Haptic Choice Reaction Time in Elite Judo Competitors

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Dedication

I dedicate this thesis to my wonderful wife Lesley and my beautiful children Kostas and Yeoryia whose love gave me the strength to overcome the challenges on the way and made this journey a truly special one.

Αφιερώνω αυτήν τη διατριβή στην υπέροχη σύζυγο μου Λέσλι και στα πανέμορφα παιδιά μου Κώστα και Γεωργία των οποίων η αγάπη μου έδωσε τη δύναμη να ξεπεράσω τις δυσκολίες στη διαδρομή και έκαναν αυτό το ταξίδι πραγματικά ξεχωριστό.

"Ο άνθρωπος πολλά μπορεί να κατορθώσει με αγάπη ολόγυρα του"

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Abstract

Rapid reactions are an essential part of performance in most sports. In Judo the main route of information input is somatosensory, yet reaction studies have historically utilised visual or audio prompts. We have addressed the gap in knowledge pertaining to judoka's cognitive performance on a suitable reaction test. We have designed a Judo-specific reaction device with a sensory signal that is consistent with the stream of tactile feedback in Judo. We set up a study to evaluate this novel haptic choice reaction test device and found it to be valid and reliable. We found mean reaction time to haptic signals to be shorter compared to visual ones, which is consistent with findings reported elsewhere in scientific literature. We also found evidence of judoka having achieved consistently shorter mean reaction times to haptic signals than people with experience in sports where the dominant sensory input is visual. We then used the haptic device to collect reaction time data from a cohort of elite judoka on multiple occasions. In order to sustain the judoka's attention during the tests we introduced competition in the testing procedure. Our approach has added to the ecological validity of the method used due to the Judo-specific sensory modality of the reaction task and because the tests took place at the judoka's training environment, during regular training sessions, and under competition pressure. We collected data under three conditions of physical intensity: Baseline (at rest), Moderate Intensity (post warm up), and Severe Intensity (post maximum effort tests). Our results show that the mean reaction time improved from Baseline by a considerable margin in a group of elite judoka at Moderate Intensity with no difference in accuracy. We found no significant difference between the mean reaction time at Baseline and Severe Intensity but there was a significant deterioration in accuracy.

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Chapter 1: Reaction Tests; Review and Testing Modalities

1.1 Introduction

Imagine a Judo athlete (judoka) who is placed high in the World rankings and has achieved qualification for the Olympic Games. Now imagine this judoka at the Olympics about to start the first match on a quest for Olympic glory after years of physically intense training and competitions. Our judoka’s first opponent is somebody who is placed a lot lower in the World rankings. The match begins, the pace picks up and at a crucial point our judoka makes a wrong decision, a wrong move, and loses! Our judoka’s Olympic dream is over. What went wrong? How could our experienced judoka make such a decision error? Was our judoka too dehydrated? Could the extent of dehydration have had a negative effect on our judoka’s cognitive performance? Perhaps our judoka’s warm up routine did not evoke the desired mental arousal level? Maybe our judoka was too fatigued mentally from the intense preparation the weeks and months prior the event? Could it be that our judoka was never able to sustain attention at the intensity needed for such a big occasion? Of course, we do not know the answer to why our judoka made an erroneous decision but all the questions above point to the fact that even though cognitive performance is the least examined performance parameter in Judo it remains a crucial factor for success.

Judo is a popular Olympic combat sport where two opponents of the same sex and similar age and body mass attempt throwing or grappling techniques against each other. Judo has been part of the modern Olympic Games since 1964 and the International Judo Federation (IJF) has 195 National Federation members. With such large participation around the World, it is unsurprising that Judo has become a highly competitive sport. The high physical demands of Judo (Franchini *et al.*, 2011; Masashi *et al.*, 2017) and the exceptional physical characteristics of elite judoka (Quintero *et al.*, 2019) have already been studied. As is the case in other sports with extremely high competition standards, such as athletics and swimming, the performance margins between the top-level judoka are extremely small. Therefore, coaches and judoka are always looking at how to best optimise training adaptations and develop the tactical and technical skills necessary to increase the chance of winning major Judo tournaments.

Judo is an open skill sport, and as such there are no pre-determined moves a judoka can apply against their opponent during a fight. A judoka must identify, and exploit, opportunities to throw or force their opponent to submission to score points within the competition rules and the time limit of a bout. In Judo, cognitive performance and physical performance are interdependent; a powerful judoka is unlikely to be successful if unable to respond quickly with the correct defensive or attacking actions. Similarly, a tactically astute judoka is unlikely to be victorious if lacking the necessary athleticism and stamina to deal with a physically strong and well-trained opponent. Thus, the study of reaction time (RT) in Judo is important because it can lead to a better understanding of judoka's cognitive performance under different training or competition conditions (*e.g.* training while fatigued or when suffering from a mild or high degree of dehydration).

Making quick and correct decisions is an important ability elite judoka need to have so fast reactions are desirable. However, these are meaningless if not coupled with excellent execution and timing of the correct defensive or attacking response. Therefore, quick reactions in themselves cannot be a determinant of high-level skilled performance in judo. As shown in other sports, the ability to decipher sport specific cues from the opponent's actions is a characteristic trait of skilled performers (Müller & Abernethy, 2006; Savelsbergh *et al.*, 2002). However, it is obvious that any skilled judoka needs to rapidly process a stream of information input during a competitive bout and make equally quick decisions on the best action (Bahmani *et al.*, 2019).

Michael Posner considered RT as an indispensable component of skilled performance that deserves more attention (Posner, 1966). Human RT has been studied extensively, mainly by psychologists, both in the general population but also in sporting populations. The study of RT through various methods has long been thought of as a way to gain an insight into the function and performance of the central nervous system (CNS). Fast RT is a fundamental factor behind successful timing of movement and quick decision making, which means that short RT is important for success and injury prevention not only in Judo but in most other sports and in many situations in daily life.

RT can be affected by several factors. For example, RT gets faster from childhood to early adulthood and then slows down, progressively, as we age (Surwillo, 1963). It is also known that a person’s capacity for fast RT reduces when the processing of more information is needed (*e.g.* when trying to make a correct choice out of four options versus two options). Similarly, reaction speed diminishes when the CNS is fatigued (*e.g.* sleep deprivation) or under the influence of drugs (*e.g.* alcohol).

In most sports the primary sensory routes used, and therefore conditioned, are the visual or aural, or both. This is reflected in the fact that widely used reaction test methods overwhelmingly utilise visual or audio prompts for their response tasks. However, Judo is mostly a kinaesthetic sport where participants react to many tactile cues during competition. To date, various studies have been conducted to examine the reaction speed of judoka but the reaction testing methods used were based on visual or audio signals (Badau *et al.*, 2018; Cojocariu & Abalasei, 2014; Javier *et al.*, 2013; Lech *et al.*, 2011; Lima *et al.*, 2004; Morales *et al.*, 2018; Sterkowicz *et al.*, 2012; Supiński *et al.*, 2014; Zukowski, 1989) despite the fact that judoka’s dominant sensory input is somatosensory and with tactile cues mostly received through their hands when they grip their opponents.

In the following sections we review academic literature from the field of mental chronometry to: 1) present a brief history of RT tests and highlight that the level of accuracy needed for such measurements required innovation in technology that was not available until the mid-19th century, 2) outline the main factors known to influence response time, 3) describe a simple classification of RT testing methods, and 4) show that different sensory signals (*e.g.* visual cue *Vs* audio cue) impact differently on response time. This latter point, regarding sensory route-based RT differences, has had a strong influence in our motivation to investigate judoka’s RTs to haptic signals.

