making under pressure in sport has been undertaken with undergraduate students or non-elite athletes. By the very nature of training and selection of ‘world class’ abilities, elite athletes may perform differently. Unsurprisingly, expertise has been shown to affect decision-making, with elite athletes making faster, more accurate decisions (Vaeyens, Lenoir, Williams, Mazyn, & Philippaerts, 2007) and showing greater knowledge of possible decision outcomes than those with less experience (Williams, Davids, & Williams, 1999). Furthermore, skilled athletes show faster responses on simple choice reaction time tasks compared to novices following acute physical exertion (Schapschröer et al., 2016). Therefore elite athletes may show more resilience to the effects of performance pressure than is evident in the literature, as they are well equipped and practiced at operating under conditions of limited resources. On the other hand, elite athletes may also be subject to the detrimental effects of performance pressure, along with their more inexperienced counterparts. Indeed the presence of ‘choking’ is well documented in elite athletic performances (Jordet & Hartman, 2008; Wells & Skowronski, 2012). In addition, highly skilled athletes have been found to verbalize more technical rules under competitive stress, suggesting a possible regression to earlier stage of learning (Whitehead, Taylor, & Polman, 2015).

In light of previous work which a) explored decision-making in sport which has largely ignored the context in which decisions occur, and b) has been mostly studied in non-elite participants, the aim of the current study is to investigate how decision-making is influenced by performance pressure in a sample of elite athletes. A key motivation of this research is to examine how it can be useful for applied populations, namely the internationally elite athletes included in the sample.

In the current study, world class elite athletes undertook tasks assessing three categories of decision-making under low and high physical performance pressure. Decision-making under risk was examined via performance of the CGT (Rogers et al., 1999), decision-making under uncertainty via the BART (Lejuez, Read, et al., 2003) and fast reactive responses and interference via the Stroop task (Stroop, 1935). Performance pressure was induced by a physical exhaustion protocol consisting of intervals of maximal exertion exercise on an wattbike. This was chosen to mimic one of the most pertinent pressures that elite athletes are routinely exposed to. decision-making in the elite sporting environment. The results of the study will shed light on whether these different categories of decision-making are influenced by physical pressure in elite athletes, and therefore examine whether findings in the current literature transfer from non-elite to elite athletes. Additionally, the study will examine whether individual responses to pressure were consistent across the three types of decision-making. Lastly, the study will discuss the application of this work in a sports setting.

6.3. Methods

6.3.1. Participants

The sample consisted of 23 elite athletes (12 males) aged 23-36 years (mean age: 28). All athletes belonged to a national training program for competition in the upcoming Olympic Games (Rio 2016). They all fell within the 'world-class' and 'successful-elite' expertise categories defined by Swann et al (2015). To emphasize the international caliber of the athletes, all had represented the UK at world-class championships and six were medal winners at London 2012 or Beijing 2008. All athletes included in the sample were from the same sport and enrolled on the same Team GB training program. The approximate average age of entry to this sport was 8 years, thus these elite athletes had approximately 20 years experience in their given domain.

Recruitment occurred with the assistance of Team GB Sport Psychologists and Coaches during a 7- day residential training camp. The squad was initially informed of the aims and procedures of the study during a group meeting. Upon expressing interest, a testing session was scheduled, during which the aims and procedures were re-explained and written informed consent obtained from each athlete. While there was no financial compensation for participation, a cash prize was awarded to the top three performers on the BART to add a competitive element into task performance. Upon completion, in conjunction with a Team GB Sports Psychologists, each athlete received a detailed debrief. The study and consent procedures were approved by the UCL ethics board in compliance with the principles of the Declaration of Helsinki.

6.3.2. Experimental Protocol

A within-subject design was used, whereby the decision-making of elite athletes was assessed under conditions of low and high physical pressure (**Figure 6.1**). Each participant was tested within a single session, at a Team GB training facility. Performance on three tasks was recorded namely the BART (Lejuez, Read, et al., 2003), the CGT (Rogers et al., 1999) and the Stroop task (Stroop., 1935). Initially participants were presented with instructions and undertook a short practice of each task. Participants then performed the decision-making tasks ‘at rest’, i.e. in the absence of any additional performance pressure. Under conditions of physical performance pressure, participants performed these tasks immediately following a protocol of intense physical exertion on a watt bike (further description of the protocol below). Performance of CGT always followed one of the physical exertion sessions, and performance of the BART and Stroop proceeded the other session (the latter two tasks being paired together as they were of shorter duration), the order in which the decision-making tasks were undertaken was counterbalanced across participants. All responses were made via a button press (for the Stroop) or a mouse click (for the BART and CGT), which were recorded automatically and entered into subsequent analyses. After completion of the experimental procedures participants were debriefed during a one-to-one session with the Sports Psychologist, Coach and member of the research team. Here psychological concepts relating to decision-making were discussed and applied to the sporting context, athletes were also provided with a profile of their individual performance.

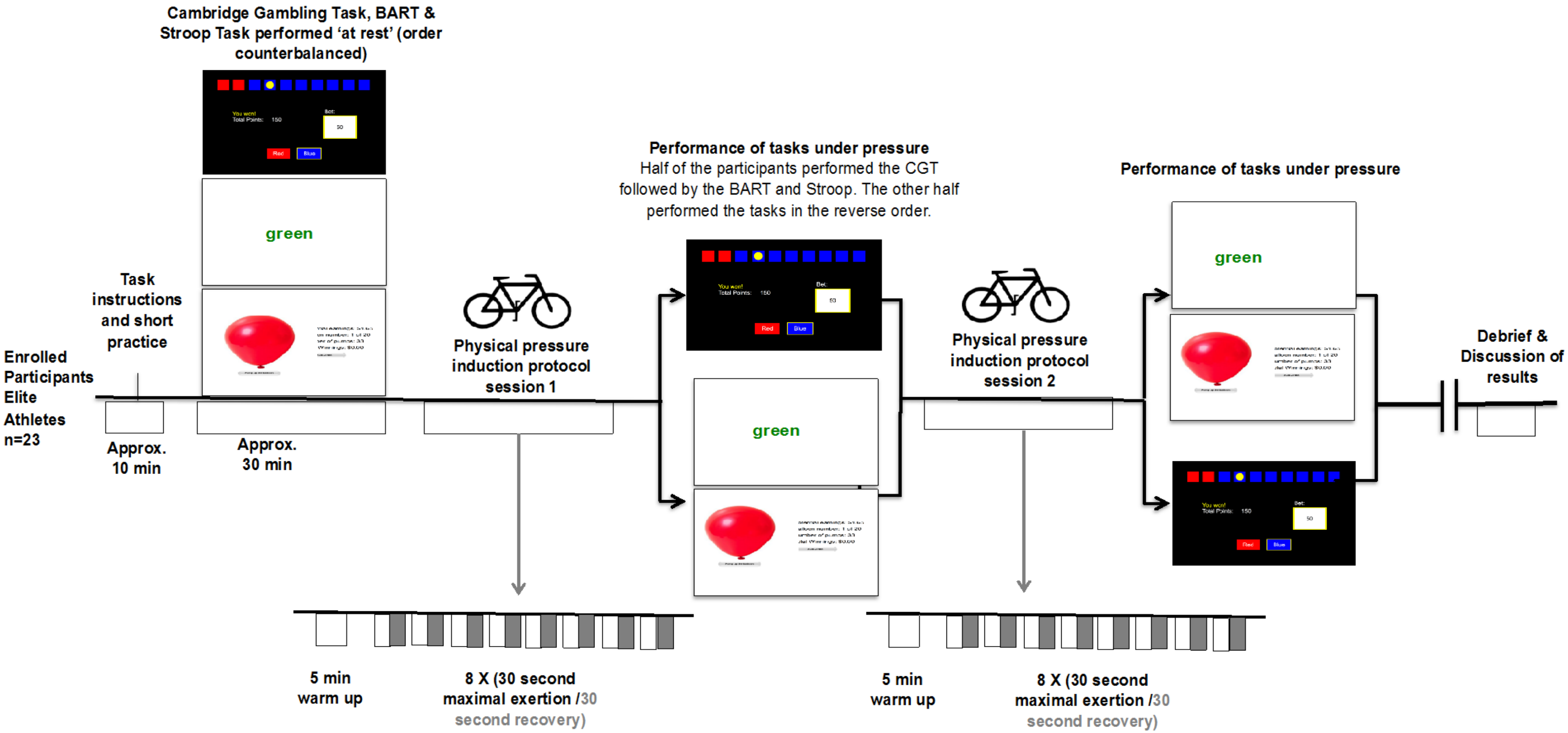


Figure 6.1: The experimental protocol; Upon enrolment, participants undertook a short practice followed by performance of the BART, the Stroop task and CGT (in a counterbalanced order) at rest, i.e. in the absence on any additional performance pressure. Physical pressure was induced via two sessions of eight-x 30 seconds maximal exertion sprints and 30 second recovery on the ergometer. Immediately following one session the BART and Stroop were performed and following the other session the CGT was performed, the order counterbalanced across participants. Upon completion participants were debriefed and received feedback and discussion of their performance.

6.3.3. Physical Pressure Induction

Physical pressure was induced via a protocol of maximal intensity exertion on an ergometer. Athletes completed two sessions of 8 repetitions of 30 seconds at maximal exertion (i.e. an all out sprint), followed by a 30 seconds of recovery. Maximal exertion was derived from self-report, athletes were given the following instruction: "You are required to cycle for 8 sequences of 30 second on and 30 second rest. We ask that you give maximum effort for each of the 30 second periods and recover afterwards". During these intense sprints, verbal encouragement was provided to help motivate the participant and ensure effort did not fall below maximal exertion. Before each repetition of maximal exertion, the participant was given a 5 second countdown. During the protocol participants pedaled a watt bike, with the resistance set by the individual athlete to a level that allowed maximal exertion. At the end of each session, participants immediately proceeded to perform the decision-making tasks. Two separate exercise sessions were undertaken to ensure that physical exhaustion was maintained across all decision-making tasks.

As a warm up, athletes completed 5 minutes of low resistance exercise, which included at least two maximal intensity exertion sprints, prior to this protocol. This was to ensure they were adequately prepared for the exercise regime to minimize the risk of injury. The 30-second duration of maximal intensity exertion was based on the Wingate Test (Vandewalle, Péerès, & Monod, 1987), a protocol devised to measure anaerobic capacity. In developing this test it was noted that participants were reluctant to endure protocols longer than 30 seconds at a time and when required to do so would initially reduce their maximal effort to save energy for the latter part of the test (Vandewalle et al., 1987). The number of repetitions was decided upon after discussion with Team GB Coaches and Sports Physiologists. The intent was to induce physical exhaustion in line with the type of physical exertion that the athlete endures during competition in order to promote ecological validity of this experiment.

6.3.4. Decision-making Tasks

All decision-making tasks were delivered via a laptop computer, with a 17-inch display screen, and run via Inquisit software version 4.0.7.0 (Millisecond Software, Seattle WA). Responses were made through mouse click or button press, and the software automatically recorded choice outcomes and response times for subsequent analysis.

6.3.4.1. BART

The BART (Lejuez, Read, et al., 2002) (**Figure 3.2**) is a standardized measure of risk taking under uncertainty. The task requires participants to inflate a series of computerized balloons for which the participant accrues money (5p per pump). However, the winnings from each balloon can only be kept if they are 'banked' before the balloon bursts. Participants are faced with the decision, in light of not knowing the bursting point, when the optimal point is to stop inflating the balloon and transfer the winnings into a safe wallet. While participants did not receive cash equating to the final sum accumulated in the safe wallet, the top three highest scorers on the task (average of low and high pressure performance) received a cash prize. The participants' objective was therefore to obtain the largest amount of money on the task in order to win the cash prize. This method of reimbursement has been used in previous studies (Fecteau et al., 2007; Sela, Kilim, & Lavidor, 2012)**.**

Further details of task parameters and delivery are outlined in Section 3.3.4.1. While in chapter 3, participants completed the standard version of the task which consists of accumulate as much money as possible over a total of 30 balloons, in the current study there were only 20 balloons in total. This shortened version of the task has been employed by a number of studies to date (e.g. Cheng & Lee, 2016; Derefinko et al., 2014; Ryan, MacKillop, & Carpenter, 2013; Vaca et al., 2013), following the observation that there is no overall change is the measurements acquired. It was beneficial in this case to make the testing procedure as efficient as possible in an elite sample whose availability was limited.

The **average adjusted number of pumps** is the standard measure of risky decision-making on the BART, which was used for the analysis in the current study. This is the number of pumps for the balloons that did not burst, and thus removes the variation that occurs as a result of the computer generated random explosion point. In previous work this variable was shown to be a strong predictor of real-world risk taking behaviours in healthy adults and adolescence (Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Crowley, Raymond, Mikulich-Gilbertson, Thompson, & Lejuez, 2006; Lejuez, Aklin, Jones, et al., 2003; Lejuez, Aklin, Bornovalova, & Moolchan, 2005; Lejuez, Aklin, Zvolensky, & Pedulla, 2003). There are other indices of performance on this task such as the amount of money accumulated and the number of balloons burst, these have also been shown to be adequate measures of risk taking, however were not additionally analyzed to avoid inflating type 1 error rates (as recommended by Lejuez, Read, et al., 2002).

6.3.4.2. CGT

The CGT (Rogers et al., 1999) (**Figure 6.2**) was used to assess decision-making under risk, where information relating to the probability of different outcomes is explicit. The task displays a simple probabilistic decision where the participant is required to guess the location of a yellow token hidden in one of ten boxes presented on screen. The boxes are coloured either blue or red and in any given trial the proportion of these vary across ratios of 9:1, 8:2, 7:2 and 6:4. Participants are required to choose where they think the token is hidden, in the red or the blue boxes, by clicking on rectangles at the bottom of the screen labeled red or blue. The participant is then given the opportunity to select the number of points they wish to gamble. The amounts that can be bet appear as a number on screen, they are always a proportion of the participant’s total points and are presented in a sequence. There are two types of bet presentation, the ascending version, whereby the amount of points one can gamble starts small and increases in magnitude (from 5%, 25%, 75% to 95% of total points). Conversely, in the descending version the bets start large and decrease in magnitude (from 95%, 75%, 25% to 5%). There was an interval between the presentations of each point score of 3 seconds. The participant is required to select the number on screen when it represents the amount of points they wish to gamble on each trial. Following this, the location of the token is then displayed to the participant, if the participant is correct in their choice, the text “You Won” appears and the amount of points are added to their total. If the participant is incorrect, the text “You Lost” appears and the amount of points gambled are deducted from their total. Sound effects from the task were delivered via headphones, including beeps for each bet presentation, with a high pitch beep for an increasing bet, and lower pitch sound for a decreasing bet.

The task consisted of a total of 48 trials, whereby the four different probability types (1:9, 2:8, 3:7, 4:6) were presented twelve times in a predefined pseudo-randomised order, half the time there were more red, and half the time more blue, boxes. The trials were presented in blocks, with eight blocks in total each containing six trials. In each block, participants began with 100 points, and the points accumulated were reset at the end of each block. The location of the token was pseudo-randomly determined, whereby 1 in every 6 trials the better choice (the colour with the highest probability) led to a loss. There were four blocks with ascending points (a total of 24 trials, with each trial type being presented 6 times) presented consecutively and three blocks with descending points. The order of ascending or descending blocks were counterbalanced across participants, but kept the same within participants across repetition of the task. Due to time constraints when testing with a specialized sample, the task used in this instance consisted of fewer number of trials than presented in the standard version of the task, which has a total of 72 trials (Rogers et al., 1999).-

The task is administered via standardized instructions (outlined in Manes et al., 2002; Rogers et al., 1999). In short, the task procedures were outlined to the participant, along with the instruction to collect as many points as possible. There were four practice trials for participants to familiarize themselves with the task, two of these consisted of the decision phase only, and the other two mimicked the task.

There are four indices of task performance that were used in the analysis. In the initial decision-making phase the **response time** is measured as the duration between when the trial is presented and when the participants indicate their choice to look in the red or blue box via a mouse click. This measure is expected to interact with the probability ratio of the trial, in particular deliberation time is likely to be less in trials with 9:1 ratios, in comparison to 6:4 trials. The **error rates** represent the quality of the decision, measured by the proportion of trials where participants chose the most likely box colour. A winning choice of blue is only counted as a correct decision if blue represents the most number of boxes in the trial.

In the second phase, the performance measure the **mean percentage points** gambled, represents the degree of risk taking on the task, with high-risk takers gambling a larger number of points. The task allows the disassociation of risk-taking and motor impulsivity. Motor impulsivity can be derived by examining the difference between the amount bet on ascending trials to that bet on descending trials. In ascending trials participants have to patiently wait for the appearance of a more risky bet, whereas in the descending trials participants can make risky bets immediately. Therefore participants high in impulsivity will bet an amount that occurs early in the sequence, for ascending trials bets will be small and for descending trials bets will be large. There was a decreased duration in point presentation in this version of the task (3 second) compared to that developed by Rogers et al., (1999) (5 second) it may be easier for participants not to display impulsivity in comparison to other studies.

Lastly, a measure of **risk adjustment** can be deduced from the amount gambled across different trial ratios and quantifies a participant's ability to vary their risk taking in response to task contingencies. Optimal behavior on the task is where larger bets are made on trials where there is a higher likelihood of winning (i.e. those with the odds ratio 9:1), in comparison to trials where the likelihood of winning is lower (i.e. those with the odds ratio 6:4). Risk adjustment is calculated as the degree to which risk taking differed between ratios, and is calculated in a manner designed to be independent from the total amount gambled (Rogers et al., 1999). It is calculated using the following equation: (*2* % bet at 9:1)+ (% bet at 8:*2)- (% bet at 7:3) – (2* *% bet at 6:4) / average % bet. A score of* 0 represents no risk adjustment, whereby participants do not adjust their bets according to the different betting ratios. This is thought to indicate a failure to use information relating to the decision (Manes et al., 2002; Rogers et al., 1999).

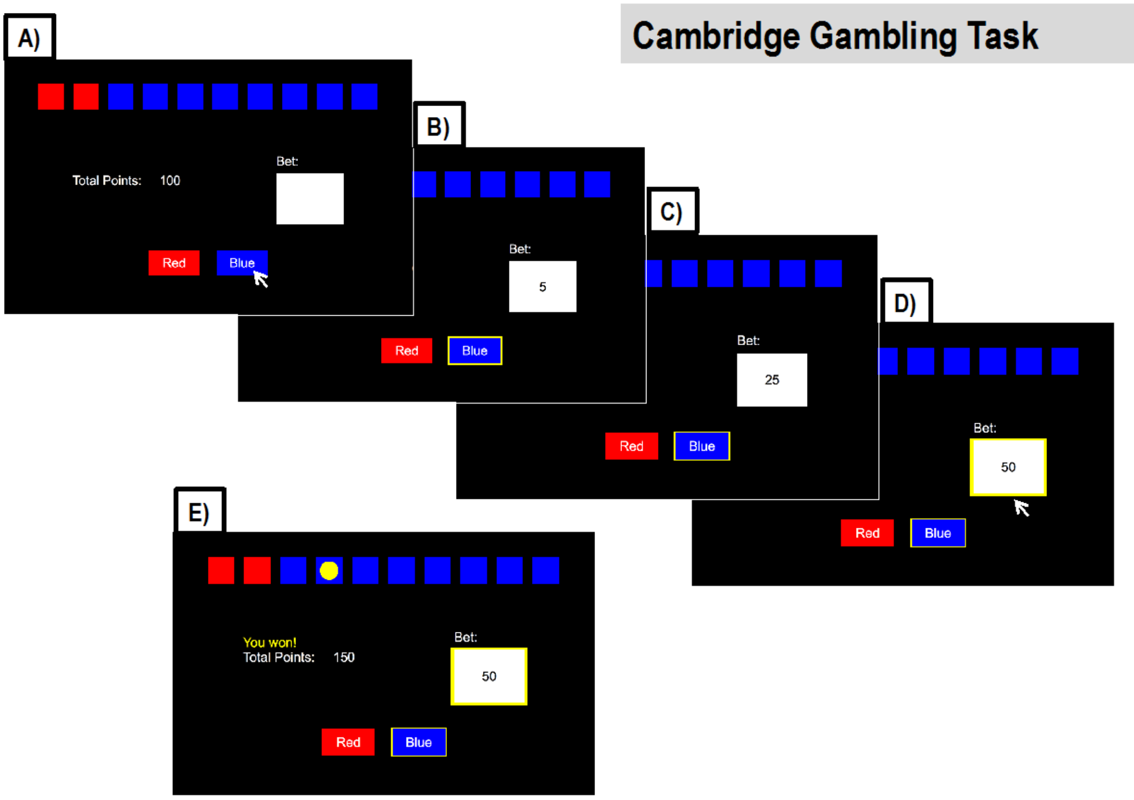


Figure 6.2: **The CGT: A)** The task displays a simple probabilistic decision whereby participants choose whether to look either the red or blue box for the yellow token. The proportions of red or blue boxes vary across ratios of 9:1, 8:2, 7:2 and 6:4. The participant click on the red or blue icon to indicate their response. **B)** A number appears in the white box representing the amount possible to gamble on their decision. **C)** In the ascending trial this amount increases every 3 seconds. **D)** When the number in the box represents the value the participant would like to gamble they are required to click on it. **E)** The position of the yellow token is revealed, if correct the value is added to the total points, if incorrect the value is subtracted.

6.3.4.3. Stroop Task

The Stroop task is a widely researched measure of interference and processing speed (for a review see MacLeod, 1991). In this task participants were instructed to name the colour of items presented on screen by pressing a corresponding key on the keyboard (d for red, f for green, j for blue and k for black).

The stimuli presented consisted of colour words (red, blue, green and black) presented in red, blue, green and black ink, as well as solid rectangle blocks in these same colours on a white background. There were three trial types: congruent trials, where the word and the ink colour are the same (i.e. the word ‘red’ written in red ink); incongruent trials, where the word and ink colour are different (i.e. the word ‘red’ written in blue ink); and control trials, which simply measure reaction times to identify a solid block of colour. The Stroop interference effect refers to the increased amount of time it takes to name the colour of a word when the ink colour and word are incongruent, compared to when the ink colour and word are congruent. This is thought to result from the automatic access of word naming being overridden in incongruent trials (MacLeod, 1991).

The task consisted of a total of 84 trials, the order of which was randomized. There were 28 congruent trials and 28 incongruent trials, with each of the four colour words being presented seven times. For the incongruent trials, each colour word was presented in the three different colours twice (i.e. red presented in blue ink, green ink and black ink), and one of the colour-word pairing (randomly selected) was presented an additional time. There were also 28 control trials, which presented solid blocks of colour, again each of the four colours were presented seven times.

The task was self-paced, whereby the stimuli remained on screen until participants made a response. Participants were instructed to make their responses as quickly and accurately as possible and to place their fingers over the response keys to ensure prompt responses. There were two measures used in the analysis of this task: reaction times to control trials and the interference effect, measured as the reaction time to incongruent minus the reaction time to congruent stimuli. Before starting, participants undertook a short practice consisting of 12 trials (four of each trial type) to familiarize themselves with the task (see **Figure 3.3**).

6.3.5. Data Analysis

To explore whether decision-making on the three tasks is influenced by performance pressure, ANOVA and paired t-tests (two tailed) were undertaken to compare task performance under conditions of low and high physical pressure. Where relevant, Mauchly's test of sphericity was performed and *Greenhouse-Geisser correction* applied. Bonferroni correction was used to correct for multiple comparisons. For each task, the dependent variables used in this analysis are laid out below.

BART: The mean adjusted number of pumps (the average pump count for balloons that did not burst) was analyzed as a measure of risk taking under uncertainty. A three way mixed ANOVA was undertaken to compare performance of the task under conditions of low and high physical pressure (within subjects factor of pressure: low pressure, high pressure) broken down by time (within subject factor of balloon number: 1-10, 11-20). A between subject factor of gender was also included (male, female).

CGT: The response times (the duration from the trial appearing on screen and the participant choosing to look in a red or blue box) and the error rates (the percentage of trials in which the participant chose the most likely box colour) were analyzed using a repeated measures ANOVA. This was undertaken to compare the dependent variable (response time or error rates) under conditions of low and high physical pressure (within subjects factor of pressure: low pressure, high pressure) with the dependent variables broken down by the odd ratios presented in the trial (within subject factor of odds ratio: 1:9, 2:8, 3:7, 4:6). This part of the analysis was collapsed across the ascending and descending trials as the presentation and selection of bets occurred after these variables were recorded.

In order to explore gambling behaviour in decision-making under risk the mean percentage number of points bet on the task were analyzed. This analysis included trials in which participants chose the most likely outcome in order to not confuse betting behavior and decision-making. A three way mixed ANOVA was used to compare the amount of points bet for ascending and descending trials (within subject factor point presentation: ascending, descending) under conditions of high and low physical performance pressure (within subjects factor of pressure: low performance pressure, high performance pressure). A between subject factor of gender was included (male, female).

Lastly, a measure of risk adjustment was derived from the data and a paired t-test was performed to compare the degree of risk adjustment under conditions of low and high physical pressure.

***Stroop Task*:** One participant was not included in the analysis due to experimenter error during data collection. Therefore 22 participants were included in the analysis. Paired t-tests were undertaken to compare reaction times on control trials and the Stroop interference effect (difference between reaction times on incongruent trials versus on congruent trials) under conditions of low and high physical pressure. Reaction times of correct responses only were included in the analysis.

Correlational analysis assessing response to pressure across tasks: It was also of interest to examine whether an individual's responses to pressure were consistent across the three decision-making tasks. The difference under pressure score was calculated for key indicators of task performance, by subtracting the score under high pressure from baseline. The variables chosen for indicators of task performance are the average adjusted number of pumps on the BART (a positive score represents better performance under pressure), the reaction time to control trials on the Stroop task (a negative score represents better performance under pressure) and the risk adjustment score on the CGT (a positive score represents better performance under pressure). The difference under pressure scores for each task were compared, using the Pearson Correlation Coefficient, in order to examine whether participants showed a consistent response to pressure across tasks. The participant who did not complete the Stroop task was excluded due to incomplete data, therefore 22 participants were included in this analysis.