Currently it is unclear what is the typical RT and accuracy in a choice reaction test in experienced judoka. Despite the rather large body of work on human RT there is little information available on RT within the context of competitive Judo training and competition. It is unclear how experienced judoka’s reactions may be influenced by their training load, warm up routines, or by the weight loss strategies they choose for acute weight loss *i.e.* dehydration to ‘make weight’ in the final days leading to competition.

To be able to contribute to the judoka’s efforts to develop outstanding skills we first need a method to examine their RT parameters that is compatible with the dominant sense used, which in the judoka’s case is tactile. With the proper method in place, we would be enabled to define the typical range of RT and accuracy in this group of athletes and then investigate how such parameter values might be affected under different conditions during a typical training cycle or through a period of competitions.

1.2 What is Reaction Time?

Reaction time (RT), also known as response time or latency, is a measure of how fast a person can complete a voluntary motor task following a stimulus. RT can be thought of as a sequence of distinct events including: 1) the arrival of the stimulus to the sensory organ, *e.g.* the acoustic wave following the firing of the starting gun reaches the tympanic membrane (eardrum) of the sprinter, 2) the processing of the stimulus in the brain, *e.g.* the sprinter perceives the vibration going through the inner ear as the firing of the starting gun, 3) the processing of the decision in the brain that initiates the relevant response, *e.g.* the sprinter recognises that the starting gun has been fired and knows it to be the signal that starts the race, 4) the neural response travelling out from the brain and through the efferent pathways to the relevant motor units, *e.g.* the sprinter’s brain generates electrical impulses (action potential) to the motor units necessary to push off the starting block, and 5) the initiation and completion of the motor response required to complete the task, *e.g.* the sprinter’s feet are pushed against the starting blocks at which point the reaction to the starting gun has been completed and the sprinter’s physical movement off the starting block has begun.

A more simplified division of RT includes: 1) premotor RT; the time it takes from the initiation of a stimulus to a change in electrical activity produced by skeletal muscles as seen with electromyography (EMG), and 2) motor RT; the time from the change in EMG to completion of the movement (Botwinick & Thompson, 1966). Of course, the latter description of RT does not exclude reflexes. However, RT of reflexes is of no interest for the purposes of competitive Judo training as a reflex does not involve a cognitive process (rather a nerve impulse through the afferent pathway to the spinal cord and then through the efferent pathway).

1.3 A brief history of Reaction Tests

For a long time, scientists had wanted to study the connection between a person's cognition and reaction to external stimuli. Studying reaction speed was thought of as a way to gain an insight into the function of the central nervous system but it was believed that reactions were too rapid to be measured accurately. Franciscus Donders, a pioneering Dutch ophthalmologist, was arguably the first scientist to have been able to measure RT in humans and did so in 1868 with the use of a phonautograph, which was an early sound-recording device, and the oscillations of a tuning fork (Donders, 1969). Other scientists followed soon after with new RT measuring devices *e.g.* Galton's simple pendulum chronograph (Galton, 1890), and with the development of computers capable of high processing power measuring RT has become an easy and straightforward process. Reaction tests have advanced remarkably and are now a staple tool in many research areas and used in a wide range of settings. For example, over the years, various reaction tasks have been designed to assess whether RT slows down with sleep deprivation (Lim & Dinges, 2008), ethanol intake (Gustafson, 1986), dehydration (Ganio *et al.*, 2011), hyperthermia (Holt & Brainard, 1976), mental fatigue (Pattyn *et al.*, 2008), and disease (Stern *et al.*, 1984).

Together with the first reliable data from reaction tests, Donders was also the first to develop three RT test methods that remain to date three of the most used RT test paradigms: 1) a simple response task, 2) a discrimination task, also known as go/no-go task, and 3) a choice reaction task. With his work Donders was able to demonstrate that RT is subject to the complexity of the test; simple reaction tasks produce shorter RTs than choice reaction tasks (Donders, 1969). It is perhaps obvious to us now, the RT from a simple reaction task only consists of the time necessary to receive the stimulus and execute the task in response. Whereas in a choice reaction task a higher level of information processing is needed that includes differentiating between signals and deciding on a choice before executing the task.

In 1952, William Hick, showed that choice RT increases logarithmically, up to a point, as the number of available response options increase (Hick, 1952). This concept is now widely known as Hick's law. Perhaps, within the context of highly competitive sports, Hick's law may provide part of the explanation as to how highly skilled and tactically astute performers can get the competitive edge; they are able to anticipate more accurately their opponents' moves and so leave themselves with fewer potential choices to respond to.

1.4 Why test Reaction Time?

Fast RT is a fundamental factor behind successful timing of movement and quick decision making, which means that short RTs are particularly important in many sports and in many situations in daily life. For example, the ability of a goalkeeper to stop the ball going into the goal, or the ability of a driver to avoid a road traffic incident are largely dependent on possessing the ability to react quickly to an expected or an unexpected situation. In psychology and medicine studies there is a plethora of different cognitive tests (Psychometrics) with RT tests carried out in a wide variety of research areas. For example, some of the data gathered have shown RTs to correlate with ageing (Deary & Der, 2005; Salthouse, 1996), intelligence (Madison *et al.*, 2016; Woodley *et al.*, 2013), and mortality (Shipley *et al.*, 2006; Yamada *et al.*, 2013).

Results from studies of RT in Judo have suggested that higher reaction speed amongst competitive judoka correlate with training experience (Supiński *et al.*, 2014) and performance level (Zukowski, 1989). But experienced athletes are likely to demonstrate shorter reaction times, including sport specific movement time, mostly due to improvements in premotor time and motor time (Lee *et al.*, 1999) from neurological adaptations that take place as a direct result of repeated practice and learning, which reduces cognitive burden and allow for better attention (Bengtsson *et al.*, 2005; Reis *et al.*, 2009). For example, an experienced driver does not have to think about the sequence of actions necessary every time the car's gear needs shifted thus, the driver's attention can be concentrated on watching for road hazards and ultimately respond faster to an unexpected situation. In contrast, inexperienced drivers are likely to respond slower in the same situation only because of the increased cognitive burden they face from having to think about the right steps to shift gears, the Highway Code rules, and watching for road hazards.

In a sport like judo, where there is a strong technical and tactical skill component, testing RT could be useful because the proper RT test could potentially expose any decline in cognitive performance (quick information processing) under different training or competition conditions *e.g.* training while fatigued, or when suffering from a mild or high degree of dehydration. However, if we are interested in investigating typical RT parameters in elite judoka then, only RT tests relevant to the kinaesthetic demands of Judo (*i.e.* haptic mode as most of the information stream during a Judo bout is tactile) should be used.

1.5 What factors influence Reaction Time?

In real life competitive environments, it is important to note that the relationship between an athlete's anxiety level and physiological arousal is critical for best performance. According to the 'catastrophe model of anxiety' elevated levels of anxiety and physiological arousal can lead to a dramatic drop in performance (Hardy, 1996). Put differently, judoka may display a complete breakdown, a 'catastrophe', in the speed and accuracy of their reactions if they have not been able to control their anxiety adequately. 'Choking under pressure' is a common phrase used mostly to describe a performance decrement under the pressure of competition (Baumeister, 1984). Outside this somewhat emotional response, which is of interest to sport psychologists, we can find a lengthy list of factors that have a more straightforward impact on the speed of reactions.

It is proven that the time needed for the brain to process information and provide a response is heavily dependent on the complexity of the information received (Donders, 1969; Hick, 1952) and the primary sensory route through which the information reaches the brain *e.g.* visual versus acoustic (Donders, 1969). The degree of familiarisation test participants have with the reaction task and conditions matters too (Fontani *et al.*, 2006; Lee *et al.*, 1999) as well as their age (Deary & Der, 2005), sex (Silverman, 2006) and fitness (Bauermeister & Bunce, 2016). It has been shown that RT results are also subject to the intensity of the stimulus (Brown *et al.*, 2008; Nissen, 1977). Within the context of elite Judo, and most other high-performance sports, factors such as age, sex, and fitness are likely to be cancelled out as experienced adult competitors are well trained and are grouped by sex and within narrow body mass limits. Other factors at play that can influence RTs may include fatigue (Corfitsen, 1994), drugs (Harms *et al.*, 1981; Kamimori *et al.*, 2015), motivation (Eckner *et al.*, 2011), and prior exercise (Ashnagar *et al.*, 2015). Exercise is usually expected to improve reaction speed, but this outcome is not consistently observed and may be subject to the method used to assess RT (Arcelin *et al.*, 1998).

Irrespective of the factors at play, there is inter-individual variability within RT results from simple and choice reaction tasks, which means that any group of people cannot produce identical RTs between them. Also, a variability exists in the RT results achieved by the same person on the same reaction task (the main reasons for this variability are discussed in Chapter 6), and the mean of the intra-individual standard deviation in RT across the same test appears to increase with age (Hultsch *et al.*, 2002). Hence, when investigating the RT ability of any athlete, it is probably more meaningful to collect enough data from which we can estimate the typical mean RT and variability instead of seeking a single RT value.

1.5.1 Simple Reaction Test Vs Choice Reaction Test

As already explained in an earlier section, from his 19th century work on RT Donders had proposed three RT testing methods, which arguably could be broadly classified into two overall methods: a simple reaction test (SRT) and a choice reaction test (CRT). In a SRT all is needed is a single response to a single stimulus *e.g.* pressing a buzzer when a light comes on. In a CRT tasks can vary considerably. A simpler CRT test requires a single response to one of two options presented (*i.e.* go/no go) *e.g.* pressing a buzzer when a light goes green but ignore it if the light turns red. But there are CRTs where the task is more complicated and a specific response is required out of several stimuli *e.g.* pressing the correct letters on a keyboard, as soon as possible, when they appear on the screen. Historically, the tests devised for the cohorts of interest have primarily utilized visual or audio stimuli.

SRTs result in faster responses compared to CRTs but the former also require the least amount of information processing by the brain. In practical terms, in open skill sports like judo or wrestling, an athlete could produce their fastest reaction possible only if they were to commit to a single counterattack against any attack by their opponent. In real life competitions it is uncommon for a competitor to insist on performing a specific move against whatever their opponent intends to do. Some competitors may fixate on reacting with a specific move but only because they are convinced that the move in mind is the best choice against what they expect their opponent will do next. However, the above is arguably an example of an expert performer who can take advantage of proprioceptive, visual or other cues and correctly anticipate their opponent’s intention (Müller & Abernethy, 2006; Savelsbergh *et al.*, 2002; Tanaka *et al.*, 2010). A limitation of SRTs is that they appear to be poor predictors of expert performance (Kida *et al.*, 2005).

SRTs cannot be used to expose those capable of short RTs but who at the same time are not good at distinguishing quickly enough the correct responses. CRTs are better tools to reveal performers who may sacrifice reaction speed for accuracy and *vice versa*. Minimising the potential speed over accuracy trade off (Heitz, 2014) is of the utmost importance in almost every competitive sport as athletes need to make quick and correct decisions. It has been argued that expert judoka are more likely to make more correct decisions and react faster (Supiński *et al.*, 2014). Judo is an unforgiving sport where a lapse in concentration can allow the opponent the necessary position advantage to achieve an ippon (judo’s equivalent to a knockout). It has been shown that under extreme fatigue conditions, as those experienced during the latter part of an intense match, judoka may still be able to react fast but with more erroneous choices (Lima *et al.*, 2004). It has also been shown that gradually more errors are made across the duration of a discrimination test (Esterman *et al.*, 2013). Therefore, when it comes to investigating RT and accuracy, it is CRTs and not SRTs that are of much greater relevance to judoka, and to those helping them optimise their training adaptations.

The use and relevance of RT results from SRTs should not be dismissed just yet as they are still important for judoka. The benefit of a SRT is in its simplicity; by not dealing with the potential data variability from having to process more complex information it is more likely to be able to reveal person’s pure reaction speed. A person’s baseline simple RT is a closer reflection of the speed with which nerve signals can be relayed via afferent and efferent pathways and how quickly muscles are activated for a given task. Whilst fast simple reactions do not predict the best performers, at the same time, a person with slow simple reaction is unlikely to fare well in any sport where there is an inherent need for quick choice reactions. The difference between simple reaction and choice reaction, for comparable tests, is of interest to researchers as it can help them deduce the processing time needed to arrive to a decision.

1.6 Sensory route

From the early beginnings of research in human mental chronometry scientists were eager to define typical response times to various tasks. and although the tasks used have been primarily based on visual and audio cues the interest in RT through tactile sensory routes (haptic) has gained momentum in recent years too (Calhoun *et al.*, 2003; Godlove *et al.*, 2014; Skedung *et al.*, 2013). There has been some interest in the olfactory route as well (Olofsson, 2014) but to date the volume of work in that area remains somewhat limited.

1.6.1 Auditory Reaction Tests

Perhaps the best known real-life example of simple RT to sound in performance sport is the 100m sprinters' race. In this quintessential event of the modern Olympics the sprinters push off the starting blocks as soon as an official fires the start gun. Modern technology allows officials to record accurately the time each sprinter takes from the start signal to when they initiate the push against the starting block. Arguably, World class sprinters are an ideal group to study reaction speed to a simple reaction test. Sprinters have conditioned themselves over years of training and competition to respond rapidly to a clearly defined signal (assuming they are performing in stadia where spectators stay quiet for the start signal).

In the Athens 2004 and the Beijing 2008 Olympic Games the mean RT, and standard deviation (SD), of the male 100m sprinters was 164 (24) msec and 162 (20) msec respectively (Paradisis, 2013). The average RT of the female 100m sprinters was 187 (29) msec in Athens and 190 (30) msec in Beijing (Paradisis, 2013). At the Berlin 2009 Athletics World Championship 100m final, where the Jamaican sprinter Usain Bolt posted his World record of 9.58 seconds, Bolt reacted in 146 msec. Other sprinters in that final, or at earlier races on the same event, recorded RTs under 120 msec (IAAF, 2009). The International Association of Athletics Federations (IAAF) rules a reaction under 100 msec as a false start. It has been argued that auditory RT as short as 85 msec is possible (Komi, 2009; Pain & Hibbs, 2007) but the IAAF rule remains in place and some evidence in support of IAAF's position has been reported elsewhere (Lipps *et al.*, 2011).

Outside high-performance sport, a useful source of data on simple reaction speed to sound stimuli is the Baltimore longitudinal study of aging (BLSA). Data on participants have been collected since 1958 and simple reaction tests to audio stimuli were introduced in 1973 for men and 1978 for women. The average simple RT to a sound in a group of 16-24 years old, a similar age bracket to that of the cohort of Olympic sprinters, was 225 (36) msec (Fozard *et al.*, 1994). Olympic sprinters can achieve much shorter RTs than the participants of the BLSA. However, any comparison between the BLSA reactions data and that from Olympic sprinters needs to be done tentatively because: 1) the testing conditions and methods differ markedly, and 2) sprinters spend years training their ability to react very quickly to a specific sound signal. It is conceivable that to reach Olympic standard, a high degree of conditioning to simple reaction to sound takes place and only those with extremely fast reaction can advance to higher levels of competition. In other words, the data from the Olympics come from a cohort made up from some of the fastest people in the World who have trained over many years to react quickly to sound. On the other hand, the data from BLSA come from a cohort with no qualitative filtering whatsoever.