Applicability of group data to individuals: In order to explore the degree to which group data applies to individuals the number of athletes whose change under pressure showed an ‘average’ response to pressure across the three tasks were assessed. In accordance with previous work an average response was calculated as a score that fell within 1 standard deviation of the mean (0.5 SD above and below) (Daniel, 1952; Rose, 2016) for the average adjusted number of pumps on the BART, the reaction time to control trials on the Stroop task and the risk adjustment score on the CGT. Again, the participant who did not complete the Stroop task was excluded due to incomplete data, therefore 22 participants were included in this analysis

6.4. Results

6.4.1. Effect of Physical Pressure on the BART

In order to examine whether decision-making changes under conditions of low and high physical pressure performance on the BART, CGT and the Stroop task were examined. For the BART the mean adjusted number of pumps was analyzed as a measure of risk taking under uncertainty (**Figure 6.3**). The ANOVA revealed no effect of gender ($F_{(1,21)}$=1.33, p=0.26) or no effect of performance pressure ($F_{(1,21)}$=3.65, p=0.07), while there was a significant effect of balloon number ($F_{(1,21)}$=43.90, p>0.01). In addition, there was no significant interactions between performance pressure and balloon number ($F_{(1,21)}$=0.13, p=0.71), performance pressure and gender ($F_{(1,21)}$=2.17, p=0.15), or balloon number and gender ($F_{(1,21)}$=0.22, p=0.64). Finally, there was no three-way interaction between balloon number, gender and performance pressure ($F_{(1,21)}$=0.01, p=0.91). Hence, in this sample of elite athletes, physical exhaustion did not induce any significant changes in the degree of risk-taking, although this is significant if the statistical threshold is reduced to a trend level (p=0.1). In this case the elite athletes present a higher degree of risk-taking under physical pressure (mean: low pressure: 38.63 pumps: high pressure: 42.62 pumps). However, it was found that the average adjusted number of pumps was higher for the later part of the task (mean: balloon number 1-10: 37.38 pumps, balloon number 11-20: 43.87 pumps), this reflects the usual learning effects found on this task.

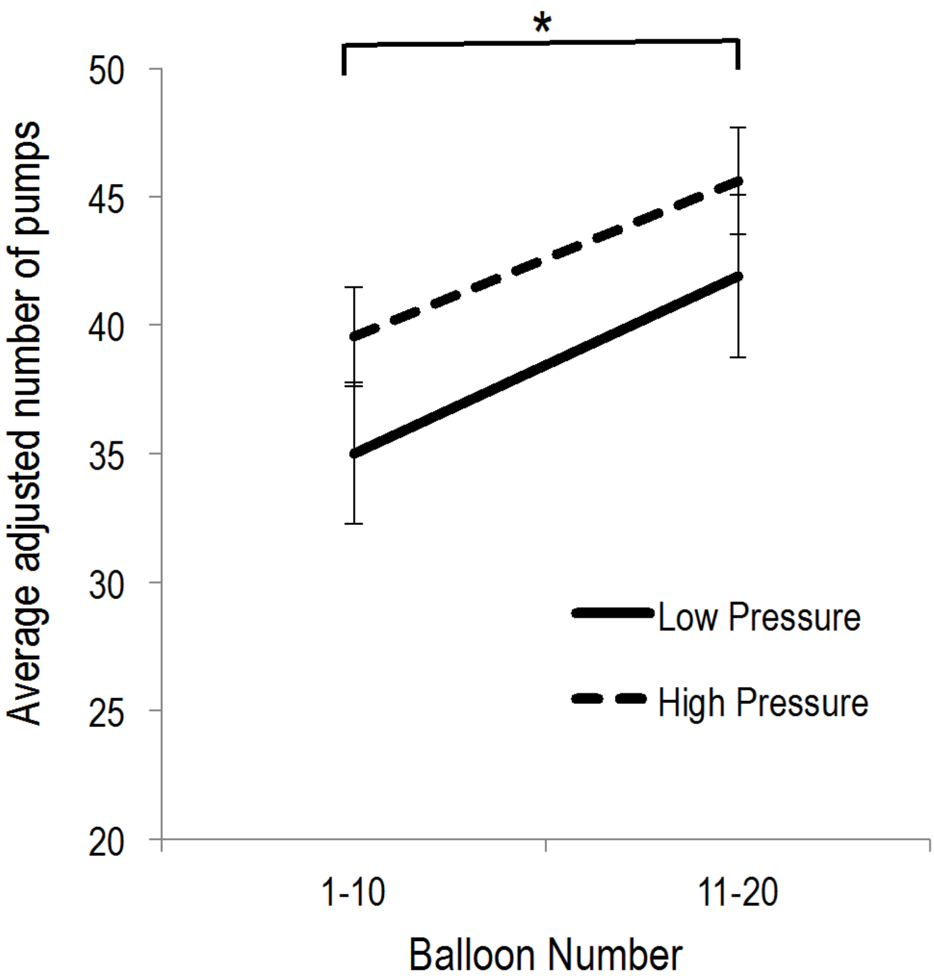


Figure 6.3: BART results*:* In elite athletes there was no significant effect of physical pressure on the mean adjusted number of pumps, a measure of risk taking under uncertainty. There was a significant effect of balloon number, with the mean adjusted number of pumps was higher for the last half of the task. * denotes statistical significance at $p<0.05$. Error bars represent SEM.

6.4.2. Effect of Physical Pressure on the CGT

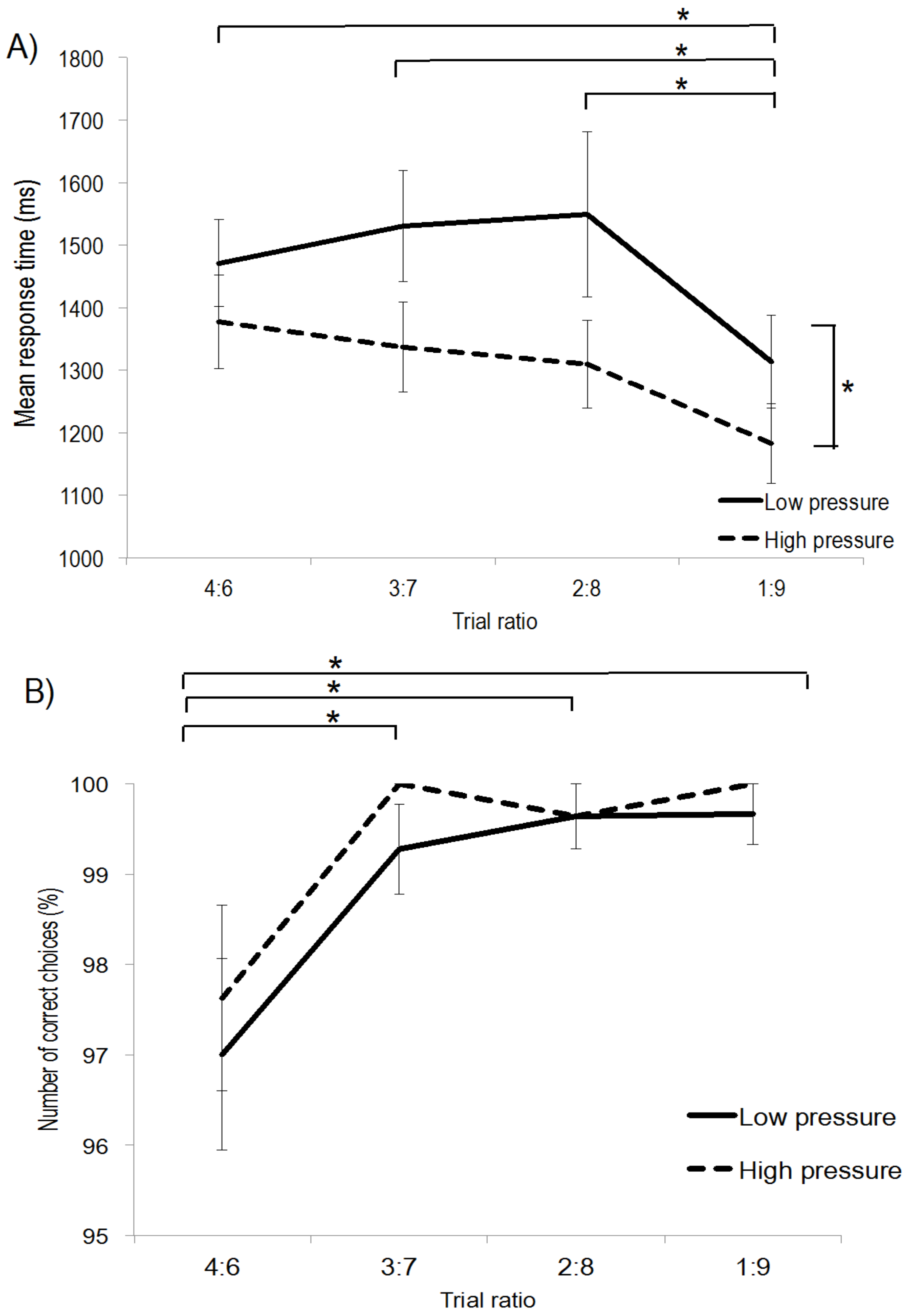
Response Times: Having examined the influence of physical exhaustion on the BART, the following analysis examines the CGT and in this case, a number of different performance measures were examined. First, a repeated measures ANOVA was performed on the response times (duration between trial onset and participants response) (**Figure 6.4**a) revealed a significant effect of physical pressure ($F_{(1,22)}$=5.63, p<0.05), with the mean deliberation time being less under conditions of high physical pressure (Mean: low pressure= 1470.71 ms; high pressure= 1377.45 ms). In addition, we found a significant effect of trial ratio ($F_{(2.12,46.70)}$=8.66, p<0.01). Pairwise comparisons revealed that the response time to trials with 1:9 ratios were significantly quicker than those with 4:6 (p<0.01), 3:7 (p<0.01) and 2:8 ratios (p<0.01). There was no significant interaction of trial ratio and physical pressure ($F_{(1.91,42.02)}$=1.34, p=0.27). This indicates that elite athletes tend to respond faster under physical pressure, and when the trial odds ratios were higher.

Error rates: A repeated measures ANOVA was performed on the error rates (% number of trials in which the participant chose the most likely box colour) (**Figure 6.4**b), this revealed, a non significant effect of physical pressure ($F_{(1,22)}$=0.95, p=0.34) and a significant effect of trial ratio ($F_{(1.30,28.53)}$=8.56, p<0.01). There was a no significant interaction of ratio and stress ($F_{(1.54,33.80)}$=0.18, p=0.77). Pairwise comparisons revealed that participants made more errors on trials with 4:6 ratios compared to those with 3:7 (p<0.05), 2:87 (p<0.05), and 1:9 ratios (p<0.05). Elite athletes were less accurate, and opted for the most likely box colour on fewer occasions, when the odds ratios were lower.

Number of points gambled: A mixed ANOVA on the mean percentage points gambled was analysed as the main measure of risk-taking (**Figure 6.4**c). This revealed an effect of physical pressure ($F_{(1,21)}$=9.08, p<0.01), as well as an effect of point presentation (ascending or descending $F_{(1,21)}$= 8.98 p<0.01), but no effect of gender ($F_{(1,21)}$=0.89, p=0.36). In addition, there was a significant interaction between physical pressure and point presentation ($F_{(1,21)}$=9.45, p<0.01), but neither between physical pressure and gender ($F_{(1,21)}$=0.15, p=0.70), nor between gender and points presentation ($F_{(1,21)}$= 4.02, p=0.53). The three-way interaction between pressure, points presentation and gender was also non significant ($F_{(1,21)}$=0.03, p=0.87). Post hoc t-tests revealed that for ascending trials there were a significantly higher number of points gambled under conditions of high physical pressure compared to low physical pressure ($t_{(22)}$=-3.69, p<0.01; Mean: low pressure: 57.13%; high pressure: 65.86%). On descending trials there were no significant differences in the number of points gambled under conditions of high and low physical pressure ($t_{(22)}$=-0.43, p=0.67; Mean: low pressure: 70.62%; high pressure: 71.32%). Hence, athletes made significantly higher bets on ascending trials under physical pressure, indicating a significant increase in risk-taking under physical pressure. On ascending trials the participant has to wait patiently for the number of points to increase, therefore this increase in risk-taking is unlikely to be due to increased motor impulsivity. Male and female elite athletes did not differ in terms of the effect that physical pressure has on the number of points bet on the CGT.

Risk Adjustment

A paired t-test revealed there were no significant differences in the measure of risk adjustment between conditions of low and high physical pressure ($t_{(22)}$=1.18, p=0.25) (**Figure 6.4**d), therefore the tendency for elite athletes to modify the amount bet according to the different reward and loss contingencies were not influenced by conditions of high physical pressure.


A)
Mean response time (ms)
1800
1700
1600
1500
1400
1300
1200
1100
1000
4:6
3:7
2:8
1:9
Trial ratio
Low pressure
High pressure
*
*
*
*
B)
Number of correct choices (%)
100
99
98
97
96
95
4:6
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1:9
Trial ratio
Low pressure
High pressure
*
*
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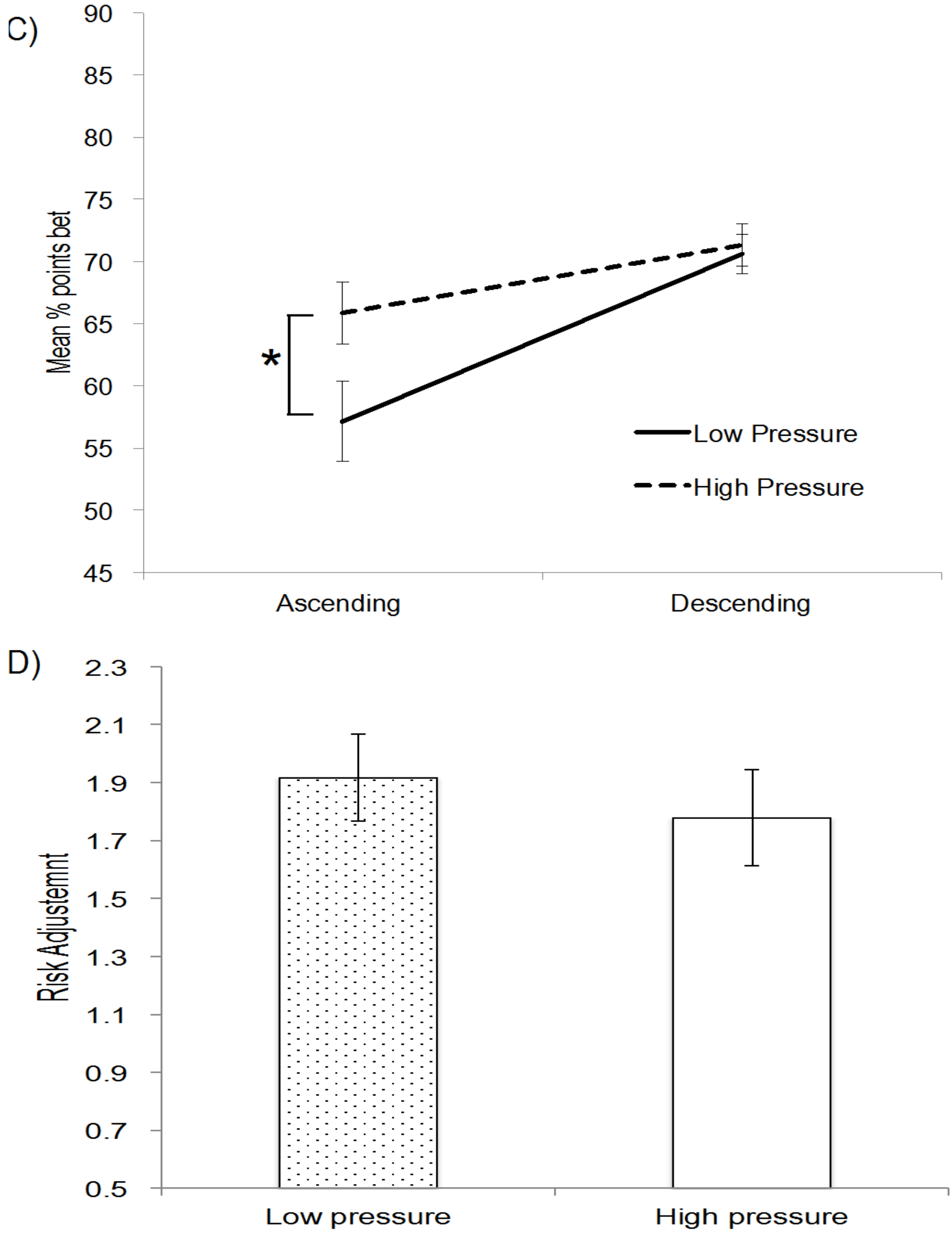


Figure 6.4: CGT results: A) The elite athletes showed significantly faster response times under physical pressure. **B)** Elite athletes were less accurate on trials with odds ratios 4:6 compared to 3:7, 2:8 and 1:9**.: C)** Physical pressure increased the amount of points gambled on ascending trials, indicating increased risk taking which is unlikely to be a result of increased impulsivity. **D)** Risk adjustment, was unaffected by. physical pressure. *denotes statistical significance at p<0.05. Error bars represent SEM.

6.4.3. Effect of Physical Pressure on the Stroop Task

There were significant differences in the reaction times to identify the colour of control trials under conditions of low and high physical pressure ($t_{(21)}$=5.85, p<0.01) (**Figure 6.5**). The elite athletes performed significantly faster under conditions of physical pressure (Mean: high physical pressure: 696.88 ms; low physical pressure: 883.62 ms). There was no significant difference in the Stroop interference effect under conditions of low and high performance pressure ($t_{(21)}$=2.01, p=0.06). Therefore increased pressure did not influence the additional time taken to identify incongruent trials in comparison to congruent trials in elite athletes. The Stroop task was performed with a high degree of accuracy both under conditions of high (97.17% accuracy) and low physical pressure (97.03% accuracy).

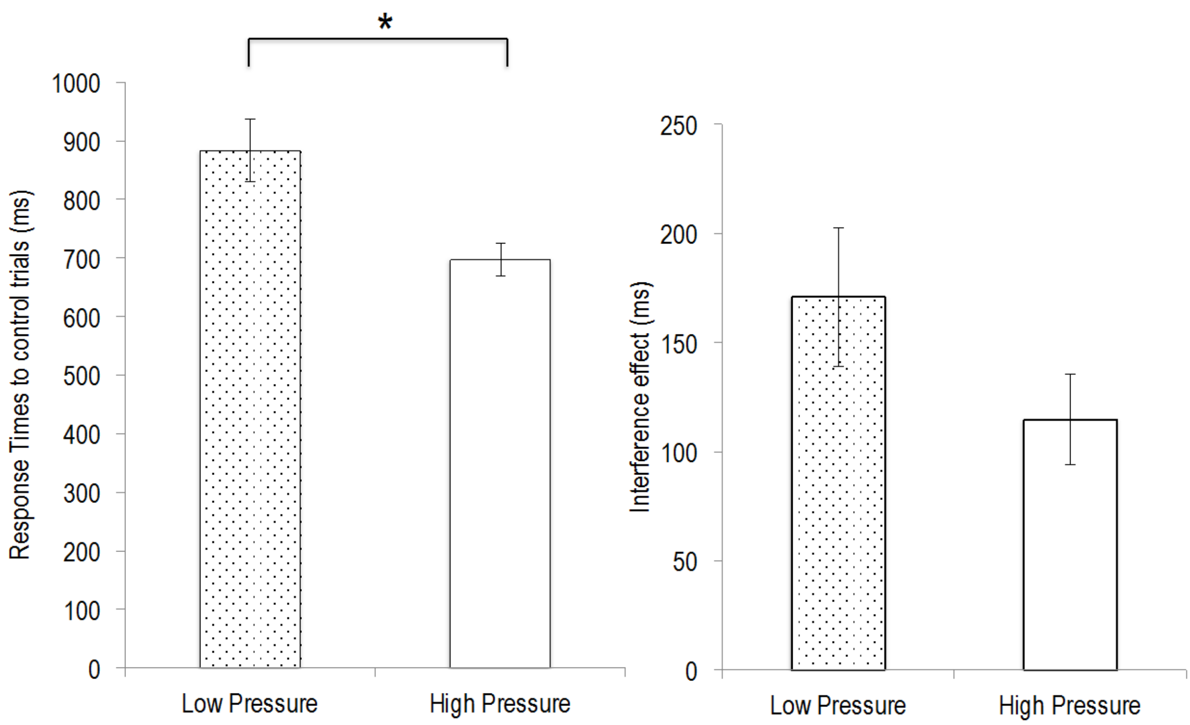


Figure 6.5: Stroop task results: The elite athletes were significantly faster responding to control trials under physical performance pressure. There were no significant differences under conditions of low and high pressure in the Stroop interference effect, i.e. the additional time taken to respond to incongruent trials compared to congruent trials. * denotes statistical significance at p<0.05. Error bars represent SEM.

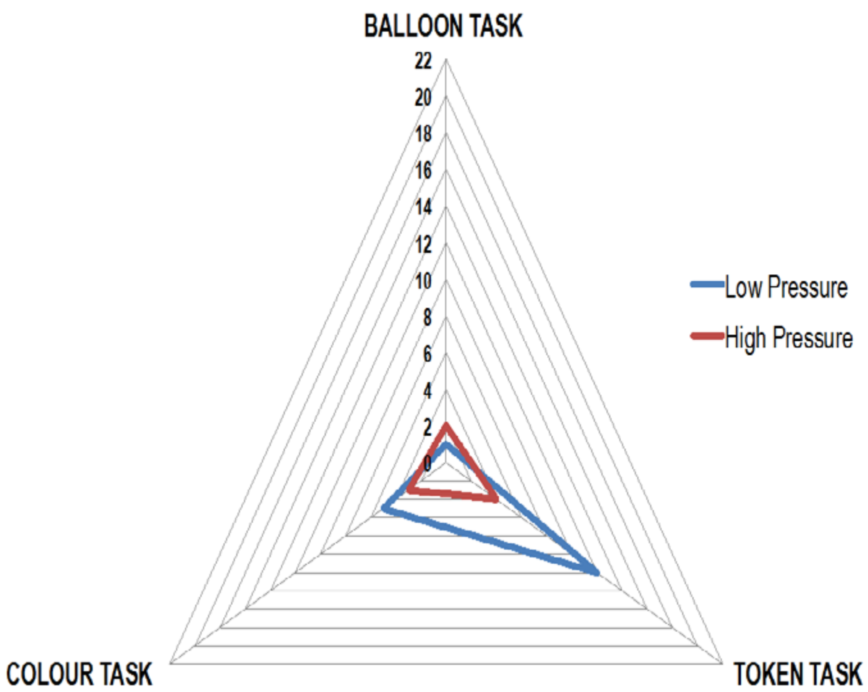
6.4.4. Correlations of Performance Under Pressure Across Tasks

To determine whether changes under pressure on key indicators of performance were consistent across the three decision-making tasks, correlation analyses were performed. However, no significant correlations between the degree of change under pressure on performance of the BART and the CGT ($r_{(22)}$=-0.12, p=0.59), BART and Stroop task ($r_{(22)}$= -0.11 p=0.63), or CGT and Stroop task ($r_{(22)}$= -0.06 p=0.80) were found. Therefore, individual participants' responses to pressure were not consistent across key indices of decision-making over the three tasks. This highlights the importance of individualize profiling of results especially in a setting where the performance of individual athletes is most important (see **Figure 6.6**) shows example results of two athletes and example feedback. It is evident that within this group there are individuals who showed very different patterns of responses to physical pressure. For example, Athlete 1 ranked highly within the cohort on the BART and Stroop and made small improvements in their rankings under pressure. The athlete also improved their rank under pressure, from 12th to 4th place, on the CGT. Athlete example 2, however, showed a much more variable response to physical pressure, on the BART task they decreased their ranking under pressure from 6th to 14th place, on the Stroop task they improved their ranking 16th to 7th ,while their ranking on the CGT remained stable.

6.4.5. Representativeness of Group Data

In order to explore the degree to which group data applies to individual athletes, an additional analysis was undertaken whereby the number of athletes who showed an average response (defined as falling within 0.5 SD above and below the mean) to pressure across the three tasks was assessed. In line with previous work (Daniel, 1952; Rose, 2016), this categorization of an 'average' responder meant that at least the middle 35% of the group were categorized as falling within the 'average' on each variable. The results of this analysis revealed that there was not one participant who showed mean responses to pressure across all three indices of decision-making which included the average adjusted number of pumps on the BART, the reaction time to control trials on the Stroop task and the risk adjustment score on the CGT. As the group average scores were not representative of the behaviour of a single individual athlete across the three measures, this highlights the importance of feeding back individual results in an to elite setting where providing insight at an individual level is paramount.

Example athlete 1:



Example athlete 2:

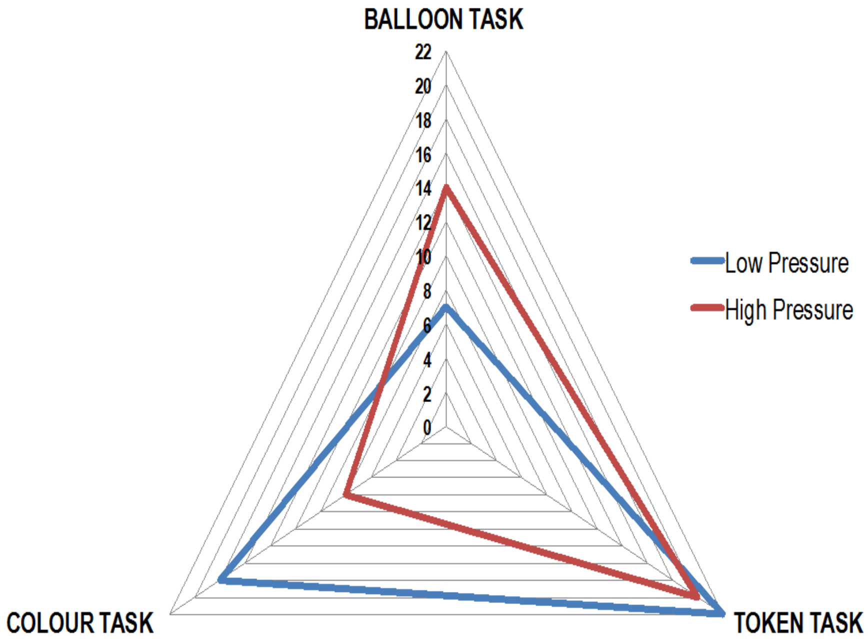


Figure 6.6: Example of individual athlete feedback; Radar graph showing performance ranking within the squad on each task for an individual athlete. (1= top performer 22= bottom performer).