1.6.2 Visual Reaction Tests

For most open skill sports quick processing of the information that reaches the brain, from the retina, via the optic nerve are decisive qualities for success. Team sports, racquet sports, combat sports like boxing and karate, and motor sports are all good examples where the dominance of visual sense and the need for fast reactions to the visual stream of information is unequivocal. Unlike the case with sprinters, there is no direct access to real life data from RTs in sports were quick reaction to visual information is crucial. For example, the RT of professional goalkeepers in penalty shootouts during major Championship finals is not measured and goalkeepers' RT ability is assessed instead through bespoke reaction tests outside of real-life football game conditions (Rodríguez-Arce *et al.* 2019). In most sports, data on athletes' reactions are not formally recorded or made available. Therefore, we cannot quantify in detail what 'fast reaction' means within the context of high-level performance for most sports. Instead, we must turn to published research from mostly laboratory-based studies to elucidate the human limits of RT to visual stimuli.

Over the years, different researchers have reported a wide range of mean RTs for simple reaction tasks to a visual cue in young and healthy individuals: 154 msec (Donders, 1969), 160 msec (J, 1885), 255 msec (Deary *et al.*, 2011), 270 msec (Der & Deary, 2006), 320 msec (Ng & Chan, 2012) and 334 msec (Soto-Rey *et al.*, 2014). Such variability in the results is most likely due to the different methods used, the different technology available, the different cohorts studied and the different aims of each study. It has been argued that the human brain needs just over 50 msec to capture and interpret an image (Maguire & Howe, 2016). Others have claimed that the brain is capable of much shorter times in capturing and interpreting images (Potter *et al.*, 2014) but such findings have been contested and not reproduced (Maguire & Howe, 2016).

In any case, even at the shortest reported RTs there is still a remarkable amount of time that needs to be accounted for between the overall RT and the time it takes to capture and interpret an image. It is possible that the time recorded beyond that required by the human brain to identify a visual cue reflects how long it takes to decide, initiate, and complete the required motor task in response to a given signal.

1.6.3 Auditory Vs Visual

For most humans vision is the most dominant sense, and it is realised through a complicated process where photons from light reach photoreceptor cells in the retina to trigger electrical impulses via the optic nerve that eventually reach the visual cortex in the occipital lobe of the brain where visual information is processed (Cornsweet, 2017). In the case of the sense of hearing the process begins when sound waves reach the eardrum to produce vibrations that travel through the inner ear and affect hair cells that in turn produce electrical impulses via the auditory nerve, which reach the auditory cortex in the temporal lobe of the brain where sound information is processed (Gelfand, 2018).

As soon as scientists devised a reliable method to record RT, they were immediately interested in comparing RTs between acoustic and visual stimuli (Donders, 1969). There have been studies where the investigators set out experiments to compare directly subjects' RTs with visual tests and sound tests, and a clear consensus exists confirming what Donders had already reported in

1868: RT to sound is shorter than RT to light (Ghuntla *et al.*, 2014; Jain *et al.*, 2015; Shelton & Kumar, 2010).

Further confirmation of shorter mean RTs to acoustic stimuli came from studies where electroencephalography (EEG) technology was used. EEG is used to measure brain electrical activity and can measure reliably brain response following a visual, audio, tactile, or other specific cues (Baudena *et al.*, 1995; Halgren *et al.*, 1998). The electrical activity recorded with an EEG is also known as an event-related potential (ERP). The ERP from auditory tests show waveforms with a higher amplitude and a shorter latency of the peaks compared to visual tests (Nordin *et al.*, 2011). Indeed, a research group used EEG and gave a group of air traffic controllers' visual and auditory tasks to investigate the relationship between visual and auditory correct responses, reaction time, and the corresponding brain areas and functions. These data proved that RT to visual cues is slower than RT to auditory ones (Abbass *et al.*, 2014). Although EEG produce useful data at a low cost, it is a method that requires tens of small sensors to be attached to a subject's scalp by a trained technician and requires a trained specialist to interpret the results. Therefore, EEG is a time-consuming method, cumbersome, and very impractical to test regularly high-performance athletes.

Faster reaction to sound compared to light may seem somewhat counterintuitive to most people. It may appear more logical to expect visual perception to result in shorter RTs considering that light travels, roughly, one million times faster than sound. However, the variance in speed for the brain to process different sensory information reflects the difference in how such information is received and processed by the CNS, which has no relevance to the difference in how fast light and sound can travel through the air.

Although there is a wealth of studies that report RTs from a plethora of different methods none provide us with results that are relevant to elite judoka. We can use data from auditory reaction tests to shape our understanding of the magnitude of speed possible in human reactions, but such knowledge is of limited use in Judo. The reaction to sound has little, if any, relevance within the context of Judo competition; judoka do not need to possess the short RT to sound sprinters exhibit. Even reaction to images is of limited importance in sports where somatosensory feedback is the dominant source of sensory input; judoka, wrestlers, and grapplers use their sense of touch to identify their opponents' joints or position to then decide their own move. The dominance of somatosensory feedback in Judo is revealed by cases such as the Georgian judoka, Zvian Gogotchuri a well-known visually impaired judoka who has competed, successfully, against World class non-visually impaired judoka. With the above in mind, it becomes obvious that we need to turn our attention to reaction tests that utilise the sense of touch.

1.6.4 Tactile sense

Humans can react very quickly to somatosensory (tactile) input as demonstrated by the reflex arc. A reflex arc is an automatic and involuntary response where some stimulus from a sensory receptor excites a nerve pathway that loops through a sensory neuron to the spine and back through a motor neuron to the effector (Podivinský *et al.*, 1992). For example, when a person touches a hot surface with their hand, unknowingly and unintentionally, they are most likely to pull their hand away from the heat source rapidly and before they consciously decide to do so. Another type of involuntary reaction is the myotatic reflex, which constantly monitors, and corrects, a muscle's length and tension by producing a muscle contraction in the agonist muscle whilst allowing the antagonist muscle to relax. The myotatic reflex is crucial to controlled movement, to averting forceful stretching of a muscle beyond its passive range, and in supporting upright posture (Dolbow & Throckmorton, 2020). Such reflexes, as described previously, are essentially the product of automatic responses and it is possible that they result in faster RTs compared to conscious reactions as the response they produce can bypass the brain. Considering that a reflex refers to an involuntary movement and not the product of conscious effort, investigating RTs in somatosensory reflex in judoka or other athletes has no practical application. In contrast, RTs that result from conscious and voluntary completion of reaction tasks could potentially lead to a better understanding of the variability that may exist in information-processing speed and accuracy in judoka.

There is little research published on RTs to tactile stimuli and this lack of information exposes a knowledge gap for sports where the dominant sensory input comes from touch. In one study 25 out of 69 female and male participants 11-60 years old took part in an experiment where they had to wear a vibrating device on their right wrist or right leg near their ankle. With their hand resting on a keypad the participants had to press a specific key as soon as they felt a vibration (Ng & Chan, 2012). After 500 responses the mean RT for this simple haptic reaction test was 385 (71) msec. The mean RT reported by Ng & Chan (2012) seems rather slow for a simple reaction task. It has long been known that RT is inversely influenced by the intensity of the stimulus (Lele *et al.*, 1954; Nissen, 1977), so it is possible that the investigators did not take into account the optimum vibration frequency for the devices they used for their experiment, which is believed to be at around 250 Hz for the surface of the palm (Cholewiak & Collins, 1991; Scheibert *et al.*, 2009).

In a different study, eight participants (mean age: 28 years old) took part in a simple reaction test where they had to grasp a pen-like tool and push it along a straight path until either an audio or tactile stimulus was presented to them at which point, they had to withdraw the tool as soon as possible (Peon & Prattichizzo, 2013). The mean RT to a vibrating alert was 205 msec, which was faster than the mean RT recorded for the same task with audio and visual alerts at 245 msec and 268 msec, respectively. But in this study the investigators also looked at RTs between different signal intensities and found that a vibrating alert of lower frequency resulted in longer mean RT compared to the higher frequency (250 Hz) vibration. And the exact same result was repeated with the audio alerts: the louder signal resulted in shorter RT than the quieter alert.

Early work in mental chronometry has revealed that the response to a haptic stimulus can be quick and reliable (Lele *et al.*, 1954) and that it can be even faster in the absence of visual cues (Jordan, 1972). In his 1972 study, Timothy Jordan, used a cohort of inexperienced fencers and had a group of them practice blindfolded a fencing-specific skill where their blade was in contact with a mechanical foil. The same skill was practiced by two other groups but with no blindfold and Jordan was able to demonstrate that the deliberate blindfolded practice of a proprioceptive fencing skill (the feedback came through the contact of the blades) resulted in faster responses to the same fencing-specific task. It was argued that the increase in tactile reaction speed when vision was blocked exposed a competition between sensory inputs, with visual perception being dominant in its demand for attention. In a more recent study, the hypothesis of an impact on RT by the senses ‘competing’ for attention was supported when it was shown that the mean RT to a visual cue in athletes with hearing impairment was shorter compared to a group of athletes without a hearing impairment (Soto-Rey *et al.*, 2014).

Considering that a multisensory interplay takes place in the brain from the various senses constantly receiving input from a stream of information from their environment (Driver & Noesselt, 2008) it is reasonable to argue against the notion of examining a sensory modality in isolation. But the counter argument to such position could be that, in comparison to tactile stimuli, the ability of a judoka to react quickly to audio or visual stimuli is likely to have limited relevance. Moreover, according to Jordan (1972) there is a potential performance benefit in proprioceptive dependent motor skills from practicing in the absence of other deliberate sensory input. Therefore, experienced judoka may have an advantage in haptic tasks compared to athletes in sports where visual or audio perception is dominant (boxing, racquet sports, team sports *etc.*). In fact, it has been suggested that judoka should be expected to achieve superior reactions in laboratory tests with tactile stimuli than athletes in combat sports whose performance is dependent on visual stimuli (Supiński *et al.*, 2014).

1.7 Haptic Technology

Perhaps a reason we do not see a wealth of studies in tactile RT that matches the abundance of studies investigating RTs with acoustic or visual tests is the limitations researchers have had in earlier decades on proper choices for haptic devices that can produce a controlled and reliable tactile signal. A growing commercial interest in exploring ways to improve interaction between users and electronic devices has led to the development of haptic technology and with it the availability of affordable and easy to use components that can generate a tactile stimulus.

Most people are familiar with the use of haptics because haptic technology is widely used in mobile phone devices (the vibration function on alerts) and computer game controls. Haptic technology is increasingly utilised, or tested for future use, in a wide variety of applications such as: operator controlled monitoring systems (Calhoun *et al.*, 2003), car safety systems (Katzourakis *et al.*, 2014), haptic communication to replace verbal navigational instructions (Moll & Sallnäs, 2009), audio-tactile methods to assist interaction of blind people with virtual environments (Miao *et al.*, 2009), haptic systems for blind members of a dance audience to enhance their experience of the choreography beyond what is possible from audio description alone (Lycouris, 2012), and haptic feedback systems incorporated in musical instruments to help musicians learn correct movements and posture (Grosshauser & Hermann, 2009).

There are several arguments in support of our research work presented in this thesis that was the product of our intention to investigate reactions in experienced judoka using haptic technology:

1. As it stands, the body of evidence in scientific literature on the limits of RT following tactile cues remains insufficient to draw firm conclusions about cognitive performance parameters relevant to elite judoka (*e.g.* How fast can they react to tactile prompts? How consistent can their RT be over a sequence of haptic choice reaction tasks? How accurately can they respond?).

2. RT results from earlier studies where haptic tasks were used are most likely inappropriate in helping us determine sensible margins of expectations on baseline RT for elite judoka. We have already explained that direct comparisons of test results between studies that have used the same sensory mode is often impossible due to the variability in the design methods used, the quality of the cohorts recruited, the type of objectives in each study, the sensory route used, and other factors. A good illustration of the above argument is the difference in mean RT results reported by Ng & Chan (2012) and Peon & Prattichizzo (2013). In both cases experimental methods were devised to test simple RT to tactile stimuli, yet the eventual mean RTs reported were vastly different: 385 msec for the former and 205 msec for the latter study.

3. A more sport-specific method to assess cognitive performance in Judo is needed. During a typical Judo bout judoka need to remain vigilant for four minutes. Any lapse in concentration from a judoka at any point within that timeframe may lead to a missed opportunity to score or allow a scoring opportunity to their opponent. By designing an experimental method to investigate cognitive performance in experienced judoka we will have developed a method to examine sustained attention.

4. Ultimately, the availability of affordable components to produce a bespoke haptic reaction testing device has removed the limiting factor that has probably stood in the way of earlier investigators who may have wanted to study RTs to tactile stimuli in Judo or other sports.

1.8 Structure of Thesis

The structure of this thesis is as follows:

In Chapter 2 we outline some of the statistical methods for the inferential analyses we have carried out and the rationale behind our choices.

In Chapter 3 we describe some of the technological and physiological mechanisms involved in haptic technology. We show how we have integrated haptic technology in a Judo-specific reaction test device built to obtain accurate and reliable data on choice RT in a group of experienced judoka. Furthermore, we outline the components that we have used to put together this novel, low cost, and practical Haptic Reaction Test device, we explain the advantages of our device over other reaction tests already available, and we describe the objectives we had in mind in its design.

In Chapter 4 we explain the rationale for having built a Judo specific haptic reaction test device and we present the study we carried out with a group of volunteers at the University of Stirling to determine the validity and reliability of our device.

In Chapter 5 we present the typical haptic choice mean RT and accuracy in a cohort of elite judoka. To the best of our knowledge, the study in this chapter is the first in academic literature to report typical mean RT and accuracy from a haptic choice reaction test specifically designed for Judo.

In Chapter 6 we present the method we employed to motivate the cohort of elite judoka to fully engage in the testing process. We outline factors that may influence the decline of focused attention and we show how we used competitiveness to determine the most probable baseline parameter values in the haptic choice reaction test.

In Chapter 7 we present the effect exercise can have at different intensity levels on elite Judoka’s haptic mean RT and accuracy compared to baseline values. We demonstrate that mean RT can improve by a considerable margin after a typical judo specific warm up session. But under conditions of extreme physical effort mean RT is comparable to that at baseline whilst accuracy deteriorates.

In Chapter 8 we discuss some points related to the earlier chapters and we put forward some recommendations for future research.

1.9 Summary

Reaction tests have historically been used by psychologists as a window to one aspect of people's cognitive abilities. In Judo and in any other open skill sport where athletes must make quick decisions, fast reactions and the ability to process information quickly are critical for success.

Tactile perception is processed differently in the brain compared to visual or auditory information. Proprioceptive based reactions and reactions to tactile input may improve in the absence of visual cues, which could potentially make experienced judoka better at responding to tactile stimuli as opposed to any other sensory modality. As touch and proprioception are the predominant sensory routes in Judo, we must give preference to haptic stimuli as the testing mode for any reaction tasks we may want to use to investigate RT parameter values in experienced judoka.