6.5. Discussion

The aim of the current study was to further our understanding about decision-making in elite sport, by investigating the influence of physical pressure on decision-making in a sample of world-class elite athletes. The primary objective is to provide insights that has real-world application in the elite sport setting. The results revealed that under increased physical pressure, elite athletes showed faster response times. They also displayed an increase in risk-taking for decisions where probability outcomes were explicit, while there were no significant differences in risk-taking when probability outcomes were unknown.

In particular, reaction times were significantly faster following physical pressure on the Stroop and CGT. This observation coincides with the findings of a recent systematic review outlining the cognitive effects of physical exertion in athletes (Schapschröer et al., 2016). Overall, athletes at an expert level were reported to show an increased facilitation in response time measures on perceptual-cognitive tasks under conditions of moderate and intense physical activity, in comparison to novices (Schapschröer et al., 2016). In this work expert athletes were broadly defined as those competing at a national level. One study included in the review similarly assessed the influence of physical exertion (up to 80% maximal exertion) on an elite sample (although of a younger age of 18 years old), revealed faster choice reaction times (Mouelhi et al., 2006). Here it was proposed that the reaction time facilitation may be due to increases in exercise-induced arousal (Cooper et al., 1973). Schapschröer et al., (2016) highlights that sporting expertise is a significant factor in how one responds to physical performance pressure and the current study suggests that this may extend to those competing at the highest elite standard. Although this conclusion is made in light of possible learning effects due to the experimental design in the current study.

The decision-making of elite athletes showed an increase in risk taking under physical pressure in response to decisions where the reward and loss outcomes were explicit. In particular, there was a significant increase in the amount bet on the CGT under physical pressure on trials with ascending presentation of points.

This indicates that the increased propensity for risk was unlikely to be due to increased motor impulsivity as elite athletes were able to wait longer durations for the bet to increase. In line with this risk adjustment did not change under conditions of increased physical pressure. Thus despite an increase in risk-taking elite athletes retained the ability to bet appropriately according to outcome probabilities, and therefore use information relating to the decision scenario under physical pressure. For decisions made under uncertainty there was no significant effect of physical pressure on risk-taking.

Together these findings partially support work that have shown risky decision-making to be modulated under conditions of elevated stress as previous literature has shown this to effect both decision-making under uncertainty (and risk (Lighthall et al., 2009; Preston, Buchanan, Stansfield, & Bechara, 2007; van den Bos, Harteveld, & Stoop, 2009). Study which examined the effect of physical exertion revealed that in non-elite athletes showed increased risk taking on the BART in males (Black et al., 2013; Pighin et al., 2015) but decreased risk taking on the BART in females (Pighin et al., 2015). In the current study there were no effects of gender on measures of risk taking under pressure on either the BART or the CGT.   In the case of elevated risk taking on the CGT, this was found to be similar for males and females, with the shift to more cautious responding under stress in females not evident in this sample of elite female athletes. Again, these discrepancies may allude to further differences between non-elite and elite athletes in terms of decision-making under pressure.

On the one hand, the finding that elite athletes take more risks when the contingencies were known, but not unknown, could reflect differences in expertise in the two types of decision-making. Decision-making under uncertainty scenarios are much more prevalent in everyday life, and the dynamic sporting environments is no exception (Schonberg, Fox, & Poldrack, 2011). As such, elite athletes are likely to have more experience in the specific coupling of decision-making under uncertainty and acute physical pressure which may account for the robustness in performance seen in the current study. An alternate explanation for the increase in risk taking specifically in situations where outcomes are explicit is one of calculable risk taking. Under pressure the elite athletes may be more willing to take risks, but only when they can deduce favourable chances of that risk paying off. This is in line with increased risk taking on ascending trials, and a resilient ability of risk adjustment, under physical pressure. Indeed a similar approach to risk-taking has been noted in previous research in females, notably that risk taking is prevalent but only when there is the estimation that risk taking will result in a win (Fox & Lawless 2004).

Together the findings highlight two important points. Firstly, that physical exhaustion has an influence on the performance of elite athletes and therefore it is important to consider the context when studying the decision-making of athletes. While on the whole elite performers decision-making was resilient to the effects of pressure, there was a speeding of reaction times and a increased propensity towards risk on decision-making under risk tasks. Secondly, that previous work in this decision-making and sport may not extend to elite athletes or those with a high level of expertise in operating under conditions of high pressure. For example, the results of the current study support the observation that quicker reaction times were observed in elite athletes under intense physical exertion, yet this was not the case in studies undertaken in healthy volunteers (Schapschröer et al., 2016). Previous work in non-elite athletes have also shown an effect of gender on risk taking under physical pressure (Pighin et al., 2015), whereas we found no differences in performance between males and females. While direct comparisons are difficult due to divergent methodologies, together these findings raise concerns over the application of decision-making research undertaken in non-elite athletes or healthy controls to elite athletes.

As this work was undertaken outside of a laboratory context in a specialized sample group it has high ecological validity. However, with this there was less control over the experiment and a number of compromises were made in terms of scientific rigor. One limitation is that the order of low and high physical pressure conditions were not counterbalanced. This meant that all elite athletes performed the tasks under conditions of low physical pressure first, followed by the tasks under condition of increased physical pressure. When performing tasks under physical pressure, participants were also undertaking the tasks for the second time, and thus the changes observed may reflect learning effects. Due to the time constraints of working with an elite population it was not possible to design the experiment with separate testing sessions. In order to reduce possible learning effects in this study, attempts were made to choose appropriate tasks. For example, the BART has been shown to have high test-retest reliability, with small increases in risk taking (2 average adjusted number of pumps) when repeated testing occurred within a single day (White, Lejuez, & de Wit, 2008). Moreover the CGT was designed to assess decision-making in the absence of other learning processes, with trials reported to be relatively independent of one another (Rogers et al., 1999).

A second issue is that completion of maximal effort during the physical exhaustion protocol was inferred via self-report and from observation of the athlete. One could argue that the lack of an objective measure of physical exertion was a limitation and would have been useful in determining that self-report was accurate. In this case it was deemed reasonable to allow the elite athletes to exert themselves to the level they felt reflected the guidelines of maximal exertion. A key goal of the current work was to provide insights that would transfer to training and performance, and therefore keeping formalization of the testing procedure to a minimum was important. In particular, elite athletes exert themselves to their own recommendation because of their own investments and motivation and this is what we aimed to replicate in the current study. It should be noted that this population is extremely driven and competitive in comparison to the usual cohort of volunteers in psychology experiments.

A further interesting result of the current study is that the degree to which participants changed under pressure did not correlate across key indicators of decision-making over the three tasks. This indicates that the effects of physical pressure is not uniform across indices of decision-making in individuals, for example an athlete who improved on one task under pressure did not necessary show similar improvements under pressure on a different task. This highlights that responses to physical stress are specific to the type of decision-making, and also specific to the individual. This finding emphasizes a key issue when examining how one assesses and applies psychological data in an elite sporting environment- the central aim of this work, relating to the application of results based on group averages in a setting where understanding the behaviour of the individual athlete is most important.

While statistical approaches based on group means used in this chapter are prevalent in almost all of psychology, and informative regarding the average response of a group of individuals, they may not be informative regarding any one individual (Rose, 2016). Rose (2016) outlines the ‘fallacy of the average individual’. Gilbert (1945) studied 4063 pilots across 10 dimensions of size in order to design the optimal cockpit, and reported that within this sample no one individual was average on all 10 dimensions (average defined as scores which fell within the middle 30% of the range of values) and only 3.5% of the sample showed average characteristics on 3 dimensions of size. Thus, if a cockpit were designed to fit the average individual, it would be a poor fit for any individual pilot. This has special relevance to elite sports psychology where understanding the behavior of the individual athlete is paramount. Indeed in the current study, there was no one athlete that presented a mean response to pressure across all three indices of decision-making. It was important to measure different types of decision-making to get a more complete picture of decision-making. This indicates that applying the results of this study based on group average to the individual one would be incorrect in the majority of cases.

Additionally applying statistical approaches based on averages disguises the unique profile of strength and weaknesses of an individual (Rose, 2016). In the case of the elite athlete, it may be that this individuality provides them with their competitive edge. Along these lines, in the current work feedback sessions were undertaken, whereby data relating to individual performance, as well as group averages were provided for context (see figure 5.8). Thus the usefulness of this profiling was in the insight it gave to the athletes and coaches, regarding the unique strengths and specific domains of improvements of the individual athlete.

The sports professionals used this knowledge to inform training interventions and tactical discussions.

Furthermore, in order to facilitate insight into decision-making in elite sporting professionals a requirement of this work was to increase understanding of key psychological principles and examine how to apply these in a sporting context. In retrospect this was addressed by the current work in a number of ways. Firstly, undertaking the experiment itself provided the athlete with first hand experience of standardized measures of psychological concepts and an opportunity to reflect on their subjective experience of how their abilities to perform were modified by physical pressure.

In order for these psychological concepts to have meaning in a sporting context, in debriefing discussions with athletes and coaches, examples of these types of decision-making within sport were developed. In order to communicate the concepts to an audience with no prior psychological knowledge real world analogies were used. For decisions which required fast reactive responses, such as responding to control trials on the Stroop task, this was described as 'gun slinging', with reference to a shooting match. Decision-making under risk on the CGT was described as 'poker playing' to represent a scenario when one takes risks in the context of having information available to them. Decision-making under uncertainty on the BART was described as playing 'chicken', with reference to a well-known game devised to test the nerve of each contender wherein two people drive straight towards each other, and the first car to swerve is named the chicken. This taxonomy was key in facilitating understanding that decision-making isn't a singular concept and of the different types of decision-making scenario. Moreover the terms provided an easy and accessible shared language for the athlete to use to reflect on their own decision-making, as well as discussing the decision-making with other athletes, coaches and other sport professionals.

6.6. Conclusion

The findings of the current study show that the decision-making of elite athletes were influenced by physical exhaustion. In particular under increased physical pressure elite athletes showed faster response times, increased risk taking for decisions where probability outcomes were explicit, but no significant change in risk-taking when probability outcomes were unknown. These responses were different to those reported in the literature in non-elite athletes and healthy controls. However, direct comparisons are difficult due to methodological differences. In addition, individual changes in performance under pressure did not correlate across tasks, highlighting that response to physical pressure across tasks were specific to the individual athlete. This finding emphasizes the limitation of statistical approaches based on group means, a key issue when examining how one applies psychological data in elite sport psychology. Indeed there was no one athlete who showed an 'average' response to pressure across the three tasks. In order to aid insight and understanding of decision-making in the elite sporting environment, the feedback of individual results was useful to provide insight into the unique strengths and weakness's of the individual athlete. The use of engaging athletes and coaches in psychological testing in order to increase insight into psychological concepts is highlighted, as well as the development of a common language to communicate key concepts. In the following chapter a similar protocol is used to assess the decision-making with semi-elite athletes.

7. Decision-making Under Physical Pressure in Semi-elite Athletes

7.1. Abstract

Background: Having investigated the influence of acute physical exhaustion on decision-making in world-class elite athletes, here a similar method is applied to semi-elite athletes. These semi-elite athletes were enrolled on a Team GB talent development program and were undergoing training for possible Olympic competition in four to eight years. They differ from elite athletes examined previously according to expertise and age. While considered elite (Swann, Moran & Piggott, 2015), the semi-elite athletes had approximately eight-years less sporting experience and were yet to obtain frequent sustained success on the international stage. Additionally, the average age of the semi-elite sample is 20 years; thus, they are still undergoing the behavioural, cognitive and neuronal changes that occur as one transitions from late adolescence to young adulthood (Blakemore & Robbins, 2012). Previous work has used broad definitions of elite status in sport, from Olympic competition to inclusion on university varsity teams; as such, it has overlooked different categories within the spectrum of elite athletes (Swann et al., 2015). Therefore, it is important to consider semi-elite athletes as a discrete point on the developmental trajectory of elite sporting expertise.

Objective: This work aims to investigate the influence of physical pressure on key indicators of decision-making in semi-elite athletes. It forms part of a wider project examining decision-making across different stages of the developmental trajectory in elite sport. In doing so, it aims to further examine how to apply and develop psychological insights useful to an elite sporting environment.

Method: 32 semi-elite athletes (Swann et al 2015) (18 males; mean age = 20 years) enrolled on a national Team-GB training program, aiming for Olympic competition in four to eight years, participated in the study. In accordance with chapter 6, performance across three categories of decision-making was assessed under conditions of low- and high-physical pressure. Decision-making under risk was measured with performance of the CGT (Rogers et al., 1999),

decision-making under uncertainty with BART (Lejuez et al., 2002) and fast reactive responses and inhibition via the SSRT (Logan, 1994). Physical exhaustion was induced via intervals of maximal exertion exercise on a watt bike.

Results: Under pressure, semi-elite athletes showed increased risk taking for both decisions where probability outcomes were explicit (on the CGT) and those where probability outcomes were unknown (on the BART). Despite making quicker decisions under pressure - with fewer errors - on the CGT, semi-elite athletes showed a reduced ability to optimally adjust betting behaviour according to reward and loss contingencies. Fast reactive responses to perceptual stimuli and response inhibition did not change as a result of physical pressure. Individual responses to pressure showed a negative correlation in that a decrease in reaction times on the SSRT under pressure were associated with an increase in risk taking on the BART. When assessing the applicability of results based on group averages to individual athletes, 17% of the sample showed an ‘average’ response (within 1 SD of the mean) to pressure across all three decision-making tasks.

Conclusion: Indicators of decision-making in a sample of semi-elite athletes are influenced by physical pressure, with a shift towards increased indiscriminate risk taking. The influence that physical pressure has on decision-making was different to that observed in world-class elite athletes; this highlights the importance of distinguishing between athletes at the elite level (Swamm et al., 2015). The application of this work to a novel sub-group of elite athletes are discussed.

7.2. Introduction

Having noted decision-making and performance under pressure as crucial factors to sporting success (Bar-Eli, Plessner & Raab, 2011; Jordet & Hartman, 2008; Kaya, 2014; Wells & Skowronski, 2012), this chapter forms part of a wider project examining these abilities across different developmental stages of elite sporting expertise. Using a similar protocol to that employed in chapter 6, the influence of physical pressure on decision-making is examined in a sample of semi-elite athletes. The semi-elite athletes were enrolled on a Team GB talent development program, training for competition at an Olympic level in four to eight years. While these athletes make a living from sport and compete internationally, several hallmarks of an elite status (Swann et al., 2015), they are yet to reach the highest levels of performance in their given sport. Thus, it is important to consider them as a separate class of athlete to provide a more nuanced view of expertise at the elite level. Importantly, they differ from the world-class elite athletes studied previously according to two key factors: experience and age.

When it comes to the development of expertise, there is the widespread acceptance that it takes 10 years - or 10,000 hours - of accumulated, deliberate practice to reach expert status within a given field (Ericsson, Krampe & Tesch-Römer, 1993). On average, semi-elite athletes have approximately 12 years of sporting expertise and are considered within the top 50 national players. In comparison to the elite athletes in chapter 5, they have, on average, eight-years less sporting experience; a difference that is likely to impact decision-making competencies and responses to performance pressure. Unsurprisingly, previous work has shown that decision-making competencies within sport develop with expertise (Abernethy, Baker & Côté, 2005). Moreover, a recent review revealed that sporting expertise modified responses to physical pressure. In particular, following intense physical exercise, athletes with a higher level of expertise showed faster responding on simple choice reaction time tasks, when compared to novices (Schapschröer, Lemez, Baker & Schorer, 2016).

Almost all research examining decision-making and expertise has explored the differences between elite and non-elite athletes, rather than examining the spectrum of elite athletes. Indeed, sports psychology has been criticized for its considerably broad definition of ‘elite athlete status’, ranging from Olympic champions to those included in a regional or university sports team (Swann et al., 2014). This led Swann et al. (2014) to propose a categorization system to distinguish the spectrum of expertise at an elite sporting level. The semi-elite athletes included in this sample would fall into the *semi-elite* and *competitive-elite* expertise categories, as outlined by Swann et al. (2014), due to their inclusion of talent development programs, competitive success at a national level and infrequent success at international competition. The elite-athletes included in chapter 6 would fall into their *successful-elite* or *world-class elite* expertise category, due to their frequent appearance and sustained success in globally recognized competition.

In addition, the semi-elite athletes are distinct in terms of age. They are in their late adolescence and early 20s (mean age = 20), in contrast to the elite athletes who were in their late 20s (mean age = 28); this is relevant as the semi-elite athletes are undergoing cognitive changes and brain developments characteristic of adolescence, a process that does not cease until the mid-20s (Arain et al., 2013). Many of these developments relate to decision-making (for a review, see Blakemore & Robbins, 2012). In terms of behaviour, this period is characterized by a tendency to engage in increased risk-taking in relation to adults (Defoe, Dubas & Figner, 2015), likely to arise from a heighted responsiveness to incentives and increased influence of socioemotional factors (Blakemore & Robbins, 2012; Chein, Albert, O’Brien, Uckert & Steinberg, 2011). In terms of anatomical brain development, regions that show late structural maturity include the DLPFC; an area involved with impulse control and weighing up the consequences of decision-making (Giedd, 2004).

Additionally, development of the corpus callosum and association tracts, including the inferior and superior longitudinal and fronto-occipital fasciculi, occurs during the 20s (Lebel & Beaulieu, 2011; Pujol, Vendrell & Junqué, 1993), changing thought to support complex cognitive processing (Blakemore & Robbins, 2012). Structural and functional brain differences between early to late adulthood have also been observed. For example, Veroude, Jolles, Croiset and Krabbendam (2013) revealed that young adults (23-25) and adolescents (18-19) engage different brain regions when performing cognitive tasks. When undertaking the Stroop task, the young adults showed stronger activation in the DLPFC, left inferior frontal, left middle temporal gyrus and middle cingulate, when compared to those in the adolescence group. Although such functional changes are yet to be fully deciphered, differences in the neural underpinnings of cognitive control are notable. These ongoing developmental changes reiterate the importance of considering semi-elite athletes as a discrete stage of elite sporting expertise.

In light of the findings from the previous chapter, and work that has highlighted the importance of considering the high pressured context in which decisions in sport occur (Hepler, 2015; Kinrade, Jackson & Ashford, 2015; Pighin, Savadori & Bonini, 2015; Smith et al., 2016), the aim of the current study was to examine this topic in semi-elite athletes. The semi-elite athletes will perform tasks assessing decision-making under conditions of low and high physical performance pressure. Decision-making under risk will be assessed via performance of the CGT (Rogers et al., 1999) and decision-making under uncertainty via the BART (Lejuez et al., 2003), as well as fast reactive responses and inhibition via the SSRT (Logan, 1994). Performance pressure was induced by physical exhaustion protocols consisting of intervals of maximal exertion exercise on a watt bike.

This studies methodology will allow a greater insight into decision-making under pressure in semi-elite athletes, which may prove useful in understanding the developmental trajectory of expertise in elite sport. In line with the previous chapter, an additional aim of this work is to examine how to apply and develop psychological insights useful to an elite sporting environment.

7.3. Methods

7.3.1. Participants

The sample consisted of 31 semi-elite athletes (16 males), aged between 18 and 27 (mean age = 20 years). All athletes were part of a Team GB national centralized program, focused on training for Olympic competition in four to eight years; i.e. not the next Olympic games but the one after that (in this case Tokyo 2020). They all fell within the 'semi-elite' and 'competitive-elite' expertise categories defined by Swann et al (2015). They are considered as a top-50 national performer in their given sport, but yet to gain international success at international competition. Moreover, they are enrolled and paid to be part of a training development scheme. All athletes included in the sample were from the same sport. The approximate age of entry for this sport is eight years and, thus, these semi-elite athletes had been training for approximately twelve years. All semi-elite athletes were able bodied with normal or corrected-to-normal eyesight.

Recruitment, ethical consent and debriefing procedures were in line with those used in the previous chapter. Recruitment and testing occurred during a seven-day residential training camp, with the assistance of the Team GB Sports psychologist and coaches. The squad were initially informed of the aims and procedures of the study via a group presentation, then a testing session was scheduled with athletes wishing to participate. While participants did not receive financial reimbursement for their participation, a cash prize was awarded to the top three performers on the BART. Upon completion, a detailed debriefing session was undertaken in conjunction with Team GB coaches and a sport psychologist. The study and consent procedures were approved by the UCL ethics board, in compliance with the principles of the Declaration of Helsinki.

7.3.2. Experimental Protocol

The protocol in this study was like that outlined in chapter 6. A within-subject design was used, whereby the decision-making of semi-elite athletes was assessed under conditions of low- and high-physical pressure (**Figure 7.1**). Testing was undertaken within a single session at a Team GB training facility. Performance on three decision-making tasks was examined via a laptop computer; these included the BART (Lejuez et al., 2003), the CGT (Rogers et al., 1999) and the SSRT (Logan, 1994). Initially participants received instructions and completed a short practice of each task. The semi-elite athletes then undertook these tasks at rest; i.e. in the absence of additional physical pressure. Following this, conditions of elevated physical pressure were induced via a protocol of intense physical exertion undertaken on a watt bike. Semi-elite athletes undertook two sessions of six repetitions, 30-second maximal exertion sprints, followed by 30 seconds of recovery. The CGT was performed following one of these sessions; the SSRT and BART followed the other. Taking this into account, the order in which the decision-making tasks were undertaken was counterbalanced across participants. After completion, the semi-elite athletes were debriefed in a feedback session where the results of the study were discussed and applied to the sporting context. Athletes were also provided with a profile of their own performance.

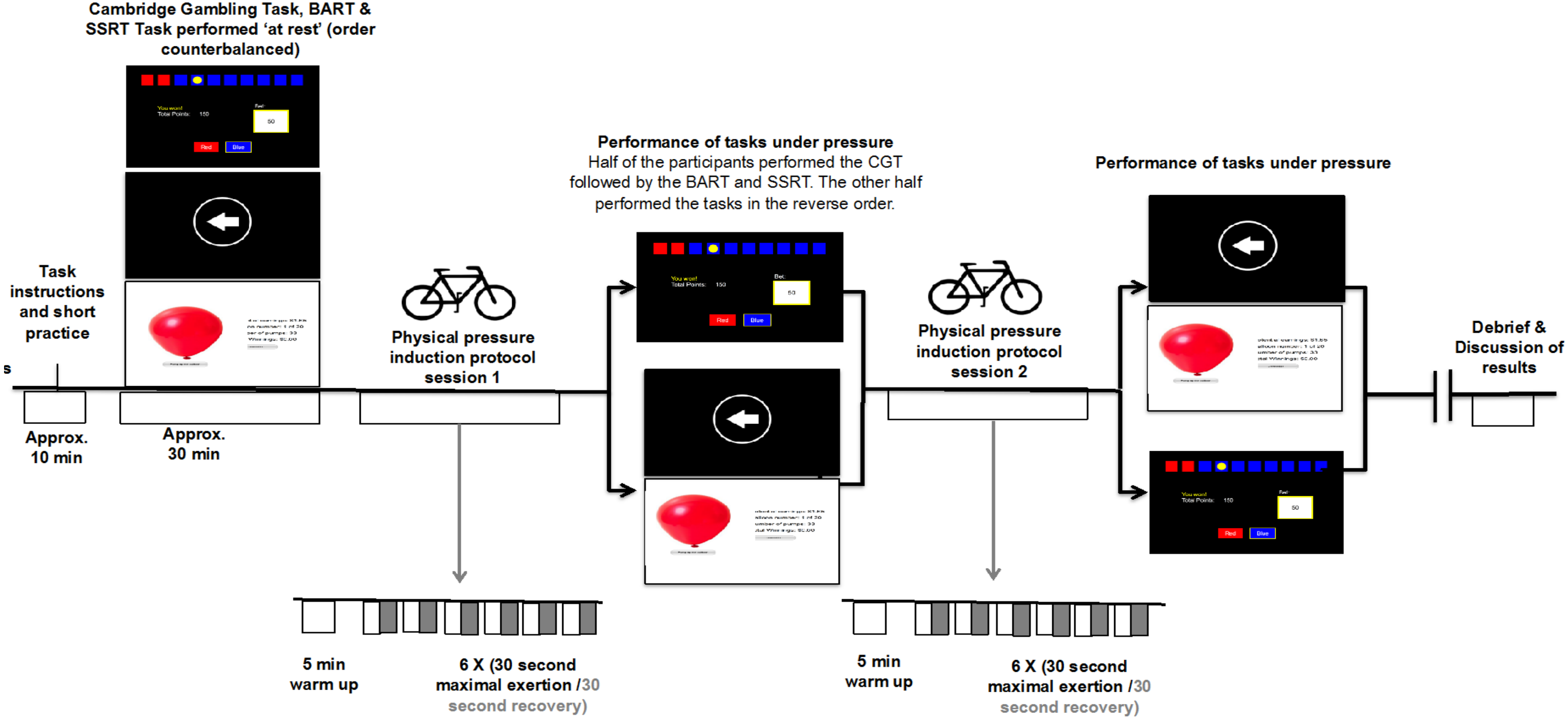


Figure 7.1: The experimental protocol. Upon enrolment, participants undertook a short practice, followed by a performance of the BART, the SSRT and CGT under conditions of low and high physical pressure. Physical pressure was induced via two sessions of six x 30-seconds maximal exertion sprints and a 30-second recovery on the ergometer. Immediately following one session, the BART and SSRT were performed and, following the other session, the CGT was performed and the order was counterbalanced across participants. Upon completion, participants were debriefed and received feedback of their individual performance; the application of this to sport was also discussed.