At this stage, it is unclear what would be considered a typical baseline RT to complex tasks and the associated error rate by experienced judoka hence we have no way of knowing to what extent, if at all, can cognitive performance be affected under different conditions. Therefore, it is important to develop a reliable haptic choice reaction test to help us carry out the necessary investigations and establish the typical baseline range in RT and accuracy in elite judoka. With such a testing method in place we can investigate how varying conditions of training, ‘weight cutting’, and competition may impact on elite judoka's baseline ability for fast, consistent, and accurate reactions.

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Chapter 2: General Methods

2.1 Participants

The data for the Judo specific chapters (see Chapters 5-7) were collected from a cohort of ten healthy judoka who compete at international level and participate at World ranking tournaments. The judoka were approached at a training session at the Scottish Judo centre, in the presence of their coaches, and were explained the purpose of the study. All judoka were given the opportunity on a later date to try the haptic test on the device and then they had at least two days to consider their decision to take part in this project. Any subsequent testing was carried out only after written consent was obtained. The study was approved by the School of Sports Research Ethics Committee of the University of Stirling (SSREC 757). Originally there were 15 judoka who had volunteered for this project and gave written consent. However, during the early stages of our study three judoka retired from the Scottish Judo Performance programme while two others relocated to different Performance programmes and were not available for regular testing. All participants knew that they could withdraw from the study at any point if they wished to do so without having to provide any explanation.

All 10 judoka who eventually participated and completed our tests (four females aged 21.3 ± 2.2 years; weighing 62.3 ± 8.5 Kg; and six males aged 21.2 ± 1.6 years; weighing 72.2 ± 8.3 Kg) were healthy, they had no injuries, and trained daily. All judoka who took part had experience in International competitions including events where they competed for the British or the Scottish Judo National Teams. We considered these athletes as elite judoka due to their experience in competitions and because of their status as members of the National Judo High Performance programme based at the Scottish Judo centre at Ratho near the city of Edinburgh.

2.2 Haptic Choice Reaction Test

After the validity and reliability study of the novel haptic device, presented in Chapter 4, all of the other tests for the studies described in Chapters 5-7 were carried out using exclusively the haptic choice reaction test. A single haptic choice RT test session involved a fixed number of 20 reaction episodes, and it took just under two minutes to complete. When considering that a Judo match lasts for four minutes we thought that a reaction test of near two minutes was a good compromise between getting enough data for analysis and not turning the test into a tedious task for the judokas.

Each reaction episode was a response to a haptic signal (vibration) that was generated from one out of the four available actuators (vibration motors) housed in specially designed handle grips (see Chapter 3 for details). The judoka where instructed to apply a judo grip with their hands on the handle in the same way they grip the sleeve of their opponent’s Judo jacket (judogi). Within each of the two grips, there were two actuators nested in opposite sides from each other and at a long enough distance to allow the user to distinguish which of the two actuators produced the haptic signal in either hand grip. The signal from the actuator higher in the grip was felt by the user’s thumb whilst the opposite actuator’s signal was felt by the user’s small finger and palm, over the hypothenar muscles. In order to prevent successful anticipation of the next haptic signal (vibration) a signal was produced at random by one of the four actuators and the time between signals (inter-stimulus time) was randomised within 1000 to 3000 msec. The frequency of each vibration from the actuators was 122Hz and such intensity was found at a pilot study to be sufficient for the users to detect the vibration source when holding the handle grips.

The reaction task required the user to respond to the haptic signal with a short and quick displacement of the device in the direction they felt the vibration to have originated from and return it to the start position. As a visual representation of the reaction task, we instructed participants to imagine Saint Andrew’s cross on the Scottish flag with the device placed on the centre. From the imaginary centre on the cross the device was to be moved sharply, with both arms, towards one of the ends of the cross in response to the signal given by the corresponding actuator, and then returned to the start point. For example, if the vibration came from the top right actuator, then the device had to be displaced sharply towards the top right edge of the imaginary cross and back. This direction would be equivalent to a North East direction if the participant was facing North. Any displacement was always done with both hands holding the device. The reason a fast displacement was required was to activate the accelerometer installed within the device, which in turn stopped the high precision timer.

2.3 Statistics

In Chapters 4-7 we have used a variety of statistical tools to carry out the necessary statistical analyses. We did not use a consistent approach for our analyses across the three chapters as our objectives were different and our choice of statistical methods for each chapter reflects our decision as to which method we considered more appropriate for the analysis and reporting of the data collected.

In Chapter 4 the test-retest reliability of our haptic device was computed through the Intraclass Correlation Coefficient (ICC), which is the most popular method for assessing the reliability of clinical instruments measuring continuous variables (Zaki *et al.*, 2013). From the various models of ICC available we chose the single rater measurement, absolute-agreement, two-way mixed-effects model (ICC [2,1]), which is considered the best approach for test-retest reliability studies (Koo & Li, 2016). Following the test-retest analysis the ICC results produced were interpreted based on the description by Koo & Li (2016) so that ICC values <0.5 indicated poor reliability, values between 0.5 - 0.75 indicated moderate reliability, values between 0.75 - 0.9 indicated good reliability, and values > 0.9 indicated excellent reliability.

In Chapter 5 we have used descriptive statistics to summarise the data that describe our cohort’s Baseline levels and we have made no inferences based on that data. For the subsequent two chapters though (Chapters 6 and 7) we have opted for Bayesian statistics and we have avoided the use of the more traditional and widely used frequentist statistics.

2.3.1 Bayesian Statistics

What we know today as Bayesian statistics stems from the work of Thomas Bayes, Richard Price, and Pierre Simon Laplace during the 18th century, even though we appear to only credit the former for the mathematical formula we now call the Bayes Theorem (Lambert, 2018). In essence, Bayes Theorem is a mathematical formula of conditional probability where the probability of an event (posterior probability) is based on prior knowledge we have from relevant information. The mathematical representation of Bayes theorem is:

$$\mathrm{p(B|A)} = \frac{\mathrm{p(A|B)\ p(B)}}{\mathrm{p(A)}}$$

Where p indicates a probability distribution, p(A|B) is called the likelihood, p(B) is called the prior distribution, p(A) is called the normalising factor, and p(B|A) is called the posterior probability. The posterior distribution is the aim of Bayesian inference. In practical terms, the Bayesian model allows us to utilise evidence in new data to update our beliefs [for a detailed description of Bayesian inference see (J. K. Kruschke & Liddell, 2018; Lambert, 2018)], hence a common phrase amongst Bayesians: “Yesterday’s posterior is today’s prior”.

Bayesian inference has been described by Kruschke (2018) as “…reallocation of credibility across possibilities, according to the mathematics of conditional probability”. We use Bayesian inference to reallocate probability from the prior distribution over some parameter to the posterior distribution according to evidence in the data (J. K. Kruschke, 2018). The use of integrals and sampling procedures required to achieve the “reallocation of credibility across possibilities” has been a technical limitation of Bayesian statistics due to computational power complexities, which made the methods we now take for granted unusable in most research analyses. However, with the rapid progress in computer technology there has been a renewed interest in Bayesian statistics in the past 30 years. Increased computational power and algorithm advances now allow us to take advantage of the Bayes' theorem (Kass & Raftery, 1995) in various applications.

A classic approach in scientific research is to use a test of statistical significance to help us decide whether a hypothesis is likely to be ‘true’ or not. Historically, the frequentist paradigm has dominated the methods used to infer an effect in scientific studies. This paradigm is based on large number of exact repeats of the study. The expected proportion of these repeats is calculated under the assumption that there is no effect. This proportion is termed the p-value. If the p-value falls below a certain cut-off the result is said to be statistically significant. Conventionally, an arbitrary cut-off point for the p-value is decided, known as alpha level (most commonly $\alpha = 0.05$ but $\alpha = 0.01$ and $\alpha = 0.001$ are used as well). This alpha level is the expected rate of false positive conclusions (assuming that there really is no effect). If the p-value is smaller than the alpha level, then the null hypothesis (*i.e.* no difference or no effect) is rejected in favour of the alternative hypothesis and the result is declared ‘statistically significant’. However, the arbitrary choice of alpha level and the reliance on the p-value as a border between ‘important’ and ‘unimportant’ results is thought to contribute to non-reproducibility of scientific studies (Sapra & Nundy, 2018).

For a more detailed discussion on the advantages of Bayesian statistics see (J. Kruschke & Liddell, 2016) but one crucial point is that the frequentist approach considers a long run of studies (that usually have not happened) whilst the Bayesian approach considers only the data at hand and what we ‘knew’ before we collected that data. One clear benefit of the Bayesian paradigm is that the results from Bayesian inference are more intuitive, especially to a non-statistician. The generation of the posterior distribution means we can make direct probability statements about the study without having to consider a large number of exact repeats. Being able to give direct probability statements is particularly useful as we want our results to be reported to and understood by coaches in the Judo high performance programme, none of whom should be expected to understand statistical concepts.

2.3.2 Bayes Factor

There is increasing support for the use of the Bayesian equivalent to hypothesis testing: the Bayes Factor (Valen, 2013). With the Bayes factor (BF) the null hypothesis and the alternative hypothesis are considered in a more balanced way and it is possible to quantify the relative support in the data for one hypothesis over the other (Liao *et al.*, 2019).

Simply put, BF is a ratio between the likelihoods, or marginal likelihoods in the case of continuous data, of the observed data from two competing hypotheses (H_0:H_1) – typically a hypothesis in support of a null effect and a hypothesis that rejects a null effect. Unlike a frequentist approach, where we would fix a probability cut-off point to declare whether we accept or reject the null hypothesis, the BF result is a probability value that gives us a measure of the odds between the two competing hypotheses, or put a different way, it quantifies the strength of the evidence in favour of the null, and the generic formula is:

$$BF = \frac{p(\text{Data} \mid H_1)}{p(\text{Data} \mid H_0)}$$

In order to provide a guide for the interpretation of the BF result, a scale of BF ranges together with descriptive statements for each one was proposed by Jeffreys in 1961 (Table 2-1) but was revised almost 30 years later with a warning that context affects interpretation *e.g.* forensic evidence in criminal trials should be supported by BF values greater than 1000 to be decisive instead of greater than 100 (Kass & Raftery, 1995).

BF(H_1:H_0) Jeffreys	**Evidence against H_0**	**BF(H_1:H_0) Kass & Raftery**	**Evidence against H_0**
1 to 3.2	Not worth a mention	1 to 3	Not worth a mention
3.2 to 10	Substantial	3 to 20	Positive
10 to 100	Strong	20 to 150	Strong
>100	Decisive	> 150	Very strong

Table 2-1. Interpretation guide of Bayes Factor result.

Next to each range is the description given for it by the authors. Note that Kass & Raftery (1995) chose different terms and higher BF ranges for the evidence against the null hypothesis than Jeffreys (1961).

We have used Bayes Factors (BF) to compare two paired means and we have assumed the data to be a random sample from a normal population. The assumption of normality is satisfied by the 'Central Limit Theorem', which states that the sampling distribution of the sample means approaches a normal distribution as the sample size is above about 20 (Lambert, 2018).

We wanted to test the difference μ between the mean values in two conditions of interest so that: $\mu = \mu_1 - \mu_2$, which allows us to develop two hypotheses:

1) Null hypothesis: There is no difference in the mean values
   $H_0: \mu_1 = \mu_2 \Leftrightarrow \mu = 0$

2) Alternative hypothesis: There is a difference in the mean values
   $H_1: \mu_1 \neq \mu_2 \Leftrightarrow \mu \neq 0$

The key steps in BF computation include the following:

1) Use integration over the prior distributions for each hypothesis so that

   $$BF[H_0:H_1] = \iint p(\text{data}|\mu, \sigma 2)\ p(\mu|\sigma^2)\ p(\sigma^2|H_1)\ d\mu d\sigma^2$$

2) Use the Jeffrey’s prior (Jeffreys, 1946) on the variance

   $$(\sigma^2):\ p(\sigma^2)=\frac{1}{\sigma^2}$$

3) Use the Cauchy prior for μ: $\mu \sim C(0, 1{*}\sigma)$, which resolves the Lindley's paradox when the BF and t-statistic give contradicting results for certain choices of the prior distribution

All of the above formulas are included in the *BayesFactor* package (Morey & Rouder, 2018), which is used for inference and testing for normal means. Also, in the same function the use of the Jeffrey’s prior on σ^2 alongside the Cauchy prior on μ under H_0 is called the Jeffrey-Zellener-Siow (JZS) prior and it is the default setting for the prior family options available in the software

2.3.3 Markov Chain Monte Carlo

Prior to the advent of modern computing power, calculation of the denominator in Bayes formula was often difficult if not impossible due to the mathematic integration required. Even with modern computers the integration is impossible. However the development of algorithms to simulate the posterior distribution has made Bayesian analysis accessible. The most frequently used algorithm is Markov Chain Monte Carlo (MCMC) sampling (Morey *et al.*, 2011).

A Markov chain is created through a ‘random walk’, a process where the previous sample value is used to randomly generate the next sample value, hence the Monte Carlo part of the MCMC (J. K. Kruschke, 2011). MCMC simulates draws directly from the posterior distribution of the parameter of interest by random sampling of representative points that converge in distribution to the target distribution (Lambert, 2018; Madigan *et al.*, 1995). And if we sample enough points, we can then determine the posterior distribution. Some MCMC algorithms commonly used include the Random Walk Metropolis, Gibbs sampler, and Hamiltonian Monte Carlo (for more details see Lambert 2018 and Kruschke 2011).

There are various open source MCMC software options available based on probabilistic programming languages like Stan, ‘Bayesian Inference Using Gibbs Sampling’ (BUGGS), and ‘Just Another Gibbs Sampler’ (JAGS), all of which interface with widely used data analysis languages like R or Python and are easy to access alongside helpful tutorials (van Ravenzwaaij *et al.*, 2018).

2.3.4 Credible Intervals

Bayesian methods allow us to make directly interpretable probability statements. We can use the posterior density to calculate Credible Intervals (CI) and we can use CI to report the range within which 95% of the posterior probability is situated (Lambert, 2018). A statement such as: “There is a 95% probability a value x is within x_1 and x_2” allows us to be clear about the range of likely values. Such clarity is not always afforded in the frequentist equivalent to the Credible Interval: the Confidence Interval. What a Confidence Interval truly tells us is that “95% of similarly constructed intervals will contain the true mean”, or in other words, if we were to repeat a study under the exact same conditions a large number of times then the true mean would be found 95% of the time within such intervals (Greenland *et al.*, 2016). The practical purpose of the CI in the context of Bayes Factors is to help us interpret the posterior probability result: if the CI does not include zero then the alternative hypothesis, *i.e.* the mean difference being different from 0, is more likely than the means being the same.