7.3.3. Physical Pressure Induction

A similar physical exertion protocol as described in chapter 6 was undertaken to induce conditions of elevated physical pressure, adjusted to the fitness level of the semi-elite athletes. Again, the protocol was undertaken on a watt bike. Athletes undertook two sessions of six repetitions, 30-second maximal exertion (all-out sprints), followed by 30 seconds of recovery. Maximal exertion was derived as a matter of self-report and athletes were instructed: “You are required to cycle for six sequences of 30 seconds on and 30 seconds rest. We ask that you give maximum effort for each of the 30-second periods and recover afterwards”. The athlete was instructed to decide on an appropriate resistance level that reflected the usual parameters they use in training. Verbal encouragement and a five-second countdown to each sprint was given to ensure high levels of motivation and adherence to the protocol. The aim was to induce physical exhaustion in accordance with the intermittent type of physical exertion that the athlete endures during competition. At the end of each session, participants quickly proceeded to perform the decision-making tasks. Two separate exercise sessions were undertaken to ensure that physical exhaustion was maintained across all decision-making tasks. Prior to undertaking the procedure, athletes undertook a warm up, consisting of low-resistance exercise and several maximal intensity exertion sprints to reduce risk of injury.

7.3.4. Decision-Making Tasks

Tasks were delivered via a laptop computer, with a 17-inch display screen, run using Inquisit software version 4.0.7.0 (Millisecond Software Seattle WA); used to automatically record responses for subsequent analysis. Participants made responses via the use of a mouse or button press.

7.3.4.1. BART

The BART (Lejuez et al., 2003) (see **Figure 3.2**) is a standardized measure of risk taking under uncertainty. The task requires participants to inflate a series of computerized balloons to accrue money (5p per pump). The winnings from each balloon can only be added to the total if they are ‘banked’ before the balloon bursts. Participants do not know when the balloon will burst and must decide when to transfer winnings to obtain the highest amount of money. The degree to which the balloon is inflated, in particular the average adjusted number of pumps, provides a measure of risk taking and is used for the analysis; this is the number of pumps for the balloons that did not burst, thus removing the variation that occurs because of the randomly-generated explosion point.

The full task parameters and delivery are outlined in section 3.3.4.1. As in chapter 6, participants undertook a shorten version of the task with 20 balloons. This has been used by many studies to date (e.g., Cheng & Lee, 2016; Derefinko et al., 2014; Ryan, MacKillop & Carpenter, 2013; Vaca et al., 2013) to make testing as efficient as possible in an elite sample whose availability was limited. While participants did not receive cash equating to the final sum accumulated in the safe wallet, the top three highest scorers on the task (average of low- and high-pressure performance) received a cash prize. This method of reimbursement has been used in previous studies (Fecteau et al., 2007; Sela, Kilim & Lavidor, 2012).

7.3.4.2. CGT

The CGT (Rogers et al., 1999) (see **Figure 6.2**) was used to assess decision-making under risk, where the probability of different outcomes is explicit. The task presents the participant with 10 boxes; these are coloured red or blue according to different ratios (9:1, 8:2, 7:2 and 6:4). There is a token hidden in one of these boxes and the participant must choose whether to look in the red or blue boxes to locate the token. The participant is then given the opportunity to select the amount of points they wish to gamble on their decision. The amounts that can be bet appear as a number on screen; they are a proportion of the participant's total points and are presented in either in an ascending (from 5%, 25%, 75% to 95% of total points) or descending (from 95%, 75%, 25% to 5%) sequence. The participant is required to click on the value when it represents their chosen gamble. If they are correct, the value is added to the score; if they are incorrect, the value is taken away from their score. The task is administered via standardized instructions which include a short practice of the task (outlined in

Manes et al., 2002; Rogers et al., 1999). Further details of task parameters and delivery are described in section 6.3.4.2).

Performance on the task is measured by several dependent variables which were used in the analysis of this task (further details on these measures can also be found in section 6.3.4.2). The **response time** was measured as the duration from trial presentation to when the participant identifies whether they chose to look in the blue or red box. The **error rate** is measured as the proportion of trials whereby participants choose to look in the most likely box colour. The **mean percentage points gambled** is used to represent the degree of risk taking; participants who show risky decision-making gamble a higher number of points. This is examined in the context of ascending or descending point presentations, to provide an indication of motor impulsivity. **Risk adjustment** was calculated from the amount gambled across different trial types quantifies a participant's ability to vary their risk taking in response to task contingencies. Optimal behaviour is when larger bets are made on trials where there is a higher likelihood of winning (i.e., those with the odds ratio of 9:1), in comparison to trials where the likelihood of winning is lower (i.e., those with the odds ratio of 6:4). Risk adjustment is calculated using the following equation: (*2* % bet at 9:1)+ (% bet at 8:*2) – (% bet at 7:3) – (2* *% bet at 6:4) / average % bet)* in accordance with previous work (Manes et al., 2002; Rogers et al., 1999).

7.3.4.3. SSRT Task

The SSRT task (Logan, 1994) was used to measure reaction times and response inhibition (see **Figure 7.2**). Response inhibition refers to the ability to suppress a response that is no longer required; it is an executive control process that allow behaviour to be adapted in response to a dynamic environment (Logan, 1994; Verbruggen, Logan & Stevens, 2008).

In this task, participants are instructed to respond as fast as possible to a 'go' stimuli - in this case the appearance of an arrow. Participants are required to indicate whether the arrow is pointed to the left (by pressing the D key) or to the right (by pressing the Y key). Participants are instructed to inhibit their responses (and not make a button press) if the arrow appears alongside a ‘stop’ signal - in this case a bleep noise. The stop signal (bleep) always appears after the go signal (arrow). The duration at which the bleep is presented following presentation of the arrow is called the stop signal delay (SSD).

The task adjusts the SSD in a stepwise procedure, according to performance. When a participant is unsuccessful at responding to a stop signal and fails to inhibit their response, the SSD is decreased; therefore, making it easier on the next trial. When the participant successfully responds to the stop signal trial and inhibits their button press, the SSD is increased; thus, increasing the difficulty on the next trial. The SSD is initially set to a duration of 250 ms and is increased or decreased by 50 ms each time - standard parameters for the task. This stepwise procedure allows the SSD duration at which the participant can withhold their response in half of the trials to be deduced. This is necessary to calculate the stop signal reaction time (SSRT).

The SSRT refers to the time taken to inhibit the response provoked by the ‘go’ signal. This is inferred indirectly and calculated as the average response time to ‘go’ trials minus the SSD duration for which the participants are successful at withholding the response 50% of the time. In more detail, the horse race model (Logan, 1994) states there are two independent processes initiated in this task: one that responds to the go signal and an inhibitory process that responds to the stop signal. Whichever process finishes first determines the behavioural response. When the duration of the stop signal delay is longer, the initiation of the stop process is delayed, thus it is more likely to finish after the go process and not influence behaviour. The SSD duration for which participants are successful 50% of the time allows the point at which the stop and go processes are aligned to be determined. Therefore, subtracting the SSD from the go reaction time allows the SSRT to be deduced.
A standard version of the task was administered (as laid out in Verbruggen, Logan & Stevens, 2008); this had a total number of 192 trials, of which 42 were ‘stop’ trials and 150 ‘go’ trials. These were presented in three blocks of 64 trials, each of which had 14 ‘stop’ trials and 50 ‘go’ trials. In half the trials, the arrow pointed right and in the other half the arrow pointed to the left. For each block,

the order of the trial type (stop or go) or arrow direction (left or right) were randomized. The blocks were separated by a black screen containing a summary of performance; this was presented for 10 seconds, following which the task automatically proceeded to the next trial. Moreover, the task started with a 10-trial practice to familiarize the participant. The instructions given to the participant were standardized and laid out in Verbruggen, Logan & Stevens (2008). Importantly, it was emphasized that the participant should not wait to respond to the go trials as the program adapts, nor should they worry if they are not successful as response inhibition was designed to be difficult. The two dependent variables on the task that will be used in the analysis are the reaction times to ‘go’ trials and the SSRT.

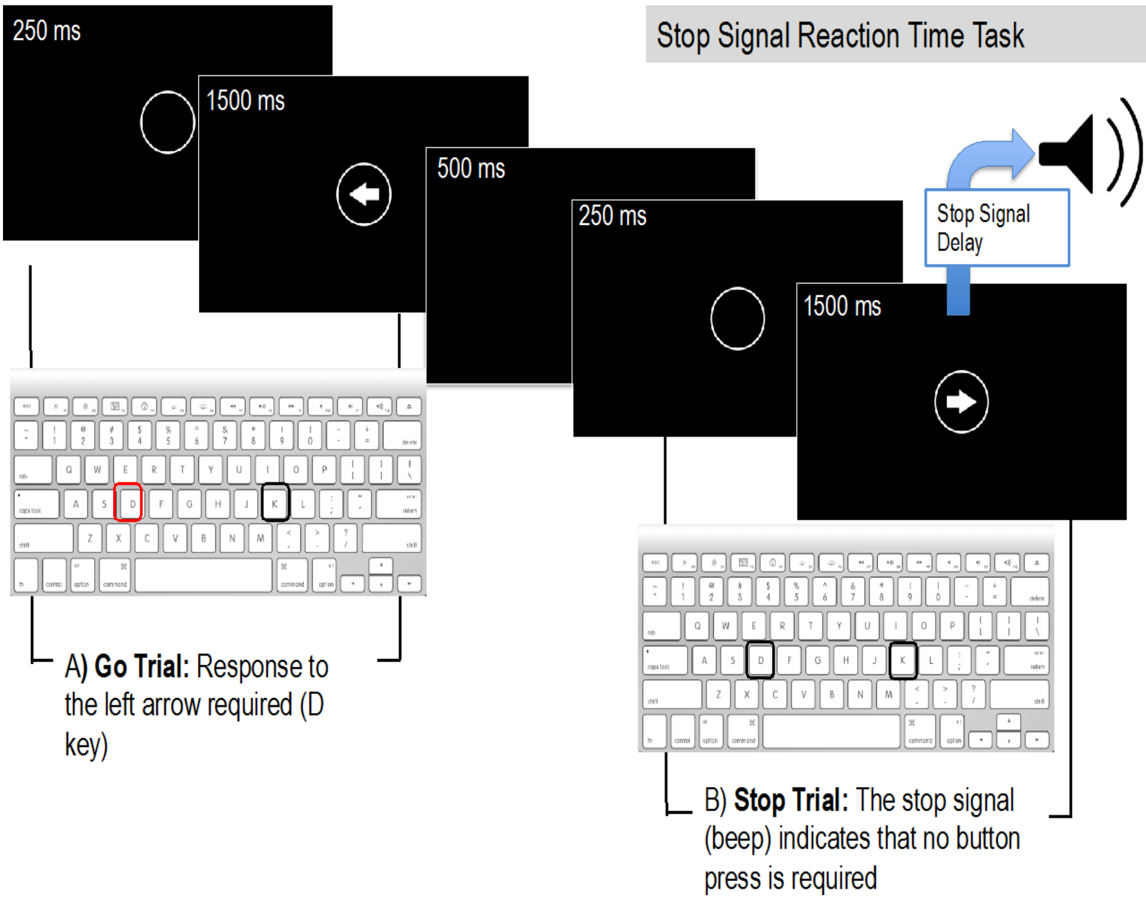


Figure 7.2: The SSRT task: **A)** On **go trials,** an outline of a circle appears on screen (for 250 ms) to alert the participant to the presentation of the arrow. The arrow appears in the circle, which points either to the left or the right. If the arrow points to the left the participant must press the D key and if it points to the right they must press the K key. Following this a blank screen is presented for 500 ms until the next trial appears**.** **B)** On **stop trials,** the presentation of the arrow is shortly followed by a beep. The beep indicates that no response to the arrow is required.

7.3.5. Data Analysis

In accordance with chapter 6, to explore whether decision-making on the three tasks is influenced by performance pressure, ANOVA or paired t-tests (two tailed) were undertaken to compare task performance under conditions of low- and high-physical pressure. Where relevant, Mauchly's test of sphericity was performed and the *Greenhouse-Geisser correction* was applied. Bonferroni correction was used to correct for multiple comparisons. For each task, the dependent variables used in this analysis are laid out below.

BART: The mean adjusted number of pumps (the average pump count for balloons that did not burst) was analysed as a measure of risk taking under uncertainty. A three-way mixed ANOVA was undertaken to compare performance of the task under conditions of low- and high-physical pressure (within-subjects factor of pressure: low pressure, high pressure) broken down by time (within-subject factor of balloon number: 1-10, 11-20). A between-subject factor of gender was included (male, female), due to previous work that has shown gender to influence risk taking under pressure.

CGT: The response times (the duration from the trial appearing on screen and the participant choosing to look in a red or blue box) and the error rates (the percentage of trials in which the participant chose the most likely box colour) were analysed using a repeated measures ANOVA. This was undertaken to compare the response times under conditions of low and high pressure (within-subjects factor of physical pressure: low pressure, high pressure) broken down by the odd ratios presented in the trial (within-subject factor of odds ratio: 1:9, 2:8, 3:7, 4:6). This part of the analysis was collapsed across the ascending and descending trials as the presentation and selection of bets occurred after these variables were recorded.

To explore gambling behaviour in decision-making under risk, the mean percentage number of points bet on the task were analysed. This analysis included trials in which participants chose the most likely outcome to not confuse betting behaviour and decision-making. A three-way mixed ANOVA was used to compare the amount of points bet for ascending and descending trials (within-subject factor point presentation: ascending, descending) under conditions of high- and low-physical performance pressure (within-subjects factor of pressure: low-performance pressure, high-performance pressure). A between-subject factor of gender was included (male, female), due to previous work that has shown gender to influence risk taking under pressure. Overall, higher gambles are indicative of increased risk taking, a large difference in the amount bet on ascending compared to descending trials is indicative of impulsivity.

Lastly, a measure of risk adjustment was derived from the data and a paired t-test was performed to compare the degree of risk adjustment under conditions of low- and high-physical pressure.

***SSRT task*:** One participant was excluded due to experimenter error (failure of audio presentation). Therefore, 30 participants were included in the analysis. Paired t-tests were undertaken to compare reaction times on go trials and the SSRT under conditions of low- and high-physical pressure.

Correlation analysis assessing performance across tasks: The following analysis was undertaken with 30 participants; this number excludes the participant who has incomplete data on the SSRT task. To examine whether an individual's responses to pressure was consistent across the three decision-making tasks, the difference under pressure score was calculated for key indicators of task performance by subtracting the score under high pressure from that under low pressure. The variables chosen as indicators of task performance are: The average adjusted number of pumps on the BART (a positive score represents better performance under pressure); The reaction time to 'go' trials on the SSRT (a negative score represents better (quicker) performance under pressure), and; The risk adjustment score on the CGT (a positive score represents better performance under pressure). The difference under pressure scores for each task were compared, using the Pearson Correlation Coefficient, to examine whether participants showed a consistent response to pressure across tasks.

Applicability of group data to individuals: To explore the degree to which group data applies to individuals, the number of athletes whose change under pressure showed an ‘average’ response to pressure across the three tasks was assessed. In accordance with previous work, an average response was calculated as a score that fell within one standard deviation of the mean (0.5 SD above and below) (Daniel, 1952; Rose, 2016) for the average adjusted number of pumps on the BART, the reaction time to control trials on the Stroop task and the risk adjustment score on the CGT. The participant who did not complete the SSRT was excluded due to incomplete data; therefore, 30 participants were included in this analysis.

7.4. Results

7.4.1. Effect of Physical Pressure on the BART

To explore the influence that pressure has on the decision-making of semi-elite athletes, the performance of the BART, CGT and SSRT under conditions of low- and high-physical pressure was assessed. For the BART, the mean-adjusted number of pumps was analysed as a measure of risk taking under uncertainty (**Figure 7.3**). The ANOVA revealed: A significant effect of physical pressure ($F_{(1,29)}$=6.38, $p<0.05$); A significant effect of balloon number ($F_{(1,29)}$= 5.12, $p<0.05$), and; No significant effect of gender ($F_{(1,29)}$= 0.52, p=0.47). All interactions were non-significant, including a non-significant interaction of pressure and balloon number ($F_{(1,29)}$=1.40, p=0.25), of gender and pressure ($F_{(1,29)}$=0.01, p=0.94), as well as of gender and balloon number ($F_{(1,29)}$=1.40 p=0.25). There was also a non-significant three-way interaction of pressure, balloon number and gender ($F_{(1,29)}$=0.71, p=0.41). Hence, in this sample of semi-elite athletes, physical pressure increased the average adjusted number of pumps; this is indicative of increased risk taking (Mean = Low pressure: 33.79 pumps; High pressure: 39.72 pumps). Also, the average adjusted number of pumps were higher for the latter part of the task (Mean = Balloon number 1-10: 32.39 pumps; Balloon number 11-20: 38.12 pumps); this reflects the usual learning effects found on this task. There were no differences in the risk taking of male and female semi-elite athletes as a result of increased physical pressure.

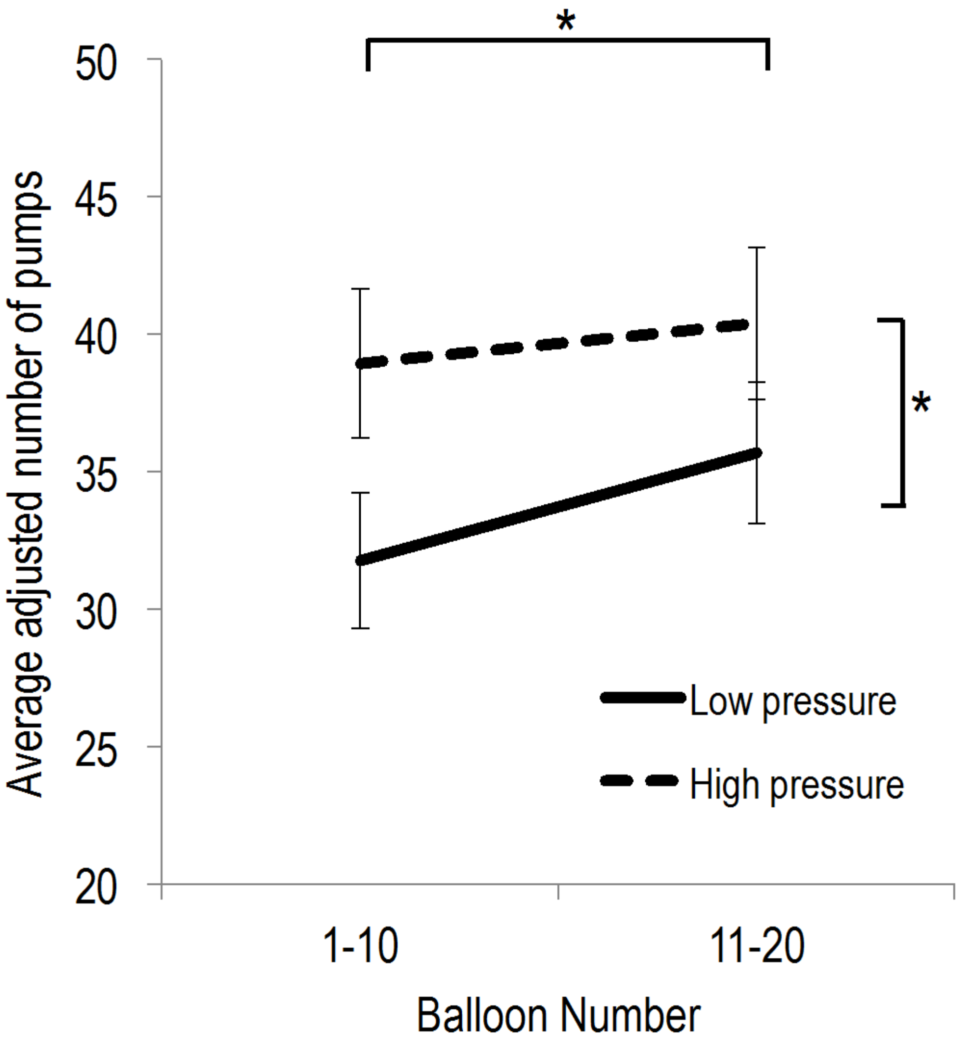


Figure 7.3: BART results: In semi-elite athletes, there was a significant increase in the average adjusted number of pumps under high physical pressure, indicative of increased risk taking. There was also a significant effect by the balloon number, with the average adjusted number of pumps found to be larger for the last half of the task. *Denotes statistical significance at $p<0.05$. Error bars represent SEM.

7.4.2. Effect of Physical Pressure on the CGT

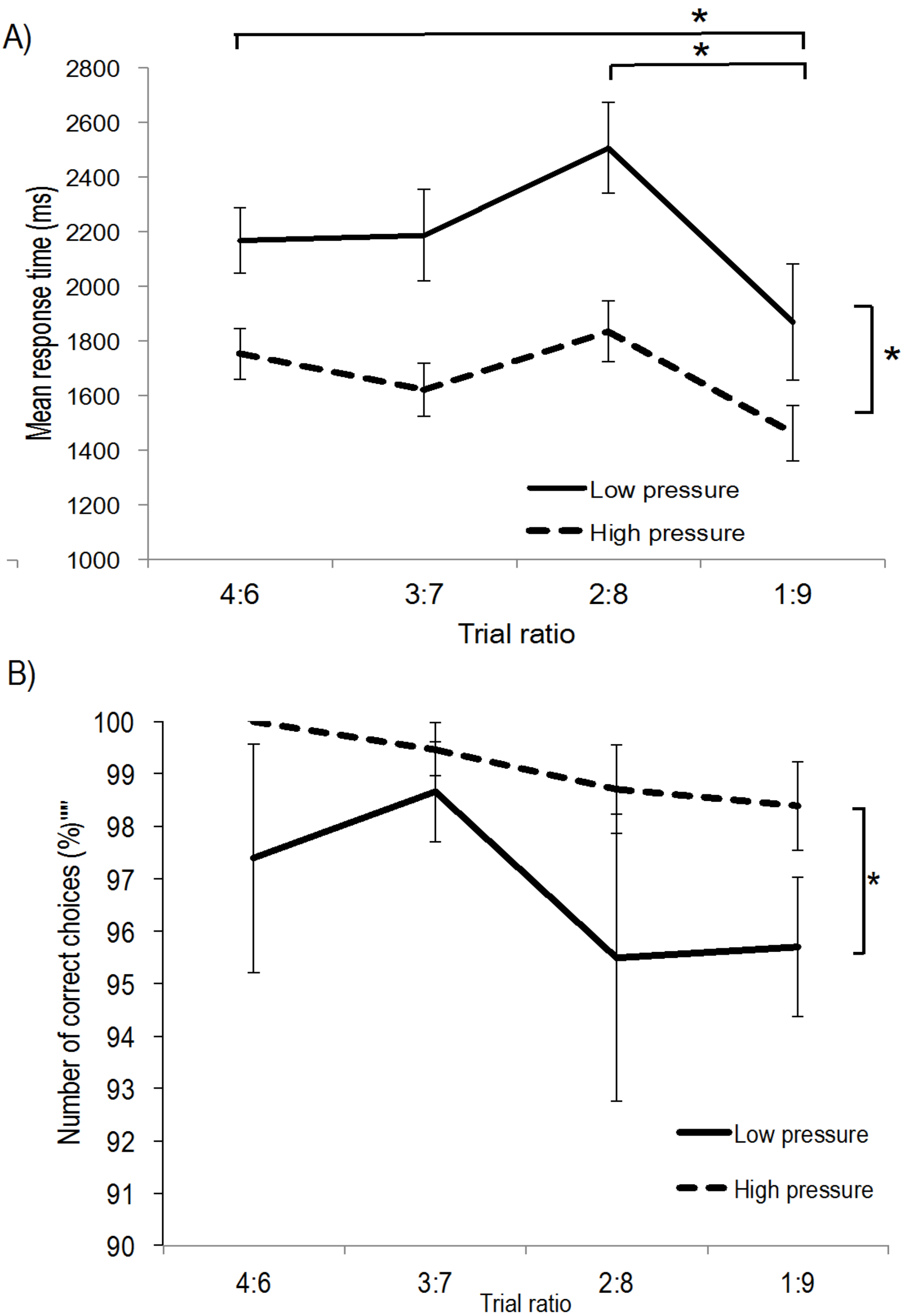
Response Times: Next, the influence of physical exhaustion on the CGT was examined. First, a repeated measures ANOVA was performed on response times (see **Figure 7.4**a). This finding revealed a significant main effect of physical pressure ($F_{(1,30)}=22.08$, $p<0.01$), with the mean deliberation time being less under conditions of high-physical pressure (Mean = Low pressure: 2168.11 ms; High pressure: 1661.23 ms). In addition, there was also a significant effect by the trial ratio ($F_{(3,90)}=8.67$, $p<0.01$). Pairwise comparisons revealed that the response times to trials with 1:9 ratios were significantly quicker than compared to those with 4:6 ($p=0.04$) (Mean: 1:9 = 1665.82 ms; 4:6 = 1960.50 ms) and to 2:8 ($p=0.001$) (Mean: 2:8 = 2170.23 ms). There was no significant interaction of trial ratio and physical pressure ($F_{(2.13,63.80)}=0.64$, $p=0.54$); this indicates that elite athletes tend to response faster under pressure and when trials ratios are higher.

Error rates: Next, a repeated measures ANOVA was performed on the error rates (% number of trials in which the participant chose the most likely box colour) (see **Figure 7.4**b); this revealed a significant main effect of physical pressure ($F_{(1,30)}=4.49$ $p<0.05$) and a significant main effect of trial ratio (Greenhouse Geisser correction applied $F_{(2.06,61.67)}=1.33$, $p=0.27$). There was a non-significant interaction of ratio and physical pressure ($F_{(2.09,62.83)}=0.33$, $p=0.73$). Semi-elite athletes were less accurate and opted for the most-likely box colour on fewer occasions under conditions of low pressure (Mean % correct = Low pressure: 96.8%; High pressure: 99.1%).

Mean percentage points bet: Next, a mixed ANOVA was performed on the mean number of points gambled (%) as a measure of risk taking (see see **Figure 7.4**c); this revealed a significant effect of physical pressure ($F_{(1,29)}=39.16$, $p<0.01$) and a significant effect of point presentation (ascending or descending) ($F_{(1,29)}=47.73$, $p<0.01$). There was also a significant interaction of physical pressure and point presentation ($F_{(1,29)}=11.99$, $p<0.01$). Post hoc tests revealed that there were significantly more points gambled under high pressure on both ascending trials ($t_{(30)}=-7.09$, $p<0.01$) (Mean = Low-pressure ascending: 50.84%; Low-pressure descending: 76.40%) and on descending trials ($t_{(30)}=-3.09$, p=0.004) (Mean = High-pressure ascending: 64.20%; High-pressure descending: 82.20%).

Additionally, there was no significant main effect of gender on the number of points gambled ($F_{(1,29)}<0.01$, $p=0.97$) and no significant interactions of gender and other main effects; including of physical pressure and gender ($F_{(1,29)}=1.02$, $p=0.32$) or points presentation and gender ($F_{(1,29)}=0.03$, $p=0.86$). There was also no significant three-way interaction of gender, point presentation and physical pressure ($F_{(1,29)}=0.34$, $p=0.57$).

Risk Adjustment: A paired t-test revealed there was a significant difference in the measure of risk adjustment between conditions of low and high physical pressure ($t_{(30)}=2.77$ $p=0.01$) (see **Figure 7.4**d). The tendency for semi-elite athletes to modify the amount bet according to the different reward and loss contingencies were reduced under conditions of high physical pressure (Mean risk adjustment score: low pressure: 1.52; high pressure: 1.10).


A)
*
*
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
Mean response time (ms)
*
Low pressure
High pressure
4:6
3:7
2:8
1:9
Trial ratio
B)
100
99
98
97
96
95
94
93
92
91
90
Number of correct choices (%)
*
Low pressure
High pressure
4:6
3:7
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1:9
Trial ratio

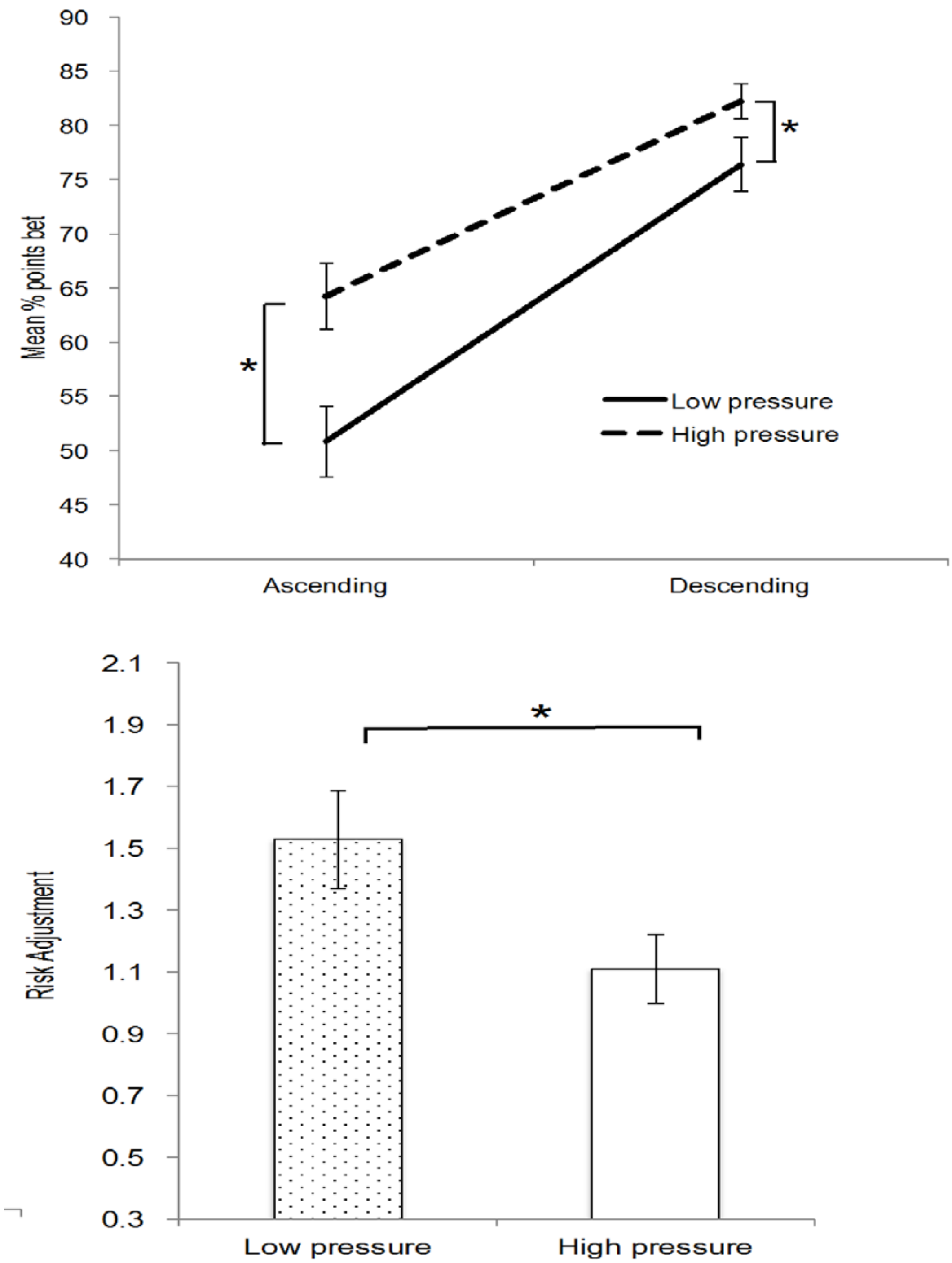

Figure 7.4; CGT results; A) The semi-elite athlete showed significantly faster response times under physical pressure. **B)** Under pressure, semi-elite athletes made significantly fewer errors compared to conditions of low pressure**.; C)** Under physical pressure, the semi-elite athletes also showed increased amount of points gambled, indicating increased risk taking. There was a significant increase on both ascending and descending trials. **D)** The degree of risk adjustment was significantly reduced under conditions of increased pressure. *Denotes statistical significance at p<0.05. Error bars represent standard error of the mean.

7.4.3. Effect of Physical Pressure on the SSRT task

Paired t-test results show there were no significant differences in the reaction time when responding to ‘go’ trials under the conditions of low- and high-physical pressure ($t_{(29)}$=0.63, p=0.53). There was also no significant difference in the SSRT task under the conditions of low- and high-physical pressure ($t_{(29)}$=-0.06, p=0.95) (see **Figure 7.5).** Therefore, increased physical pressure did not influence reaction times to ‘go’ trials or respond to inhibition processes as assessed by the SSRT task.

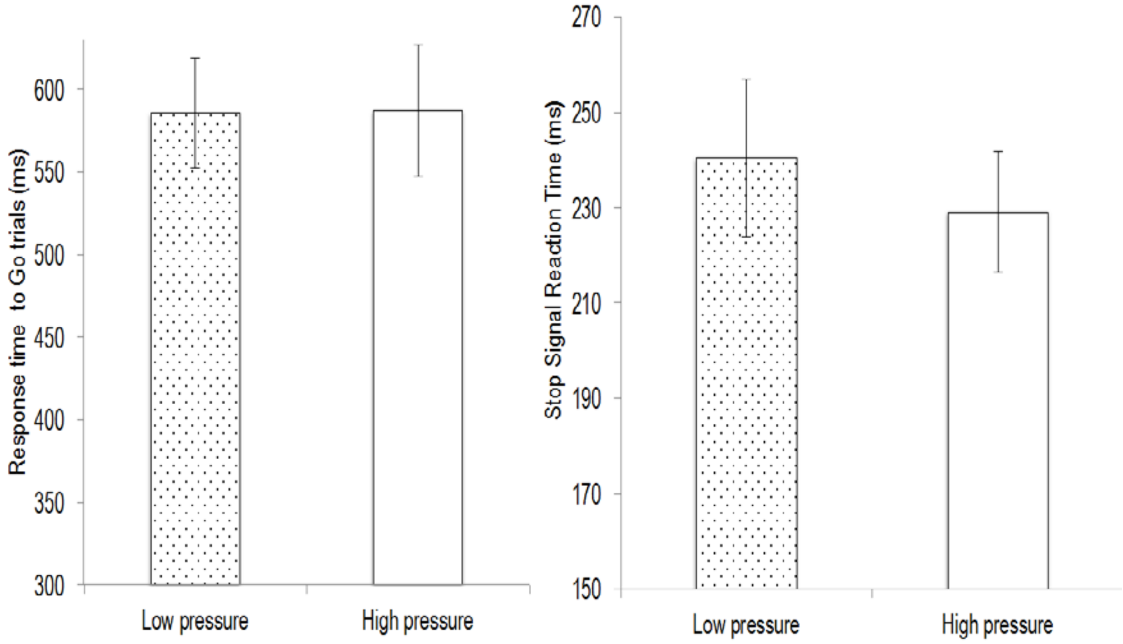

Figure 7.5: SSRT task results: The semi-elite athletes showed no significant differences under conditions of low- and high-pressure in the time taken to respond to ‘go’ trials (left) or on the SSRT (right). *Denotes statistical significance at p<0.05. Error bars represent SEM.

7.4.4. Correlations of Performance Under Pressure Across Tasks

Pearson correlations were undertaken to examine whether individual responses to pressure were consistent across key indicators of performance the three decision-making tasks. There was a significant correlation when comparing the two performances on the BART and on the SSRT task ($r_{(30)}$=-0.62, p<0.01); this showed that as reaction times decreased under pressure on the SSRT, the degree of risk taking under pressure on the BART increased (see **Figure 7.6**). There were no further significant correlations when comparing the degree of change under pressure on the BART and the CGT ($r_{(30)}$=0.16, p=0.39) or on the BART and SSRT task ($r_{(30)}$=0.01, p=0.99).

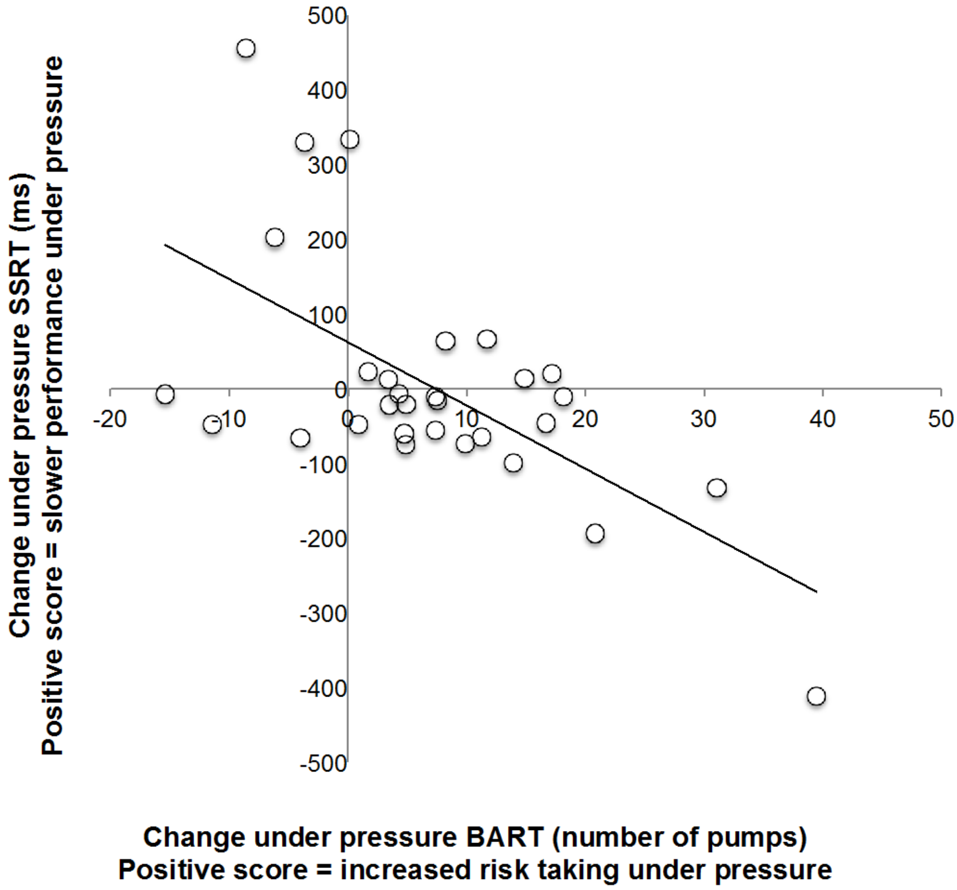

Figure 7.6: There was a significant negative correlation when comparing the difference under pressure performance on the BART and the SSRT task. This showed that quicker reaction times to 'go' trials on the SSRT under pressure were associated with increased risk taking on the BART under pressure.

7.4.5. Representativeness of Group Data

To explore the degree to which group data applied to individual athletes, the number of athletes who showed average responses (defined as 0.5 SD above and below the mean) to pressure across key performance indicators of decision-making tasks were assessed. In line with previous work (Daniel, 1952; Rose, 2016), this categorization of an 'average' responder meant that, at least, the middle 43% of the group were categorized as falling within the 'average' on each variable. The results of this analysis revealed that there was 16.67% of the sample who were average responders across the average adjusted number of pumps on the BART, the reaction time to control trials on the Stroop task and the risk adjustment score on the CGT.

As the group average scores were not representative of the behaviour of athletes across the three measures in the large majority of cases, this highlights the importance of feeding back individual results in an elite setting, where providing insight at an individual level is paramount.

7.5. Discussion

The goal of the current study was to investigate the influence of physical exhaustion on key indicators of decision-making in semi-elite athletes. The study formed part of a wider project assessing decision-making across different developmental stages of elite sporting expertise and, in doing so, examined how to increase psychological insight in this environment. The main findings were that, under the conditions of physical pressure, semi-elite athletes showed increased risk taking, as well as a reduced ability to modify behaviour in line with explicit reward and loss contingencies. There was no change to fast reactive responses of perceptual stimuli and response inhibition under conditions of increased physical pressure.

The decision-making of semi-elite athletes showed an increase in risk taking under physical pressure, in response to both decision-making under risk and uncertainty. On the BART, there was an increase in the adjusted number of pumps under conditions of high pressure; which may be notable given the high correlation that performance on this task has with real-world risk taking behaviours (Aklin, Lejuez, Zvolensky, Kahler & Gwadz, 2005; Crowley, Raymond, Mikulich-Gilbertson, Thompson & Lejuez, 2006; Lejuez et al., 2003). On the CGT, while semi-elite athletes made fewer errors and were faster to respond to simple probabilistic decisions under physical pressure, they also opted to gamble a higher number of points. In this case the increase in risk taking was evident for across both ascending and descending point presentations trial types. These findings support the previous work that has shown modulations to risk taking following physical exertion (Black, Hochman & Rosen, 2013; Pighin et al., 2015). In line with the notion that the physiological responses to exercise is akin to those observed under stress/arousal, the results also align with work that has shown risk taking to be affected by other sources of acute stress (for a review: Starcke & Brand, 2012). One finding from the previous body of work not supported by the current study: the influence that gender has on risk taking under pressure. In particular, males have been reported to show an increase, while females a decrease, in risk taking under pressure, across both non-elite athletes under physical exertion (Pighin et al., 2015) and non-athletic healthy samples following stress induction paradigms (Lighthall et al., 2009; 2012; van den Bos, Harteveld & Stoop, 2009; Preston et al., 2007). In the current study, there was no effect of gender on measures of risk taking across two different decision-making tasks and the behaviour of male and female semi-elite athletes did not significantly differ from one another. The shift towards more cautious decision-making reported in female healthy volunteers and non-elite athletes was not evident in semi-elite female athletes.

On the CGT, the semi-elite athletes also showed a significant reduction in risk adjustment and the ability to gamble appropriately according to different probability ratios under pressure. This measure is thought to reflect the degree to which the participant can use information relating to the decision to appropriately modify ones propensity for risk (Clark, Manes, Antoun, Sahakian & Robbins, 2003; Rogers et al., 1999). Together, the results of the CGT show an increase in risk taking (in the number of points bet) and a decrease in the responsiveness to optimal betting scenarios (reduced risk adjustment). Thus, such a pattern may indicate a sub-optimal shift in risky decision-making under pressure in semi-elite athletes. This may be noteworthy in a sporting context, while reductions in risk taking have been linked to performance decrements in elite sport (Jordet & Hartman, 2008; Paserman, 2007), the relationship between risk taking and sporting performance is likely to be one of adaptability. In some circumstances, taking risks would provide the athlete with the competitive edge; i.e., in a football match when the losing team substitutes a defender for an attacker as they enter injury time. While in others, the potential exposure to negative outcomes that risk entails means playing it safe is optimal; for example, in a football match when the team which is in the lead and decides to adopt a defensive strategy as they enter injury time (Bronson & Merryman, 2013).

In relation to reaction times, fast reactive responses to perceptual stimuli - i.e., the time taken to respond to ‘go’ trials on the SSRT task - did not change under increased physical pressure. There were also no differences in the time taken to inhibit responses measured by the SSRT. Considering the intense level of the physical exhaustion protocol undertaken by the semi-elite athletes the consistency in responding may be indicative of expertise. However, in consideration of the previous research, the lack of significant improvements on this measure is notable. In particular, a recent review in this area reported high-intensity levels of physical exertion to have faciliatory effects on response time measures on perceptual-cognitive tasks, but only in athletes with high levels of sporting expertise (Schapschröer et al., 2016). While the semi-elite athletes are within the top-50 national players in their chosen sport, faster responses under physical exertion were not evident. These differences may allude to the variation of abilities across elite samples which, due to the broad definition in elite status in the current review, could not be teased apart (Schapschröer et al., 2016).

At an individual level, there was a consistent response to physical pressure across indices of performance on two of the decision-making tasks. There was a significant correlation of performance on the BART and the SSRT, with semi-elite athletes showing quicker reaction times to 'go' trials under pressure and showing increases in risk taking on the BART. This indicates that semi-elite athletes may show a more general orientation at an individual level in terms of responding to physical pressure.

Together, the indiscriminate increases in risk taking and lack of facilitation in fast reactive responses to perceptual stimuli in semi-elite athletes may be indicative of reduced resilience to physical exhaustion; this is in comparison to world-class elite athletes performing a similar protocol and showing faster reaction times in perceptual stimuli (notably to a different task) and there were no impairments on their abilities to adjust risk taking according to task contingencies under pressure. Importantly, the differences here highlight that elite athletes are not a homogenous group and the importance of considering differences between expertise at the elite athletic level (Swann et al., 2014). As well as expertise, the two groups of athletes were distinct in terms of age, which may help to explain the differences noted here. The semi-elite athletes who are in their late teens to early 20s are still undergoing the cognitive changes and brain developments characteristic of adolescence; those abilities that are important in determining decision-making (Blakemore & Robbins, 2012). In particular, there is a heighted tendency to engage in increased risk-taking during this time in relation to young adults (Defoe et al., 2015), which is in line with the findings from the current study.

As a similar protocol was used to chapter 6, with the limitations discussed in the previous chapter also applying here; these include a lack of counterbalancing of low- and high-pressure conditions. When performing under conditions of high-physical pressure, participants were also undertaking the tasks for the second time. Therefore, small improvements in performance may be due to the design of the study. While the lack of counterbalancing of low- and high-pressure conditions were not optimal, it was a necessary compromise due to the constraints of working with an elite population to whom time and access were limited. Moreover, adherence to the physical exertion protocol was devised via self-reporting and monitoring - no objective measure was taken.

A further goal of this study was to explore how psychology can be applied to improve insight into decision-making within the elite sporting environment. In accordance with chapter 6, the results highlight the limitation of statistical approaches based on group averages. When examining the number of athletes that showed average responses to increased physical performance pressure, 16% of the sample presented a mean response to pressure across three indices of decision-making. Thus, in the large majority of cases, it would be incorrect to apply results based on group means to the individual athlete. Therefore, in line with chapter 6, the feedback of individual results - along with group means for context - provided the most useful in a context where understanding the behaviour of individuals is most crucial.

Moreover, building on the framework developed in chapter 6, the implementation of features that had been a success were applied to this new sample. In keeping with previous work, the application involved individualized feedback sessions and the further development of the decision-making taxonomy. These sessions provided the athlete, coaches and sport psychologist the opportunity to apply decision-making concepts and insights from performance of the study to an individual athlete sporting practice. These included the implementation of accessible terminology based on key psychological concepts represented with the chosen decision-making tasks, to allow the development of a common language of decision-making that aids understanding and communication among sports professionals. In addition, features of the testing environment that were in keeping with the sporting culture, such as the competitive element whereby prizes were awarded to the top three performers (gold, silver and bronze), increased motivation among the athletes. It also meant that the application was mainly practitioner led and, in several cases, interventions based on specific sporting decision scenarios or attributes were developed.

7.6. Conclusion

The findings of the current study show that the decision-making of semi-elite athletes were influenced by physical exhaustion. Under physical pressure, semi-elite athletes showed increased risk taking for both decisions where probability outcomes were explicit and where outcomes were unknown, as well as a reduced ability to adjust risk-taking behaviour according to the odds. There were no differences in fast reactive responses to perceptual stimuli under physical pressure, despite previous findings of faciliatory effects on these measures. The influence of physical exhaustion on semi-elite athletes was different from those observed previously in elite world-class athletes, highlighting the importance of considering the differences between athletes at the elite level. The application of this work to a novel sub-group of elite athletes were examined. The importance of feedback of individual patterns of behaviour in the elite sporting environment is highlighted. Work in the following chapter investigates the influence of mental pressure on decision-making in junior-elite athletes who are at the earliest point of entry to elite sport programs.

8. Decision-Making Under Mental Pressure in Junior-Elite Athletes

8.1. Abstract

Background: Having investigated the decision-making of world-class elite and semi-elite athletes, here the abilities of those at the earliest stage of entry to elite sport are examined. Junior-elite athletes have undergone initial national selection according to their potential for later success at an international level and are younger than athletes examined previously (mean age = 13 years). Decision-making under mental pressure is explored in this sample. During performance an athlete encounters a wide array of mental pressures, these include the psychological impact of errors, negative feedback and requirements for sustained attention in a dynamic environment (Anshel & Wells, 2000; Mellalieu, Neil, Hanton, & Fletcher, 2009). Such factors increase the cognitive demands of the athletes, inducing distracting anxiety related thoughts known as rumination (Beilock & Gray, 2007). Mental pressure has been shown to reduce performance in decision-making tasks where reward and loss contingencies are explicit, with a shift towards increased risk taking (Pabst, Schoofs, Pawlikowski, Brand, & Wolf, 2013; Starcke, Pawlikowski, & Wolf, 2011). Mental pressure has been shown to exert detriments in decision-making speed in comparison to physical stress, highlighting the importance of considering a range of different pressures encountered by athletes (Hepler, 2015).

Objective: To investigate the influence of mental pressure on key indicators of decision-making in junior-elite athletes. Thus this chapter explores those at the earliest stage of entry to elite sport, and concludes a wider project examining decision-making across developmental stages in elite sport. In doing so this work further explores how psychological insights can be applied and developed in an elite sporting environment and in particular tailored to the requirements of junior athletes.

Method: 17 junior-elite athletes (10 males, mean age =13 years) enrolled on a national youth athletic development program participated in the study. Performance across three categories of decision-making was assessed under conditions of low and high mental pressure. Decision-making under risk was measured with the CGT (Rogers et al., 1999), decision-making under uncertainty with BART (Lejuez et al., 2002), and fast reactive responses to perceptual stimuli via the Visual Search task (Treisman, 1982). Mental pressure was induced with the addition of a concurrent verbal memory task, whereby participants had to memorize and later recall a list of words. This was used to increase cognitive load and mimic the distracting effects of anxiety related rumination.

Results: In junior-elite athletes, fast reactive responses to perceptual stimuli (on the Visual Search task) were slower under conditions of mental pressure. Decision-making under risk (on the CGT) was also affected by mental pressure. In particular there was an interaction of mental pressure and gender on the amount of points gambled, indicating a higher level of risk taking in male athletes in comparison to female athletes. For decision-making under uncertainty there was no influence of mental pressure on risk taking. There were no significant correlations in the degree to which individuals' responses changed under pressure across the three measures of decision-making. When assessing the applicability of results based on group averages there were no junior-elite athletes who showed an 'average' response (within 1SD of the mean) to mental pressure across all the three decision-making tasks.

Conclusions: Mental pressure affects decision-making in a sample of elite junior athletes, with a similar pattern of results seen in previous research, for example a slowing of response times, and modulations in the performance of decision-making under risk tasks, that have a higher requirement for working memory. In relation to sport these findings may suggest that novel situations that place high cognitive demands on the athlete may be particularly influenced by mental pressure. The results also highlight that at this stage in the athletic development trajectory male and female junior-elite athletes respond differently to mental pressure. The application of this work in youth athletes are discussed.

8.2. Introduction

Following on from work investigating world class elite and semi-elite athletes, this chapter concludes a wider project examining the development of decision-making in elite sport. It does so by exploring the influence of mental performance pressures on the abilities of junior-elite athletes. Junior-elite athletes are at the earliest stage of entry to elite sporting programs, having undergone national selection according to their potential for later success at an international level. These athletes are younger than those assessed previously with a mean age of 13 years. Moreover they have approximately five years of experience in their given sport, and thus much less exposure of the coupling of decision-making skills and performance pressures.

Previous work, including that laid out in this thesis, has established that decision-making abilities are influenced by the stressors that athletes encounter during performance (Hepler, 2015; Kinrade, Jackson, & Ashford, 2015; Pighin, Savadori, & Bonini, 2015; Smith et al., 2016). Performance pressure has been broadly categorized into, physical stress, such as physical exhaustion, and injury, as well as mental stressors, that include the desire to perform at one's best often exacerbated by the importance of the competition, the impact of errors, sources of negative feedback and requirements for sustained attention in a dynamic environment (Anshel & Wells, 2000; Mellalieu et al., 2009). One way in which mental pressure has been proposed to influence performance is via increased cognitive load, with irrelevant thoughts such as worrying diverting mental resources away from the task in hand (Beilock & Gray, 2007). In research, in order to mimic conditions of increased mental pressure, the addition of a distracting dual task is often used. Hepler (2015) compared the effects of mental pressure (the addition of a dual subtraction task) and physical pressure (physical exertion) in non-elite athletes. This study revealed mental and physical pressure to exert different effects on decision-making, mental pressure was found to impair decision-making speed, while physical pressure had no effect (Hepler, 2015). This highlights the importance of considering a range of different sources of pressure in the understanding of athletic performance.

Previous work in this area has mainly been undertaken with adult samples. In particular, in non-elite adult athletes with sports specific decision-making tasks, mental pressure has been reported to increase decision speed (Hepler, 2015; Smith et al., 2016) and to impair accuracy of choices (Smith et al., 2016), especially in complex scenarios (Kinrade et al., 2015). Interestingly, in the latter study the levels of self-reported rumination arising from the mental pressure manipulation predicted response decrements. Work by Beliock, Kulp, Holt & Carr (2004) in non athletic healthy adults further highlight that the influence of mental pressure (induced via socio-evaluative stressors and performance related rewards) may depend on task requirements, in particular tasks that placed high demands on working memory were found to be selectivity impaired. This is also evident when examining the influence of mental pressure on different types of decision-making. In particular under mental pressure (increased cognitive load) reduced performance on decision-making under risk have been reported, with a suboptimal shift towards risky strategies observed (Pabst, Schoofs, Pawlikowski, Brand, & Wolf, 2013; Starcke, Pawlikowski, & Wolf, 2011). Decision-making under uncertainty tasks however have been shown to be less susceptible to mental pressure. Indeed Turnbull, Evans, Bunce, & Carzolio (2005) reported that increased mental pressure (cognitive load) did not affect performance on the Iowa Gambling Task, this was proposed to be due to a reduced requirement for working memory (Starcke, Pawlikowski, & Wolf, 2011). Moreover mental pressure has also been found to interfere with visual search strategies in athletes, in that they show increased fixations for shorter duration (Liu & Zhou, 2015) and a decreased ability to detect peripheral stimuli (Janelle & Singer, 1992).

Due to the age group of the junior-elite athlete cohort they may show notable differences in their decision-making and responses to pressure. Cognitive abilities go through profound changes in the transition from early adolescence to adulthood (Blakemore & Robbins, 2012). In particular early adolescents show an increase in risky decision-making especially in ‘hot’ contexts, where there is feedback of rewards and losses, in comparison to late adolescents and adults (Defoe, Dubas, & Figner, 2015). Additionally, during this time visual search strategies are developing, with those in later childhood shown to have a reduced ability to switch attention from one item to another (Trick, 1998). Differences in how these junior-elite athletes respond to mental stress may also be likely. On the one hand, adolescents show increased stress volatility, displaying for example a heightened response to laboratory stress induction protocols in comparison to adults (Tottenham & Galvan; 2016). On the other, individuals with high working memory capacities have been reported to be most affected by mental pressure, as these individuals employ cognitively demanding strategies that fail when resources are limited (Beilock & Carr, 2005). As such, in this age group who have reduced working memory capacities in comparison to adults (Gathercole, Pickering, & Ambridge, 2004), the effects of mental pressure on decision-making may be less severe.

In order to investigate the influence that performance pressure has on decision-making, junior-elite athletes will be assessed under conditions of low and high mental pressure. Mental pressure was induced via the addition of a dual task, whereby the participant has to memorise a list of words. In adherence to chapter 6 and 7, decision-making under risk will be assessed via performance of the CGT (Rogers et al., 1999) and decision-making under uncertainty via the BART (Lejuez et al., 2003). Fast reactive perceptual responses will be assessed via performance of a Visual Search task (Treisman, 1982).

Thus this study aims to provide greater insight into the abilities of those at the earliest stage of entry on elite sporting development programs and together with chapter 6 and 7 provides a detailed look at the development of decision-making abilities in elite athletes. Mental pressure has been shown to modulate markers of optimal decision-making in non-athletic adults and non-elite athlete samples. Whether similar findings are also present in junior-elite athletes will be examined. As in previous chapters, a central aim of this work is to explore how psychological insights can be applied and developed in an elite sporting environment and in this case tailored to the requirements of junior athletes.

8.3. Methods

8.3.1. Participants

The sample consisted of 17 junior-elite athletes (10 males), aged between 12 and 14 (mean age = 13 years). All junior-elite athletes had undergone selection to be part of a national youth development program, designed to develop skills for progression onto a Team GB training pathway and later success at an international level. All junior-elite athletes included in the sample were from the same sport. The approximate age of entry for this sport is eight years old, thus the junior-elite athletes had been training for approximately five years.

Junior-elite athletes were recruited via collaboration with Team GB Sports Psychologists and Coaches working within the program. Recruitment, testing and debriefing took place during weekend training camps. Parents and athletes were informed about the purpose and the procedures of the study and provided consent prior to participation. Elite- junior athletes did not receive financial reimbursement for their participation. Upon completion a detailed debriefing session was undertaken in conjunction with Team GB coaches, a sports psychologist and a member of the research team. The study and consent procedures were approved by the UCL ethics board in compliance with the principles of the Declaration of Helsinki.

8.3.2. Experimental Protocol

A within-subject design was used, whereby the decision-making of junior-elite athletes was assessed under conditions of low- and high- mental pressure (**Figure 8.1**). Testing was undertaken in a single session. Performance on three decision-making tasks was examined via a laptop computer; these included the BART (Lejuez et al., 2003), the CGT (Rogers et al., 1999) and the Visual Search task (Treisman, 1982). Initially participants received instructions and completed a short practice of each task. The tasks were undertaken at rest; i.e. in the absence of additional mental pressure, and under conditions of high mental pressure. The order in which these conditions were undertaken were counterbalanced across individuals, and separated by a short break. Mental pressure was induced via increased cognitive load whereby participants simultaneously performed a dual word memory task. Athletes were presented with a verbal list of single words, which they were required to memorize and recall at the end of each task. After completion, the junior-elite athletes and parents were debriefed in a feedback session where the results of the study and relevant psychological concepts were discussed.

8.3.3. Mental Pressure Induction

To induce elevated mental pressure, junior-elite athletes undertook a secondary dual task to increase cognitive load. The athletes were required to simultaneously remember a verbal list of words presented to them while performing each decision-making task. For each task there was a unique list of twenty words, of which all were concrete nouns (bed, kettle, flower etc) and matched on frequency. The words were presented at varying intervals over a maximum duration of 4 minutes, so that it was difficult for the participant to predict their presentation.

Participants were instructed that they must memorize the words presented to them and to write these down at the end of each task. Participants were advised that one efficient method of performing this was via subvocal rehearsal, whereby one repeats the words in mind so as to not forget. The aim of this dual task was firstly, to mimic distracting ruminative thoughts provoked by stressful situations and secondly, to expend the processing resources available for a given task, thus increasing the demands placed on the junior-elite athletes.

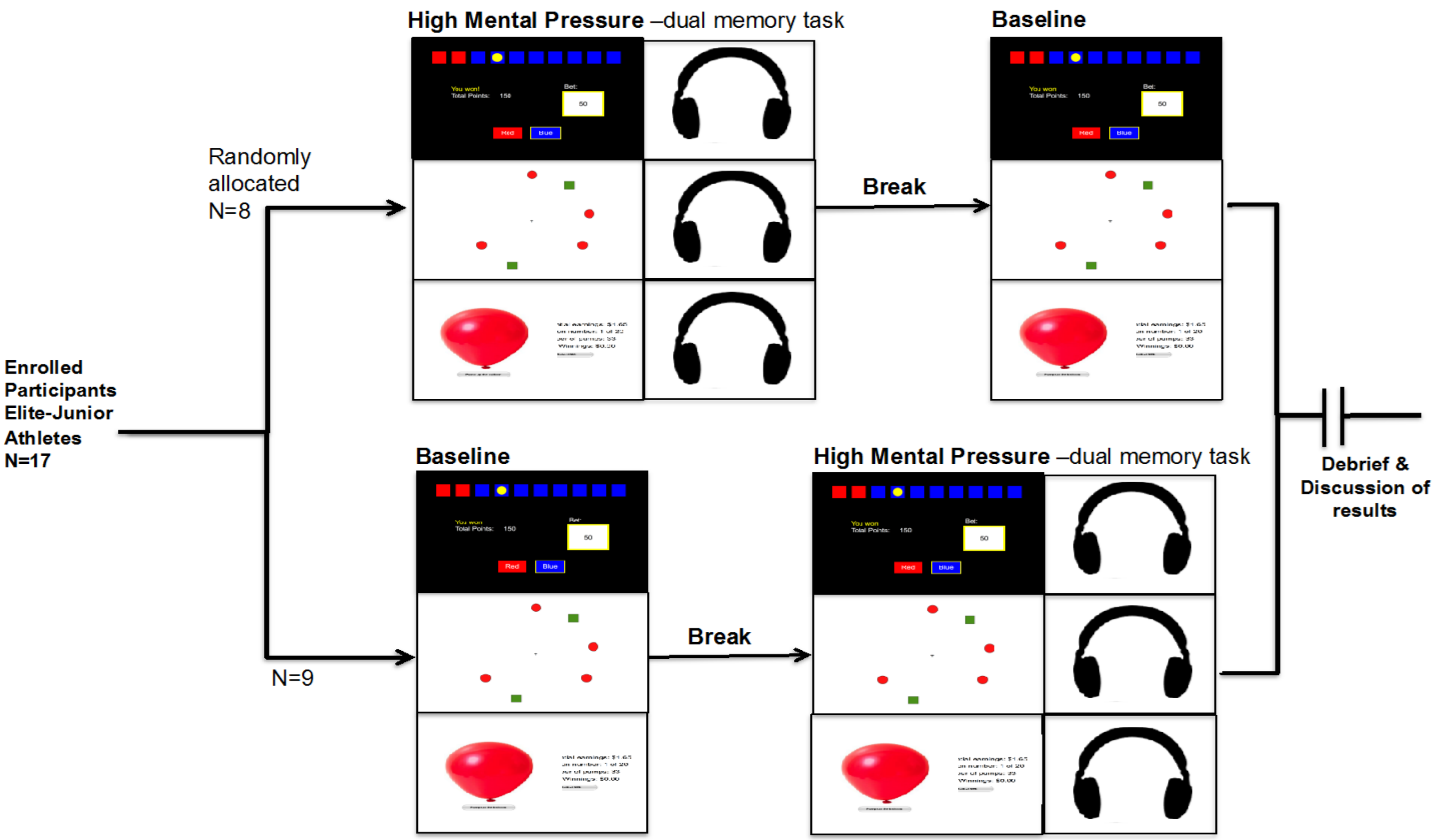

Figure 8.1: The experimental protocol. Upon enrolment, junior-elite athletes undertook a short practice of the tasks. The BART, the CGT and Visual Search task were undertaken both at rest and under conditions of high mental pressure (in a counterbalanced order). Mental pressure was induced by dual word memory task designed to increase cognitive load and mimic distracting thoughts. Upon completion, athletes and parents were debriefed where they received feedback of their individual performance.

8.3.4. Decision-making Tasks

Tasks were delivered via a laptop computer, with a 17-inch display screen. They were run using Inquisit software version 4.0.7.0 (Millisecond Software Seattle WA), which was used to automatically record responses for subsequent analysis.

8.3.4.1. BART

Decision-making under uncertainty was measured via performance of the BART (Lejuez et al., 2003) (see **Figure 3.2**). In this task participants are required to accrue money (5p per pump) through the inflation of a number of computerized balloons. For the winnings of each balloon to be added to the total, participants must decide to transfer winnings from each balloon into a safe wallet, before the balloon explodes. In light of not knowing when the balloon will explode participants have to decide when to transfer the winnings in order to obtain the maximize winnings. The administration of the task, including task parameters and delivery, is identical to that laid out in section 6.3.4.1. To summarize, a well validated shortened version of the task including 20 balloons were used (e.g. Cheng & Lee, 2016; Derefinko et al., 2014; Ryan, MacKillop, & Carpenter, 2013; Vaca et al., 2013), to make testing as time efficient as possible. Unlike in previous chapters the junior-elite athletes did not receive cash incentives for performance of this task.

The average adjusted number of pumps provides a measure of risk taking on this task, which was used for the analysis. This is the number of pumps for balloons that did not burst, removing the variation resulting from the randomly generated balloon explosion points.

8.3.4.2. CGT

Decision-making under risk was measured by the performance of CGT (Rogers et al., 1999) (see **Figure 6.2**). Full details of the task parameters and delivery are described in section 6.3.4.2. In short, the participant is required to guess the location of a yellow token, hidden in one of ten boxes presented on screen. The boxes are coloured red or blue according to different ratios (9:1, 8:2, 7:2 and 6:4).

Once the participant indicates the colour box they wish to gamble on, they then have to select a wager. The amounts that can be bet appear as a number on screen, either in an ascending (from 5%, 25%, 75% to 95% of total points) or descending (from 95%, 75%, 25% to 5%) sequence. If the participant is correct the value is added to the score, if they are incorrect the value is deducted.

The following dependent variables will be used in the analysis in this task. **The response time** measured as the time taken for the participant to identify whether they chose to look in the blue or red box. **The error rate** measured as the proportion of trials whereby participants look in the most likely box colour. The **mean percentage points gambled** represents the degree of risk taking on the task, and is examined in context of ascending or descending point presentations, to provide an indication of motor impulsivity. **Risk adjustment** quantifies a participants ability to vary their risk taking in response to probability ratios, and is calculated using the following equation: (*2* % bet at 9:1)+ (% bet at 8:*2)- (% bet at 7:3) – (2* *% bet at 6:4) / average % bet).*

8.3.4.3. Visual Search Task

The Visual Search task (Treisman, 1982) was used to measure reaction times to perceptual stimuli. In this task participants are required to search visual arrays in order to identify the presence or absence of a target image, in this case a red square. There were three different types of distractor items, a green square, a green circle and a red circle. The number of items presented in one display is known as a set size. The set sizes used in this task were three, six or nine items arrays. There were two different trial types; ***target present*** where the items displayed on screen included a red square*, and* ***target absent*** where the items displayed on screen did not include a red square. If the red square was present participants were instructed to press the U key, and if the target was absent press the I key. Participants were instructed to place their index and middle finger over these keys to ensure a prompt response. They were instructed to make their responses as quickly and accurately as possible (see **Figure 8.2**).

Each trial began with the presentation of a blank white screen with the word 'Ready' in the centre. This was presented for 750 ms to orientate the participants' attention at the beginning of the trial. A blank screen followed this with a central fixation cross for 600 ms, which was preceeded by a visual array. The items of the array were located in one of nine designated positions equally spaced in a circle formation (181 mm diameter). The visual array stayed on screen until the participant made a response. Following this there was an inter-trial interval of 750ms, consisting of the presentation of a blank screen.

The task was arranged into three blocks, with each block consisting of 108 trials. There were 54 target present and 54 target absent trials (18 of each set size). The distractors were randomly sampled without replacement from 12 different images, four of each of the three distractor types, after the 12 random drawings the pool resets. Set size and trial type were randomised within block. The locations of distractor and target images were also randomised within each block but with the constraint that all locations were equally as likely, i.e. the target image would appear equally as often (six times) in each of the nine possible positions per block. Each block was separated by a blank screen which instructed participants to press the space bar when they wished to continue to allow a short break if needed.

Before commencing the task, participants undertook a short practice consisting of 5 trials to familiarize themselves with the task. These were identical to the task, except that there was feedback given. If a wrong answer was given during the practice a red cross appeared on screen, if the correct answer was given the task continued to the next trial. The two dependent variables on the task used in the analysis, were reaction times and error rates for target absent and target present trial types of each set size.

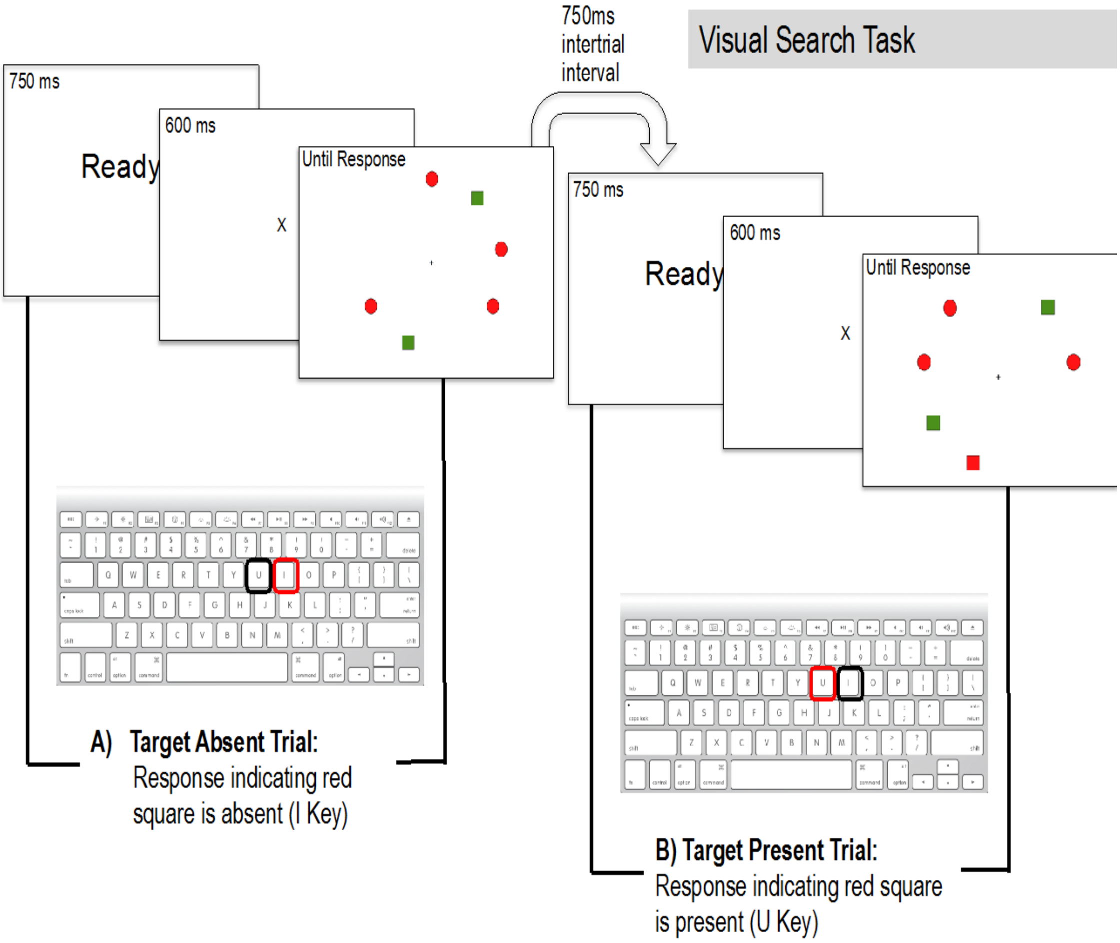

Figure 8.2: Visual Search task: Figure presents target-absent and target-present trial types. **A)** On target absent trials, the word 'ready' appears in the centre of the screen for 750ms followed by the presentation of a fixation cross for 600ms. The stimulus array is then presented. In this case there is no red square among the items presented, therefore the participant is required to press the I key. Following this there is an inter-trial interval of 750ms. **B)** On target present trials a red square is presented among the items in stimulus array, therefore the participant is required to press the U key.

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8.3.5. Data Analysis

Performance of the dual task

The numbers of correct words recalled were counted in order to assess whether participants were performing the task. A one way ANOVA was undertaken to assess whether there were differences in the performance of the dual task across decision-making tasks (BART, CGT, Visual Search).

Group statistical analysis

In accordance with chapters 6 and 7, to explore whether decision-making on the three tasks is influenced by performance pressure, ANOVA or paired t-tests (two tailed) were undertaken to compare task performance under conditions of low and high physical pressure. Where relevant, Mauchly's test of sphericity was performed and *Greenhouse-Geisser correction* applied. Bonferroni correction was used to correct for multiple comparisons. For each task, the dependent variables used in this analysis are laid out below.

BART: The mean adjusted number of pumps (the average pump count for balloons that did not burst) was analyzed as a measure of risk taking under uncertainty. A three way mixed ANOVA was undertaken to compare performance of the task under conditions of low and high physical pressure (within subjects factor of pressure: low pressure, high pressure) broken down by time (within subject factor of balloon number: 1-10, 11-20). A between subject factor of gender was included (male, female), due to previous work that has shown gender to influence risk taking under pressure.

CGT: The response times (the duration from the trial appearing on screen and the participant choosing to look in a red or blue box) and the error rates (the percentage of trials in which the participant chose the most likely box colour) were analyzed using a repeated measures ANOVA. This was undertaken to compare the response times under conditions of low and high pressure (within subjects factor of physical pressure: low pressure, high pressure) broken down by the odd ratios presented in the trial (within subject factor of odds ratio: 1:9, 2:8, 3:7, 4:6). This part of the analysis was collapsed across the ascending and descending trials as the presentation and selection of bets occurred after these variables were recorded.

In order to explore gambling behaviour in decision-making under risk the mean percentage number of points bet on the task were analyzed. This analysis included trials in which participants chose the most likely outcome in order to not confuse betting behavior and decision-making. A three way mixed ANOVA was used to compare the amount of points bet for ascending and descending trials (within subject factor point presentation: ascending, descending) under conditions of high and low physical performance pressure (within subjects factor of pressure: low performance pressure, high performance pressure). A between subject factor of gender was included (male, female), due to previous work that has shown gender to influence risk taking under pressure. Overall, higher gambles are indicative of increased risk taking, a large difference in the amount bet on ascending compared to descending trials is indicative of impulsivity.

Lastly, a measure of risk adjustment was derived from the data and a paired t-test was performed to compare the degree of risk adjustment under conditions of low and high physical pressure.

***Visual Search Task*:** Mean reaction times and error rates were analyzed for target absent and target present trial types of each set size. A repeated measures ANOVA was undertaken to compare performance of the task under conditions of low and high mental pressure (within subjects factor of pressure: low pressure, high pressure), for target-absent and target-present trial types (within subjects factor trial type: target-present, target-absent) broken down by set size (within subject factor: set size 3, 6 and 9). Reaction times for correct responses only were included in the analysis.

Correlation analysis assessing performance across task: As performed in previous chapters, the following analysis was undertaken to examine whether individuals' responses to pressure were consistent across tasks. The difference under pressure score was calculated for key indicators of task performance, by subtracting the score under high pressure from that under low pressure. The variables chosen for indicators of task performance are; the average adjusted number of pumps on the BART (a positive score represents better performance under pressure), the reaction time on the Visual Search task (a negative score represents better performance under pressure) and the risk adjustment score on the CGT (a positive score represents better performance under pressure). The difference under pressure scores were compared, using Pearson Correlation Coefficient, in order to examine whether participants showed a consistent response to pressure across tasks.

Applicability of group data to individuals: In order to explore the degree to which group data applies to individuals the number of athletes whose change under pressure showed an 'average' response to pressure across the three tasks was assessed. In accordance with previous work an average response was calculated as a score that fell within 1 standard deviation of the mean (0.5 SD above and below) (Daniel, 1952; Rose, 2016) for the average adjusted number of pumps on the BART, the reaction time on the Visual Search task and the risk adjustment score on the CGT.

8.4. Results

8.4.1. Dual Task Performance

In the mental pressure condition the average number of words that junior-elite athletes recalled were 8.5 (with a range of 3-16). On two occasions the participants scored less than four correct items. There were no significant differences between the three tasks on the amount of words recalled ($F_{(2,32)}=2.33$, $p=0.11$). Therefore the junior-elite athletes were performing the concurrent verbal memory task consistently across the decision-making tasks in the mental pressure condition.

8.4.2. Effect of Mental Pressure on the BART

In order to examine whether decision-making changes under conditions of low and high mental pressure, performance was assessed across the three decision-making tasks. Firstly on the BART the mean adjusted number of pumps was analyzed as a measure of risk taking under uncertainty (see **Figure 8.3**). The ANOVA revealed no effect of mental pressure ($F_{(1,15)}<0.01$, $p=0.94$) and no effect of gender ($F_{(1,15)}=0.77$, $p=0.39$), while there was a significant main effect of balloon number ($F_{(1,15)}=14.42$, $p<0.05$). In addition, there was no interaction between mental pressure and balloon number ($F_{(1,15)}=0.95$, $p=0.34$), mental pressure and gender ($F_{(1,15)}=0.98$, $p=0.34$), or balloon number and gender ($F_{(1,15)}=3.76$, $p=0.79$). Finally there was no three way interaction between mental pressure, balloon number and gender ($F_{(1,15)}<0.01$, $p=0.99$). Therefore in this sample of junior-elite athletes, mental pressure did not induce any significant changes in the degree of risk taking on decision-making under uncertainty. However it was found that the average adjusted number of pumps was higher for the latter half of the task (mean: balloon number 1-10: 27.27; balloon number 11-20: 34.01), this reflects the usual learning effects found on this task.

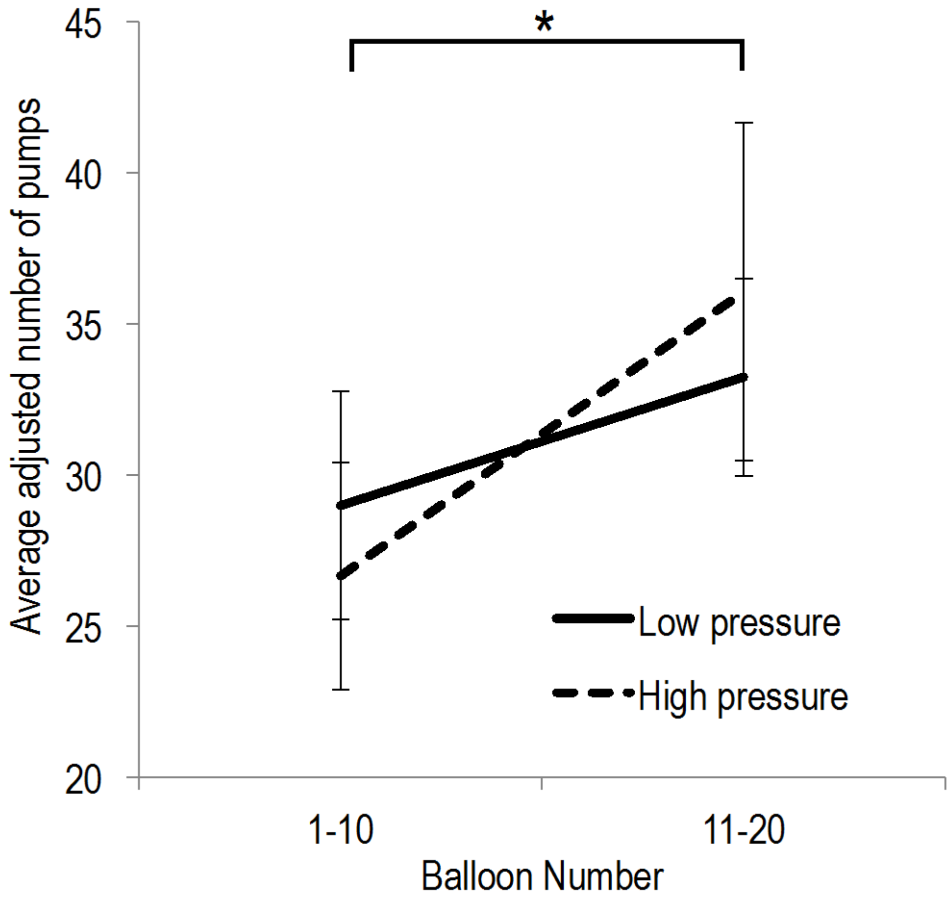

Figure 8.3: BART results: In junior-elite athletes there was no significant effect of mental pressure on the mean adjusted number of pumps. There was a significant effect of balloon number, with a higher pump count for the last half of the task. *denotes statistical significant at $p<0.05$. Error bars represent SEM.

8.4.3. Effect of Mental Pressure on the CGT

Reaction Times: Next, the following analysis examines the influence of mental pressure on the CGT. For this a number of different performance measures were analysed. First a repeated measures ANOVA performed on response times (**Figure 8.4A**) revealed no significant effect of pressure ($F_{(1,16)}$=0.44, p=0.52), but a significant effect of trial ratio ($F_{(1.79,28.60)}$=4.68, p=0.02). Pairwise comparisons revealed that the response times for trials with 1:9 ratios (mean: 1749.77 ms) were significantly quicker than those with 6:4 (p<0.05) (mean: 2369.50 ms) and 2:8 (p<0.01) (Mean: 2149.72 ms). There was no significant interaction of mental pressure and trial ratio ($F_{(3,48)}$=1.30, p=0.28). This indicates that junior-elite athletes respond faster when the trial odds ratios were higher, but mental pressure had no effect on the time taken for participants to indicate a simple probabilistic choice on this task.

Error Rates: Next a repeated measures ANOVA was performed on the number of errors made on the task (% number of trials in which the participant chose the most likely box colour) (**Figure 8.4B)**. There was no significant effect of mental pressure ($F_{(1,16)}$=0.83, p=0.37) or trial ratio ($F_{(1.41,22.49)}$=2.45, p=0.12) and no interaction of mental pressure and trial ratio ($F_{(1.65,26.35)}$=0.18, p=0.80). Therefore the accuracy of junior-elite athletes was not affected by mental pressure or by different odd ratios presented in the trial.

Number of points gambled: Following this a mixed ANOVA was performed on the mean percentage points gambled. This revealed no effect of mental pressure ($F_{(1,15)}$=0.36 p=0.56) or gender ($F_{(1,15)}$=1.21, p=0.29), but a significant interaction of mental pressure and gender ($F_{(1,15)}$=5.41, p=0.03). Post hoc independent t-tests revealed that under pressure there were significant differences at a trend level (p<0.1) between male and female junior-elite athletes ($t_{(13.68)}$=2.04, p=0.06), whereby male athletes bet more points compared to female athletes under pressure (mean points bet (%): females= 56.8%; males= 68.5%). At baseline there were no differences between male and female junior-elite atheletes (mean point bet (%): females= 61%; males= 60%) (equal variances assumed: $t_{(15)}$=-0.25, p=0.81) (**Figure 8.4C).**

There was also a significant effect of point presentation ($F_{(1,15)}$=37.67, p<0.01), whereby a higher number of points were gambled on ascending compared to descending trials (mean points bet (%): ascending= 39%; descending= 84%). This large difference is indicative of motor impulsivity, as junior-elite athletes did not wait patiently on ascending trials for the points to increase. Lastly there were no other significant interactions, including no interaction of point presentation and gender ($F_{(1,15)}$=1.83, p=0.20) or mental pressure and point presentation ($F_{(1,15)}$<0.01, p=0.97), or a three-way interaction between mental pressure, point presentation and gender ($F_{(1,15)}$=0.27, p=0.61).

Risk Adjustment: A paired t-test revealed there were no differences in the measure of risk adjustment between conditions of low and high mental pressure ($t_{(16)}$=-0.09, p=0.93) (**Figure 8.4D)**, therefore the tendency for junior-elite athletes to modify the amount bet according to the different reward and loss contingencies were not influenced by conditions of high mental pressure. Junior-elite athletes scored poorly on this measure consistently.

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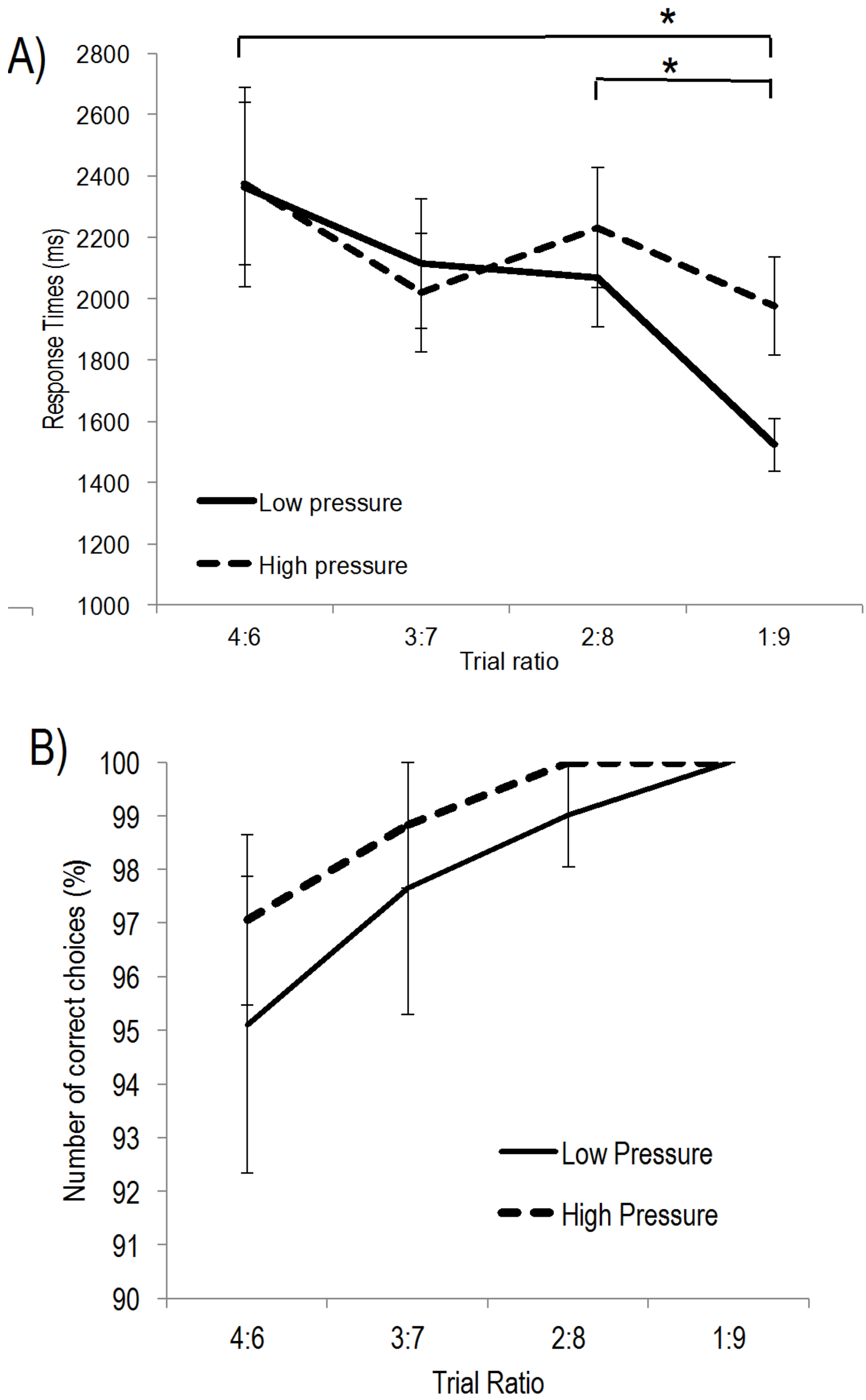
A)
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Trial ratio
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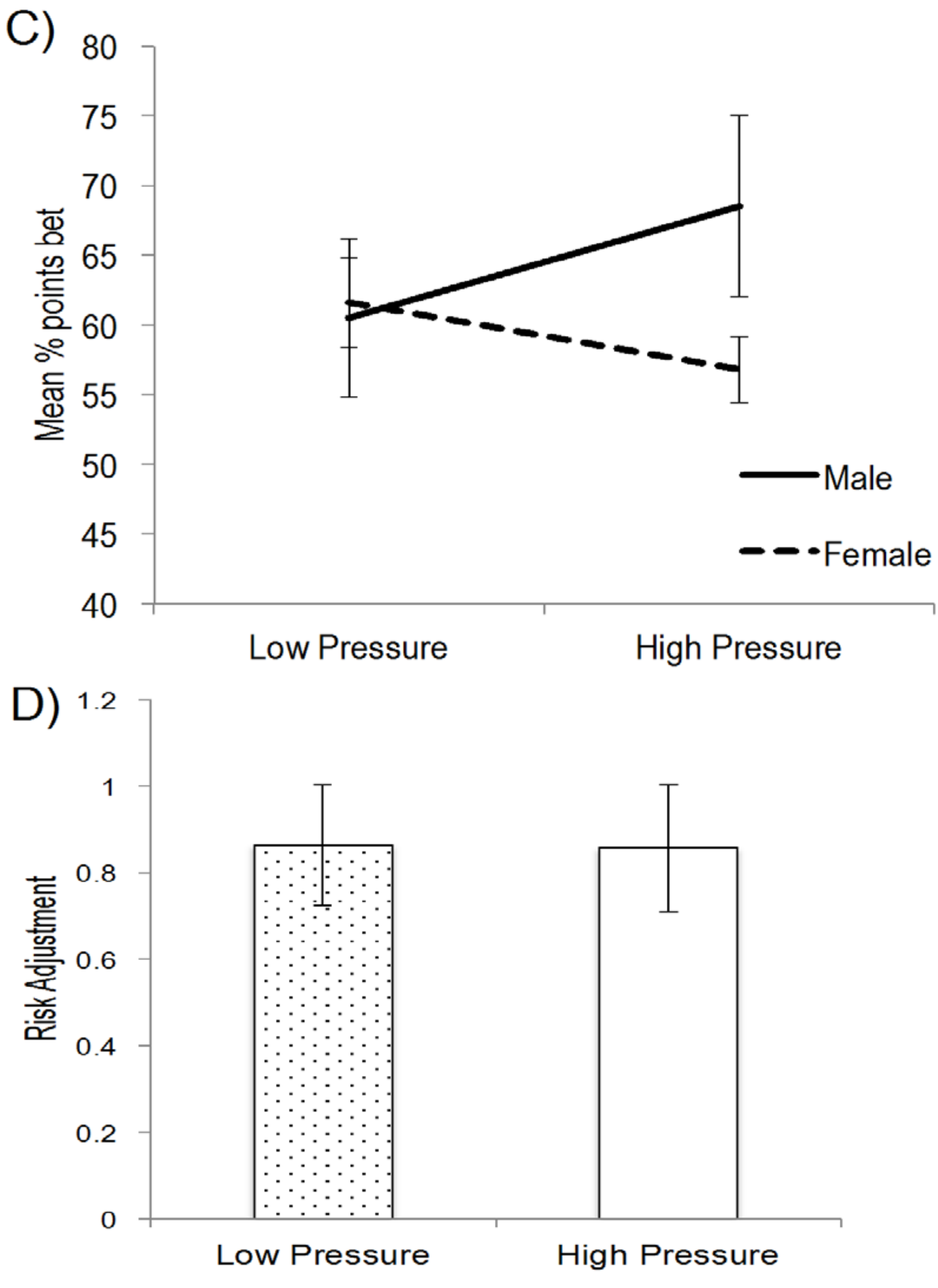

Figure 8.4: CGT results continued C) There was a significant interaction of mental pressure and gender on the amount of points gambled. Under mental pressure the amount bet was higher for male compared to female athletes at a non-significant trend level ($p<0.1$). **D)** There was no effect of mental pressure on risk adjustment. * denotes statistical significance at $p<0.05$. Error bars represent SEM.

8.4.4. Effect of Mental Pressure on the Visual Search Task

Reaction Times: The reaction times on the visual search task (from trial onset to participant indicating the presence or absence of an object), were analyzed (**Figure 8.5**a). Repeated Measures ANOVA revealed an effect of mental pressure on reaction times ($F_{(1,16)}$=5.30, p=0.03) and junior-elite athletes were slower to respond under conditions of mental pressure (mean: low pressure: 824.90ms; high pressure: 969.05ms). There was also a significant effect on the time taken to respond to trials when the target was present or absent ($F_{(1,16)}$=8.11, p=0.01), and the athletes were faster to respond when the target was present (mean: target present: 855.08 ms; target absent: 938.87 ms). Lastly, there was a significant effect of set size ($F_{(2,32)}$=23.18, p<0.01), pairwise comparisons revealed that junior-elite athletes were significantly faster at responding for set sizes of 3, than set sizes of 9 (p<0.01) and set size of 6 (p<0.01), and significantly faster at responding for set size 6 than set size 9 (p<0.01) (Mean response time: set size 9: 651.23ms; set size 6: 893.78ms; set size 3: 845.91ms).

There were no significant interactions of any of the main effects, including mental pressure and trial type ($F_{(1,16)}$ =0.86 p=0.37), mental pressure and set size ($F_{(2,32)}$=0.12, p=0.88), and of set size and trial type ($F_{(2,32)}$=0.53, p=0.59). There was also no three way interaction of mental pressure, set size and trial type ($F_{(2,32)}$=0.32, p=0.73).

Error Rates: Repeated measures ANOVA revealed that there was no significant main effect of mental pressure on the number of correct responses on the visual search task ($F_{(1,16)}$<0.01, p=0.94) (see **Figure 8.5**b). There was also no effect of set size on the number of correct responses ($F_{(2,32)}$=0.28, p=0.76) and no effect on whether the target was absent or present ($F_{(1,16)}$=0.93, p=0.35) on the number of correct responses. Moreover there were no interactions between any of the main effects including, between mental pressure and trial type ($F_{(1,16)}$=1.79, p=0.68), mental pressure and set size ($F_{(2,32)}$=0.77, p=0.47), or trial type and set size ($F_{(2,32)}$=1.83, p=0.18). There was also no three way interaction of mental pressure, trial type and set size ($F_{(2,32)}$= 1.85,p=0.17).

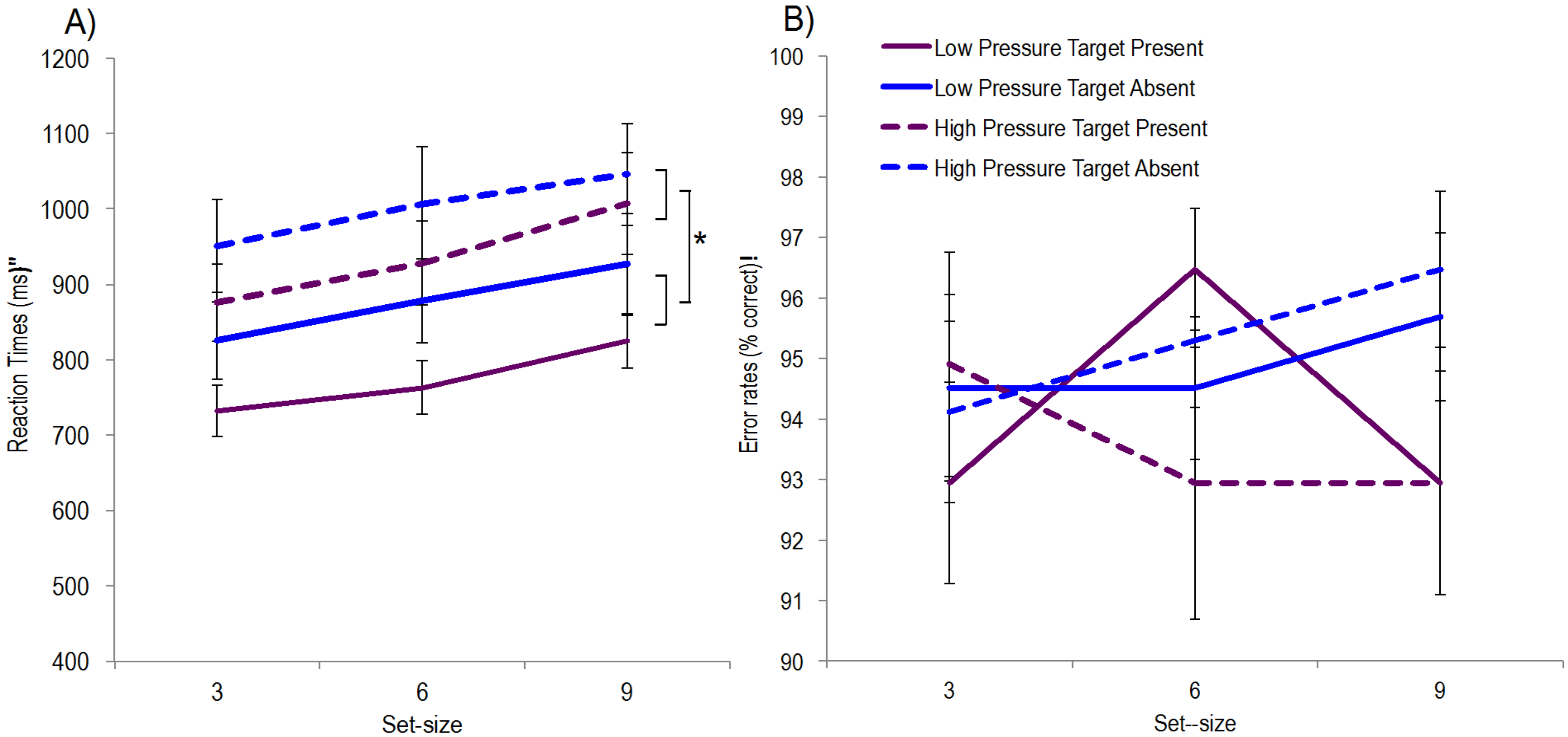

Figure 8.5 Visual Search task results: A) Reaction times: Under high mental pressure junior-elite athletes were slower to respond. There were also faster reaction times when the target was present and when set size was smaller (not marked on the graph) **B) Error rates:** There were no differences in the number of errors made under conditions of mental pressure. * denotes statistical significance at $p<0.05$. Error bars represent SEM.

8.4.5. Correlations of Performance Under Pressure Across Tasks

Pearson Correlation Coefficient were undertaken to examine whether individual responses to pressure were consistent across the key indicators of performance on the three decision-making tasks. The results showed that there were no significant correlations between the degree of change under pressure on performance of the BART and the CGT ($r_{(16)}$= -0.03, p=0.90), on the BART and Visual Search ($r_{(16)}$= 0.08, p=0.76). There was also no significant correlation on performance of the Visual Search task and the CGT ($r_{(16)}$=-0.36, p=0.17). Therefore, individual participants' responses to pressure were not consistent across key indices of decision-making over the three tasks.

8.4.6. Representativeness of Group Data

In order to explore the degree to which group data applies to individual athletes, the number of athletes who showed an average response (defined as falling within 0.5 SD above and below the mean) to pressure across all three tasks was assessed. In line with previous work (Daniel, 1952; Rose, 2016), this categorization meant that at least the middle 35% of the group were categorized as falling within the 'average' range for each variable. The results revealed that there were no athletes who showed mean responses to pressure across all three indices of decision-making. As the group average scores were not representative of the behaviour of a single individual athlete across the three measures, this highlights the importance individualized profiling of results in an elite sport setting.

8.5. Discussion

The study examined the effects of mental pressure on key indicators of decision-making in junior-elite athletes. Results revealed that fast reactive responses to perceptual stimuli were slower in junior-elite athletes under conditions of mental pressure. Decision-making under risk, where reward and loss contingencies were explicit, were also influenced by mental pressure. In particular there was an interaction of mental pressure and athlete's gender, whereby under pressure male athletes showed higher levels of risk taking than female athletes. For decision-making under uncertainty there was no influence of mental pressure on risk taking.

The findings of the current study show that in junior-elite athletes mental pressure impaired fast reactive responses to perceptual stimuli. In particular, athletes were slower to identify the presence or absence of an item in a visual array. This slowing was seen to be similar across trial types, and while reaction times were also increased for larger set sizes and when the target was absent (compared to present), there was no interaction of these factors with mental pressure. The findings of increased reaction times under conditions of mental pressure have also been reported in non-elite adult athletes on sport specific decision-making tasks (Hepler, 2015; Kinrade, Jackson, & Ashford, 2015). In line with this, visual search strategies have also been reported to become more erratic in athletes under competitive pressure, in that eye movements show an increased number of fixations for shorter duration (Liu & Zhou, 2015) and a decreased ability to detect peripheral stimuli (Janelle & Singer, 1992). Deployment of visual attention plays an important role in sport whereby the athlete is responsible for monitoring a dynamic environment consisting of multiple players (Williams, Davids, & Williams, 1999), moreover visual attention has shown to differentiate the performance of novice and expert athletes (Alves et al., 2013).

Mental pressure was also found to influence decision-making under risk where probability outcomes were explicit. In particular there was an interaction of mental pressure and gender on the amount of points gambled on the CGT. Under mental pressure male junior-elite athletes showed a higher level of risk taking than females (although post hoc comparisons only reached a non significant trend level $p<0.1$). These respective shifts in the propensity for risk taking across genders have also been reported following acute physical exercise in non-elite adult athletes (Pighin et al., 2015), as well as in a number of studies examining the influence of stress (experimentally induced elevated cortisol levels) on decision- making (Lighthall et al., 2009; 2013; Preston et al., 2007).

The mechanisms underlying the gender related shifts in risk taking are unknown, however the main theories put forward are evolutionary in particular differences in intrasexual selection (Pighin et al., 2015). One study reported elevated cortisol to elicit opposing responses at a neural level in males and females performing a decision-making task (Lighthall et al., 2012). Under stress males showed increased activation in the insula and putamen, regions associated with risk estimations, but decreased activation in females. Moreover increased activation of the dorsal striatum was strongly associated with increased reward collection in stressed males, but not in stressed females (Lighthall et al., 2012). The differences observed here may therefore be a result of elevated cortisol in response to mental stress.

Lastly mental pressure did not affect risk taking for decision-making under uncertainty, as indicated by the mean adjusted number of pumps on the BART. Robust performance of decision-making under uncertainty to mental pressure has been reported previously (Turnbull et al., 2005). The differences observed here in comparison to those for decision-making under risk may be due to differences in underlying task requirements. In particular in the current study, mental pressure was operationalized as a dual working memory task. This protocol was used to mimic task irrelevant thoughts, such as worrying, that consume cognitive resources, diminishing those available for the task in hand. It has been proposed that decision-making under risk is particularly vulnerable to mental pressure as these tasks rely heavily on working memory resources, whereas decision-making under uncertainty is unaffected by mental pressure as they rely to a greater extent on automatic intuitive processing (Starke et al., 2011). In relation to sport these findings suggest that the influence of mental pressure may be particularly heightened when the junior-elite athlete is in a novel situation that places high demands on executive processing resources (Beilock & Gray, 2007). One line of argument that proposed that individuals with high working memories are most detrimentally affected by mental pressure (Beilock & Carr, 2005), may have hinted that the performance decrements of mental pressure reported in the literature in adult populations are less severe in this age group who have reduced working memories. However the overall pattern of results reported here are similar to those in previous studies in adults.

The findings from the current study also showed that there was no correlation in the degree to which junior-elite athletes changed under pressure across key performance indicators on the three tasks. This indicates that the influence of mental pressure was not uniform across decision-making abilities in these athletes. In particular an athlete who showed robust performance under pressure on one task or ability did not necessarily show similar improvements under pressure on a different task or ability. This reiterates the importance of examining a range of different measures of decision-making in order understand performance under pressure in athletes. Importantly it highlights that understanding the unique strengths and weaknesses across a number of abilities together with the use of profiling individual athletes may be particularly insightful.

A key aim of the current work was also to examine how these insights in decision-making can be applied in an elite sport context; and in this case how this can be tailored to athletes at a junior level. As in previous chapters the application of this work centered upon the decision-making taxonomy, including explanations of decision-making constructs using analogies. By this point, the elite athletes and semi-elite athletes of chapter 6 and 7 (all of whom were from the same sport) had applied the concepts represented by the tasks to their sport that proved useful here. Again the taxonomy was useful in developing the idea that decision-making is not a single concept, but instead is comprised of disparate skills and scenarios. A second aim was to provide a common language by which decision-making skills can be conceptualized and communicated between sporting professionals.

In line with previous chapters, the results of this chapter also highlight the limitation of statistical approaches based on group averages in an elite sporting context. In particular there were no elite- junior athletes who showed an 'average' response to pressure across all types of decision-making. This again highlights that applying results based on group means to individual junior-elite athletes in the large majority of cases is unlikely to be useful. In order to help the junior-elite athlete use this taxonomy, instead of feeding back position ranking within the sample of athletes tested, it was thought to be more appropriate to provide descriptions of decision-making styles under conditions of low and high mental pressure, for example; under pressure you were best at 'gun-slinging' decision-making and under low pressure you best at 'poker-playing' decision-making.

As the junior-elite athlete is at the beginning of their training on elite programs, it could be argued there is more scope to embed decision-making education within their development. Historically when training an athlete the onus is placed on the improvement of physical ability, while psychological attributes involved in sporting performance receive less attention with the underlying assumption that they develop intuitively with practice (Furley & Wood, 2016). Therefore in this group of junior-elite athletes there was greater emphasis on the development of the coach, who also performed the decision-making tasks and received individual feedback on their own decision-making performance within the taxonomy.

8.6. Conclusion

In conclusion, mental pressure affected the risk-taking of junior-elite athletes for decision-making where probability outcomes were explicit, while there was no effect for decision-making under uncertainty. Moreover under mental pressure elite junior athletes showed slower reaction times to perceptual stimuli. Mental pressure, operationalized as increased cognitive load to mimic task irrelevant thoughts, may have consumed working memory, impairing decision-making scenarios that require these resources. Mental pressure may also have had a detrimental impact on the allocation of attention in visual search. In relation to sport these findings suggest that novel situations that place high cognitive demands on the athlete may be particularly influenced by mental pressure. In order to develop understanding of decision-making within this sample, there was a greater focus on the coach, who also undertook the protocol for education purposes.

9. General Discussion

This thesis had the translational goal of understanding and increasing insight into the decision-making processes of elite athletes. It focused in on two areas: Firstly, the utility of tES methods as a tool for modifying decision-making was explored, to assess the potential for use in decision-making training in athletes; Secondly, the influence of performance pressure on decision-making across different developmental stages of elite sport was examined. The key findings, limitations and implications for this work are summarized below.

9.1. tES Work

9.1.1. Principle Findings

There have been a number of proposals for the application of tES techniques in sport to enhance abilities that underlie peak performance (Banissy & Muggleton, 2013; Okano et al., 2015; Reardon, 2016; Vitor-Costa et al., 2015). Before findings could be generalized beyond the laboratory, it was important to establish the reliability of behavioural effects in the cognitive neuromodulation literature. In chapter 3, the ability of tDCS applied to the DLPFC to modulate risky decision-making was assessed via conceptual replication of Fecteau et al., (2007). In this case, tDCS was found to have no effect on decision-making; this finding added to two further studies that also reported no effect of tDCS on performance of the BART (Cheng & Lee, 2016; Weber, Messing, Rao, Detre & Thompson-Schill, 2014). Together, these findings raise doubt about the efficacy of tDCS to modulate decision-making and, in chapter 4, the mechanistic basis of this failure to replicate was explored. The physiological effects of tDCS (chapter 4) and, later, hf-tRNS (chapter 5) were examined using parameters common in the application of these techniques. The findings from these chapters revealed that the effects of tES are fragile to changes to stimulation parameters. Our understanding of the polarity dependent shifts in corticospinal excitability induced by tDCS comes from work that has applied stimulation using unilateral electrode arrays at 1mA (current densities of 0.029mA/cm^2). In the application of tDCS for cognitive neuromodulation, researchers have deviated from these parameters; for example, in Fecteau et al., (2007), tDCS was applied using bilateral montages at

2mA (current densities of 0.057mA/cm^2). Despite these divergent parameters, the assumption that tDCS is exerting anodal-excitatory/cathodal-inhibitory effects remain. Fecteau et al., (2007) proposed that reductions in risky decision-making resulted from concurrent excitation and inhibition of bilateral DLPFC. The findings from chapter 4, however, reveal that anodal and cathodal tDCS delivered with bilateral electrode arrays (at 1 and 2mA) did not induce respective excitatory or inhibitory effects on corticospinal excitability. Therefore, this guiding assumption is undermined in studies which apply stimulation with these parameters - which accounts for a large majority of the cognitive neuromodulation literature (e.g., Boggio et al., 2010; Cohen Kadosh, Soskic, Iuculano, Kanai & Walsh, 2010; Fecteau et al., 2007; Snowball et al., 2013). All but one study - Beeli, Koeneke, Gasser and Jancke (2008) – examining decision-making and tDCS have applied stimulation via bilateral electrode montages.

Similarly, in chapter 5, the assumptions that underpin the application of an emerging neuromodulatory technique – tRNS - were examined. Again, the findings of this chapter reveal that the characteristic excitatory effects established when hf-tRNS was delivered with unilateral electrode arrays for 10 minutes (Terney, Chaieb, Moliadze, Antal, & Paulus, 2008), do not withstand deviations from these parameters. Using parameters common in the application of this approach, namely bilateral montages and durations of 20 minutes, hf-tRNS was not found to exert consistent excitatory shifts in cortical excitability. Again, the assumption embedded in much of the literature is that the excitatory effects remain, despite divergent stimulation parameters (e.g.: Cappelletti et al., 2013; Chawke & Kanai, 2015; Popescu et al., 2016; Romanska, Rezlescu, Susilo, Duchaine & Banissy, 2015; Vanneste, Fregni & De Ridder, 2013). These findings are in line with several other demonstrations from the physiological sciences, which have highlighted the importance of stimulation parameters in determining the effects of tES. In particular, the importance of electrode montage was demonstrated in one of the earliest studies in the tES field: Nitsche and Paulus (2000) explored electrode placement in assessing the rapid induced effects of weak DC stimulation. Here, the unilateral electrode array produced the most robust effects and, thus, it persisted as convention in subsequent studies (Nitsche & Paulus, 2000). The effects of tES techniques have also been reported to not be present using extra-encephalic montages, when the reference electrode is placed off the head (Moliadze, Antal & Paulus, 2010). In addition, the unilateral and bilateral electrode montages have also been shown to induce differing effects on functional connectivity, as assessed by fMRI (Lindenberg, Sieg, Meinzer, Nachtigall & Flöel, 2016; Sehm, Kipping, Schäfer, Villringer & Ragert, 2013); while computational modelling work has suggested that differences in inter-electrode distance between these two montages may influence the spatial locality, depth and the amount of current reaching the cortex (Bestmann, de Berker & Bonaiuto, 2015; Datta et al., 2010; Faria, Hallett & Miranda, 2012; Miranda, Faria & Hallett, 2009). Moreover, there have been other indications that duration is an important factor in determining the effects of brain stimulation techniques; in particular, longer durations of anodal tDCS (Paulus, Antal & Nitsche, 2013) and TBS (Gamboa, Antal, Moliadze & Paulus, 2010) change the induced effects from excitation to inhibition.

Together, the results showed: i) A failure to replicate the behavioural findings of Fecteau et al. (2007) of tDCS modulating risky decision-making, within the wider context of a number of other non-replications (Cheng & Lee, 2016; Fecteau et al., 2014; Horvath et al., 2015; Minati, Campanhã, Critchley & Boggio, 2012; Weber et al., 2014); ii) Findings that undermine the physiological assumptions upon which much of this work is predicated. The assumption of anodal-excitation/cathodal-inhibition with tDCS, or corticospinal excitation with tRNS, was not supported using parameters common in the cognitive neuromodulation field. These assumptions are fundamental in that they guide study design and are used to interpret results. As such, the results of chapters 3, 4 and 5 undermine the original proposal of tES for cognitive neuromodulation, suggesting that these techniques are not robust enough to warrant application in elite athletes at this time.

9.1.2. Implications

The results from these three chapters led to unintended implications of advancing our understanding of tES, In particular in highlighting that parameters used in the application of these techniques should be based on the parameters used to establish the physiological effects. At present, studies in the cognitive neuromodulation field have wrongly extrapolated the physiological findings of tES to all work that applies stimulation regardless of the parameters used. In particular, it is clear that there are two fundamental principles held by the literature (which are more like historical accidents) that may not be true. Firstly, that anodal is always excitatory and cathodal always inhibitory. In addition to the work here, there are several reasons or examples of other cases where this is not true; for example, the non-homogenous morphology of the brain and likelihood of current clustering within certain structures is likely to create both increased and decreased excitation under each electrode (Bestmann et al., 2015). In addition Batsikadze, Moliadze, Paulus, Kuo & Nitsche (2013) showed cathodal tDCS, delivered at 2mA (current density 0.057mA/cm^2), induced excitatory shifts in corticospinal excitability. The second principle held by the literature is that the effects of tES are linear - i.e., in relation to intensity and duration. The data presented here joins other examples of when this has not been the case (Batsikadze et al., 2013; Gamboa et al., 2010).

A number of studies have highlighted concerns of non-replicability in relation to the application of tES approaches in its application for cognitive neuroenhancement (Horvath et al., 2015; Riggall et al., 2015; Sahlem et al., 2015; Vannorsdall et al., 2016). For instance, a recent meta-analysis found there to be no evidence of cognitive effects in healthy populations from single-session tDCS (Horvath et al., 2015); however, the selection criteria for this meta-analysis have been criticized (Price, McAdams, Grossman & Hamilton, 2015). Further, a recent study into researchers perspectives in this area highlighted non-reporting of negative findings and weak methodological rigor as issues facing the field (Riggall et al., 2015). The physiological findings of chapter 4 and 5 may provide an explanation for other non-replication results within the literature.

9.1.3. Future Directions

These findings highlight avenues for future work, in particular the importance of a more detailed examination of the physiological effects of tES techniques; not only at parameters used in application, but also whether these extend to other groups, such as older adults and atypical populations. Additionally, an examination of whether the physiological effects of tES remain unchanged when applied to the brain's non-resting state; i.e., while engaged in a cognitive task.

9.2. Decision-Making Under Pressure in Elite Athletes

9.2.1. Principle Findings

The second part of the thesis examined the influence pressure has upon indices of decision-making across three developmental stages of elite sport. In chapters 6 and 7, the influence of physical exhaustion was examined. In chapter 6, world-class elite athletes who have had frequent success on the international stage (including six Olympic medal winners) were shown to have faster reaction times in response to physical pressure. Physical pressure was also found to increase risk taking when reward and loss contingencies were explicit (on the CGT), but did not affect risk taking when probability outcomes were unknown (on the BART). There was also no change to a measure of risk adjustment under high pressure; thus, despite an increase in risk taking, elite athletes retained the ability to use information relating to the decision to appropriately modify behaviour. Overall, in elite athletes, this may indicate a calculable shift towards risk taking and resilience to physical pressure.

In chapter 7, a different pattern of behaviour was observed in response to physical exhaustion in semi-elite athletes. These athletes were enrolled on a Team GB talent development program, training for possible Olympic competition in four to eight years. In response to physical exhaustion, there was increased risk taking for both decision-making, where probability outcomes were explicit (on the CGT) and unknown (on the BART). In addition, semi-elite athletes showed a significant reduction in the ability to adjust gambles, according to probability ratios and, thus, use information to appropriately modify one's propensity for risk. Together with the increase in risk taking and a decrease in responsiveness to ideal risk-taking scenarios, this may indicate a sub-optimal shift towards risk taking. In addition, under physical pressures, there were no changes to fast reactive responses to perceptual stimuli and response inhibition on the SSRT.

In chapter 8, the influence of mental pressure was examined in junior-elite athletes who are at the earliest stage of entry to elite sport - a first in athletes of this age and expertise level. Mental pressure caused an increase in reaction times. For decision-making, where reward and loss contingencies were explicit (on the CGT), there was an interaction of gender and mental pressure; males showed an increase and females a decrease in risk taking. Mental pressure had no effect on decision-making under uncertainty (on the BART).

Together, the findings from these chapters highlight two points: Firstly, when studying decision-making in sport, it is important to consider context in which athletes operate. Almost all prior work in this area has examined decision-making without consideration of the mental or physical pressures of performance that the athletes encounter, while the findings in the thesis have demonstrated these to have an influence on the decision-making of even those with high levels of expertise. This oversight in much of the work is surprising, considering the anecdotal importance that performance under pressure has in sport. For example, reports from elite coaches describe the technical and physical differences between elite athletes as minimal, that the distinguishing feature is one’s ability to consistently make optimal choices on the day under the pressure of competition (Thelwell, Harwood & Greenlees, 2016).

Indeed, almost all the work that has considered the influence of performance pressure on decision-making has been undertaken with non-elite athletes. A second important point of conclusion to discern from this thesis is that expertise may be crucial in determining how decision-making is influenced by performance pressure; that results from non-elite athletes may not be representative of elite athletes. The findings of faster response times under physical pressure in elite athletes aligns with a previous review, which reported athletes with greater expertise to show more facilitation in reaction times in response to performance pressure. The findings of the semi-elite athletes who did not show reaction time facilitation under physical pressure may allude to the variation of abilities at the elite athlete level. This variation, due to the broad definition of expert athletes, could not be discerned from the Schapschroer et al. (2016) review. Thus, the findings here extend these observations - to those competing at the highest elite standard. This latter point emphasizes a broader criticism of sport expertise psychology and of the wide inclusion criteria of an elite athlete; in previous studies, this ranges from Olympic champions to those included in university sports teams (Swann et al., 2014). This may be masking the nuance of abilities at the elite level and unmasking this is one of the successes of the current thesis.

In relation to risk taking, different patterns of decision-making were also evident in elite and semi-elite athletes, with a shift towards indiscriminate risky decision-making in semi-elite athletes under conditions of physical pressure. Modulations to risk taking have also been reported in previous work following laboratory protocol that elevate cortisol (Lighthall et al., 2009; Preston, Buchanan, Stansfield & Bechara, 2007; van den Bos, Harteveld & Stoop, 2009) and in responses to physical exertion (Black et al., 2013; Pighin et al., 2015). The gender differences reported in non-elite athletes in response to physical pressure, such as the increased risk taking in males and decreased risk taking in females, were not reported in elite and semi-elite athletes. The shift towards more cautious decision-making was not evident in elite and semi-elite females. Again, these differences indicate the failure of transfer between work undertaken in elite and non-elite athletes. There was, however, a gender-by-stress interaction in the level of risk taking on the CGT in junior-elite athletes; males showed higher levels of risk taking under pressure in comparison to female athletes. Although comparisons should be made with caution, due to differences in the stress induction protocol used in these studies, it is of interest that across all three groups there were modulations of some sort in risk taking as a response to pressure. This highlights that further investigations into how changes in risk taking on these tasks directly relate to sporting performance are warranted.

Differences in terms of expertise may underlie the observations between elite and semi-elite athletes. The world-class elite athletes have at least five years' more experience than their semi-elite athletes and, therefore, more experience in the coupling of decision-making and stress. In line with this, previous work has shown decision-making competencies within sport develop with expertise (see section 2.5.3), as well as that expertise modifies responses to physical pressure (Schapschroer et al., 2016). The elite and semi-elite athletes also differed according to age, which may also allude to the differences observed here (mean age = Elite: 28; Semi-elite: 20). There are marked changes in behavioural, cognitive and neuronal development that occur as one transitions from adolescence to adulthood - which will influence decision-making (Blakemore & Robbins, 2012) - and these changes do not cease until the mid-20s (Arain et al., 2013). The finding of increased indiscriminate risk taking under pressure may be reflective of adolescence being a time of increased risk taking in relation to adults, which is thought likely to arise from a heightened responsiveness to incentives. They may also be reflective of structural and functional brain differences relating to cognitive control between adolescence (18-19 years) and young adults (25 years) (Veroude, Jolles, Croiset & Krabbendam, 2013). In addition, differences in adolescence, in terms of increased stress volatility, have been reported and, thus, the influence of pressure may be more marked.

The junior-elite athletes also differed in terms of the type of pressure they were exposed to. When comparing reaction time measures under mental pressure, junior-elite athletes' reaction times were slower; while under physical pressure, elite and semi-elite athletes were either facilitated or remained stable. This may be due to the different mechanisms by which these types of stress exert their effects. For instance, improvements due to physical pressure have been linked to increases in physiological arousal (and increased cerebral blood flow) because of physical exertion (McMorris, Tomporowski & Audiffren, 2009). In addition, mental pressure may have a more pronounced influence, as this is congruent with the type of task performed (Hepler et al, 2015). However, direct comparisons with other chapters should be undertaken with caution, due to additional differences in terms of age and expertise in these samples. These observations highlight that direct comparison of different types of performance pressures in the same athletes would be an interesting avenue for further exploration.

9.2.2. Limitations

In addition to mapping the influence that performance pressure has on decision-making at various points of elite athlete development, a key aim of this work was in examining how psychology could be applied to increase insight into decision-making in an elite sport setting. Undertaken with a specialized sample group, this work has high ecological validity. However, in some instances, these goals were competing which required a number of compromises.

Firstly, there was no counterbalancing of low and high pressure conditions in chapter 6 and 7; therefore, when performing the tasks under high pressure, the elite and semi-elite athletes were also performing these for the second time. It was a necessary compromise due to the nature of working with elite athletes, to whom time and access were limited. Thus, testing was required to occur within a single session. While conditions could have been counterbalanced within a single session across participants, as undertaken with mental pressure in the junior-elite athletes, this was not undertaken due to the likely carry over effects of physical exhaustion. To reduce the influence of learning effects, attempts were made to choose tasks whereby performance was robust to repeated testing. However, one cannot be certain that improvements in task performance; for example, in the reaction times of elite athletes was not due to learning. Despite this, the comparison between elite and semi-elite athletes - who were subject to similar protocols - are valid. On the other hand, this limitation replicates exactly what athletes do: they perform the training and then under pressure – real-life is not counterbalanced.

The second limitation is that completion of maximal effort on the physical exhaustion protocol (in chapters 6 and 7) was inferred via self-reporting and observation. One could argue that the lack of an objective measure of physical exertion was a limitation. In this case, it was deemed reasonable to allow the elite athletes to exert themselves to the level they felt reflected the guidelines of maximal exertion. A key goal of the current work was to provide insights that would transfer to training and performance, therefore keeping formalization of the testing procedure to a minimum was important. During a performance, elite athletes exert themselves to their own recommendation because of their own investments and motivation, which was replicated in the current work. Notably, this population is very driven in comparison to the usual cohort of volunteers in psychology experiments. However, physiological measures - such as heart rate, blood lactate levels or cortisol levels - would have allowed further conclusions regarding the underlying mechanisms of the effects observed.

A third limitation relates to the selection of tasks. Standardized, well-validated measures were chosen to represent clearly defined psychological constructs relating to decision-making. The influence of stress on these measures has been well documented, as has the application of these across different age groups. While this gave the work laboratory-based confidence, how the performance on these tasks translates to decision-making in sport is unknown. Indeed, the tasks do not capture many aspects of sporting decisions, including their dynamic evolving nature, as well as the type (i.e., complex motor skill compared to button presses) and variability of response output required (i.e., unpredictability in response outcomes is key to successful decisions in sport).

In addition, the choice of task for fast reactive decision-making showed the progression of the work in this thesis, while a consistent measure would have been beneficial in terms of comparison across athletes. The Stroop task used in elite athletes was not the most appropriate measure to capture fast reactive responses. Thus, the Stroop task was replaced by the SSRT in the semi-elite athletes group. In the junior-elite athletes, the SSRT was replaced by the Visual Search task due to the perceived difficulty of the SSRT that incrementally increases accuracy to the level of 50%. In addition, the Visual Search task was used due to the interest in pattern matching in this population.

9.2.3. Application of Work to Elite Sport

The application of this work, to increase insight into decision-making in elite sporting professionals, was examined; this centred on several key themes, including the importance of individualized feedback, the development of a decision-making taxonomy, as well as aligning the work within the sporting culture.

9.2.3.1. The Importance of Individualized Feedback

In elite sport understanding the behavior of the individual athlete is paramount. This goal is in contrast to the majority of psychological research that makes statements about the average responses of groups of individuals. This approach has been criticized due to its inaccuracies regarding any one individual in particular; this has been termed 'the fallacy of the average individual' (Rose 2016).

In assessing how this information can be of use to elite sporting professionals, this thesis examined the representativeness of the results based on group means to individual athletes; doing so by assessing the number of athletes that showed an 'average' (defined as falling within 1 SD of the mean) response to pressure across the three categories of decision-making. In the elite and junior-elite cohort, there was no one individual athlete that presented an average response to pressure across the three indices of decision-making, while 16% of the semi-elite athlete cohort showed an average response to pressure. These findings highlight that applying results based on group means to understand the behaviour of the athletes would not be representative in most cases. It is surprising that this even needs to be said, but the pretense of translation from population to individual is perhaps the weakest link in all of sports psychology.

Therefore, the application of this work centered upon individualized profiling of athletes that were presented during feedback sessions, consisting of the elite athletes, coach, sports psychologists and a member of the research team. In addition to how the individual athlete performed under pressure, the feedback consisted of the average performance of the group, to provide context from which to interpret the behaviour of the individual. The profiling was beneficial in the insight it gave regarding the unique strengths and weaknesses of the athlete, in relation to the group, which would have been masked with application of group performance averages only. In the case of elite sport, it is likely to be this individuality that provides athletes with the competitive edge. In addition, the personalized nature of feedback meant that training interventions and tactical discussions could be tailored to the needs of individual.

9.2.3.2. The Development of a Decision-Making Taxonomy

Across the feedback sessions, a taxonomy of decision-making was developed, which provided a framework that could be used to conceptualize decision-making and tailored to the individual athlete. The taxonomy was based on the three types of decision-making assessed during the study. It was developed in conjunction with the coaches and athletes who provided sporting examples of the psychological constructs examined.

The taxonomy increased psychological insight in this population, a) by highlighting the notion that decision-making is not a singular concept and of the different types of decision-making scenarios. b) By offering the opportunity for coaches and athletes to apply psychological principles to their practice. And c) it also provided an accessible shared language by which sport professionals could use to understand their own, and others' decision-making, and communicate these constructs with one another.

In the application of this framework, a key challenge was in how best to communicate the different decision-making concepts to an audience with no prior knowledge of psychology; this centered on the use of analogies to represent concepts relevant to the type of decision-making, which provided accessible, easily memorable and terminology. Decision-making under risk on the CGT was described as 'poker playing', to represent a scenario in which one takes risks considering having information about the reward and loss probabilities - i.e. the cards in their hand. This type of decision-making was identified as most applicable to tactical decisions in sport. Regarding decision-making under uncertainty on the BART, this was described as 'playing chicken', with reference to a well-known game devised to test the nerve of each contender whereby two people drive straight towards each other; the first car to swerve (and, thus, miss a head on collision) is named the 'chicken'. As neither driver knows the behaviour of the other, this type of risk taking was thought a relevant metaphor for decision-making under uncertainty. In sport, this type of decision-making was common to dynamic play, where athletes make decisions - i.e., decide who to pass to - with incomplete knowledge relating to opponents' positions and intentions. Fast reactive decision-making has been described as 'gun slinging'; a shooting match whereby a person must shoot a target as quickly as possible but with the requirement to not hit innocent bystanders. These terms gave the decision-making tasks, undertaken by the athletes, real-world validity.

9.2.3.3. Acknowledging the Sporting Culture

A collaborative effort was needed for the successful application of this work, thus aligning the project within the sporting culture was necessary to increase 'buy-in' from coaches and athletes - this was done in a number of ways. Firstly, coaches were included from the inception of the project. They highlighted a need to increase insight in decision-making and the lack of formal training in these skills in their coaching practices; attributes that were often assumed to develop implicitly with practice. Moreover, the decision-making tasks used in this work were initially road tested with the coaches during a training day. This first-hand experience of the coaches was fundamental in the development of the decision-making taxonomy and, with the junior-elite coaches, the psychological insights were mainly targeted at the level of the coach. In addition, the perspective of decision-making under pressure aligned with the expertise of the sport psychologist - i.e. in helping athletes cope with performance anxiety and stress. Thus, the project was not solely targeted at an area of expertise traditionally thought to be the knowledge of the coach - i.e., tactical decision-making and allowed for the collaborative implementation of the project.

A key issue highlighted by coaches in the collaboration with scientists is the balance between the amounts of time that research takes away from training, in relation to the performance improvement gains (Farrow & Raab, 2008). Tangible performance gains are difficult to discern, especially at an early stage of a research project. One way to deal with this concern was to embed the current study as a training exercise within the given sport. Indeed, 'resilience training', whereby exercises are performed under adverse conditions to increase difficulty is common to the training of elite athlete, which has a similar ethos to the protocol applied in this setting. In line with this, the experimental protocol was designed to have a competitive component, in that gold, silver and bronze prizes (cash) were awarded to the top scorers on the BART; this even further increased engagement among the athletes who thrive on competition.

9.2.4. Future Directions

The work in this thesis has outlined guidelines of how psychology can be applied in an elite sport setting to improve insight into decision-making; these may be helpful in future collaborations between scientists and sports professionals.

In addition, the work here began to explore the influence that performance pressure has on decision-making, across different developmental stages of elite sporting expertise. There are many avenues for further exploration and improvement. The athlete is exposed to numerous sources of pressure during performance. In the current work, the influence of physical exhaustion and mental pressure were examined. Direct comparison of these types of pressure in the same athletes would allow a more detailed picture regarding the influence each has on decision-making, as would examining the effects of these types of pressure in combination (during competition they rarely present in isolation). The investigation of other sources of pressure may also be informative. One important pressure for the athlete not examined here is time pressure. The intensity of performance pressure could also be manipulated; to show the level of pressure needed for modulations in decision-making in these populations. To examine the underlying mechanism that may be responsible for pressure-related changes, physiological measures could be recorded - such as testosterone and cortisol. Lastly, an examination of how the measures of decision-making within the proposed taxonomy directly relate to decision-making in sport would also be useful in taking this work forward.

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