2.3.5 HDI + ROPE Decision Rule

When we make comparisons between mean values it is possible to get statistical significance for small differences regardless of how meaningful they are in real world applications. Thus, as well as being satisfied that differences are unlikely to arise by chance, we also need to define a change that has practical significance. Such concerns about the magnitudes and uncertainties of the parameters are not addressed by either the p-value or BF.

Kruschke uses the term ‘Highest Density Interval’ (HDI) to describe the range of most credible values in a distribution and the term ‘Region Of Practical Equivalence’ (ROPE) to describe the range of values that are equivalent to the null value for practical purposes (J. K. Kruschke, 2011, 2018). Kruschke proposes combining HDI and ROPE to create a rule that accounts for real world practicality when producing probability statements about the parameters rather than relying on p-values and significance levels (J. K. Kruschke, 2013). More specifically, if the HDI range lies entirely within the ROPE limits then we should accept the null value, on the other hand, if the HDI range lies completely out with the ROPE limits then we should reject the null value, and for any other scenario the outcome should be “undecided” as some, but not all, of the HDI values are practically equivalent to the null value. In essence, Kruschke proposes a rule that accounts for real world practicality when producing probability statements about the parameters, rather than relying on p-values and significance levels (Kruschke, 2013).

Kruschke (2011) suggested we use the HDI and ROPE to create decision rules but we need to consider how to set the ROPE limits. At what distance from the null value should the credible values lie to reject the null value? How close is close enough and how far is far enough? ROPE limits can be set by either empirical evidence (expert knowledge) or mathematical calculations (*e.g.* null +/- typical error of a test). In our case, we did not have sufficient data to empirically determine the change necessary in the means of the parameter values to declare ‘practical significance’. Therefore, we opted for a mathematical approach however we are confident that in the future, as more data accumulate, a more direct approach will be possible. There are alternative methods that can work as decision rules. For example, the Minimal Detectable Difference (MDD) is used in clinical research as a tool to establish the minimum magnitude by which an outcome has to change to be noticeable (Hill *et al.*, 2019). However, the simplicity and practicality of the HDI + ROPE decision rule make it a straightforward method to apply and interpret.

Kruschke (2018) suggests that when specific knowledge on appropriate ROPE limits is lacking then the ROPE can be calculated as the product of the standardised population value (σ) times half of a small Cohen's effect size (d). For example, if we have $\sigma = 30$, then the ROPE = $\sigma \times d = 30 \times (\pm 0.1) = \pm 3$. However, because we are interested in values that may be equivalent to a small effect or higher, we have used the same approach as outlined above only we set the d value to ± 0.2 to reflect the conservative approach we need to take in what is new research and with no prior studies on similar cohorts to draw recommendations from. Hence, the ROPE formula we have used to set its limits: ROPE = $\sigma \times d = \sigma \times (\pm 0.2)$

2.3.6 Effect Size

The effect size (d) was developed by Joseph Cohen to allow comparison of effects in different studies (Cohen, 1988). There are various 'effect sizes' and Cohen's d is used to examine mean differences. Cohen's d is known to have an estimation bias when sample sizes are small. Therefore, a correction factor is used for sample sizes below 50 (see equation 2 below):

Cohen's Equation (1) $$d = \frac{M_E - M_C}{\text{SD pooled}}$$

Corrected Cohen's Equation (2) $$d\ (\text{corrected}) = d \times \left(\frac{N - 3}{N - 2.25}\right) \times \sqrt{\frac{(N - 2)}{2}}$$

Pooled Standard Deviation Equation (3) $$\text{SD pooled} = \sqrt{\frac{(SD_E^2 + SD_C^2)}{2}}$$

In the above equations N refers to the total sample size; M is the mean, where the subscripts E and C refer to the experiment and control group respectively, SD is the standard deviation (Durlak, 2009)

Typically, d values are reported within two decimal places and where a positive value exists it suggests a positive effect for the intervention group whilst a negative d suggests a negative effect. Of course, a positive d does not mean a superior or successful outcome *e.g.* if we were studying the effect size of an intervention on levels of depression then a negative d would be superior. In our case, when we compare the mean RT between two conditions then a positive d would indicate faster responses for the second condition. On the other hand, when we compare mean accuracy rate between two conditions then a positive d would indicate more errors for the second condition.

We use the conventional interpretation of the ES d results (Cohen, 1988):

- Small effect = 0.2
- Medium Effect = 0.5
- Large Effect = 0.8

But we understand that the cut-off points outlined above were suggested by Cohen as a ‘rule of thumb’. Ultimately the onus is on the investigators to decide how to evaluate the importance of their findings in the wider context of their research (Durlak, 2009).

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Chapter 3: Development of a Novel Haptic Reaction Test Device

3.1 Haptics

Since the time of the Greek philosopher Aristotle (384–322 B.C.) and until almost the modern era it was believed that humans only had five senses: hearing, vision, taste, smell, and touch, with a sixth sense being considered as one of a somewhat supernatural dimension. This fallacy still prevails in modern popular culture even though many diverse types of sensory receptors in the human body have been discovered including: baroreceptors (blood pressure), chemoreceptors, mechanoreceptors, nociceptors (pain), proprioceptors (body position), thermoreceptors (temperature), and others.

Necessary information from an electric or electronic device to its user is conveyed mostly through the senses of vision and hearing. Whether the light emitting diode (LED) on a computer, to indicate when it is on, or the high pitch audio alert from the rear side sensors, when reversing a car that is approaching an obstacle, the use of audible and visual alerts has been dominant in most products. There are situations though where audio or visual alerts are unsuitable. A sound alert in a very noisy environment may be ineffective. Visual alerts displayed out-with the visual field of the person who needs to be alerted to some action or danger can be futile. For example, an image alert to an imminent engine failure on a car's dashboard can be missed by a driver who is concentrated on the motorway traffic ahead. In the turn of the 21st century, and following a much better understanding of human physiology, haptic technology has allowed for an alternative route of communication between a device and its user via vibration signals that can be detected by the human body's mechanoreceptors.

The word 'Haptic' originates from the ancient Greek 'ἁπτικός': relating to touch or sensitive to touch. Haptic technology makes use of tactile sensors, in particular the mechanoreceptors found in the fingertips and palms, to establish an interaction between the user and a device. In this study when we refer to haptic technology, we specifically mean the generation of vibrations by a device that are experienced by a user to deliver a signal or message of some kind.

There are various sensory receptors located in glabrous skin (*i.e.* skin devoid of hair follicles such as over the palms and soles of the feet). There are four major types of mechanoreceptors that can relay information to the central nervous system about touch, pressure, vibration, and cutaneous tension (Figure 3-1). These mechanoreceptors are: the Pacinian corpuscles (sensitive to vibration), the Meissner's corpuscles (sensitive to light touch), the Merkel cells (grip control), and the Ruffini corpuscles (sensitive to skin stretch). With the discovery of cutaneous mechanoreceptors and the subsequent understanding of their properties (Johnson, 2001) the field of haptic technology and communication has developed considerably. It has been shown that the Pacinian corpuscles can respond to a vibration amplitude as low as 10 μm and frequency as low as 40 Hz (Brisben *et al.*, 1999; Skedung *et al.*, 2013), with the maximum sensitivity achieved at around 250 Hz (Scheibert *et al.*, 2009). This level of sensitivity of mechanoreceptors in the glabrous skin means that vibration signals that can exceed detection threshold can be produced by small, specialised components (actuators) in electronic devices with low energy demands and at a low cost.

The use of haptic feedback is now widespread with notable examples being the feedback from touch screens when pressing tactile switches, or onscreen keyboards, and haptic perception in virtual reality systems in some video games. In fact, most people experience haptic technology daily through the vibration alert that they may receive from their mobile phones, game controls or other devices.

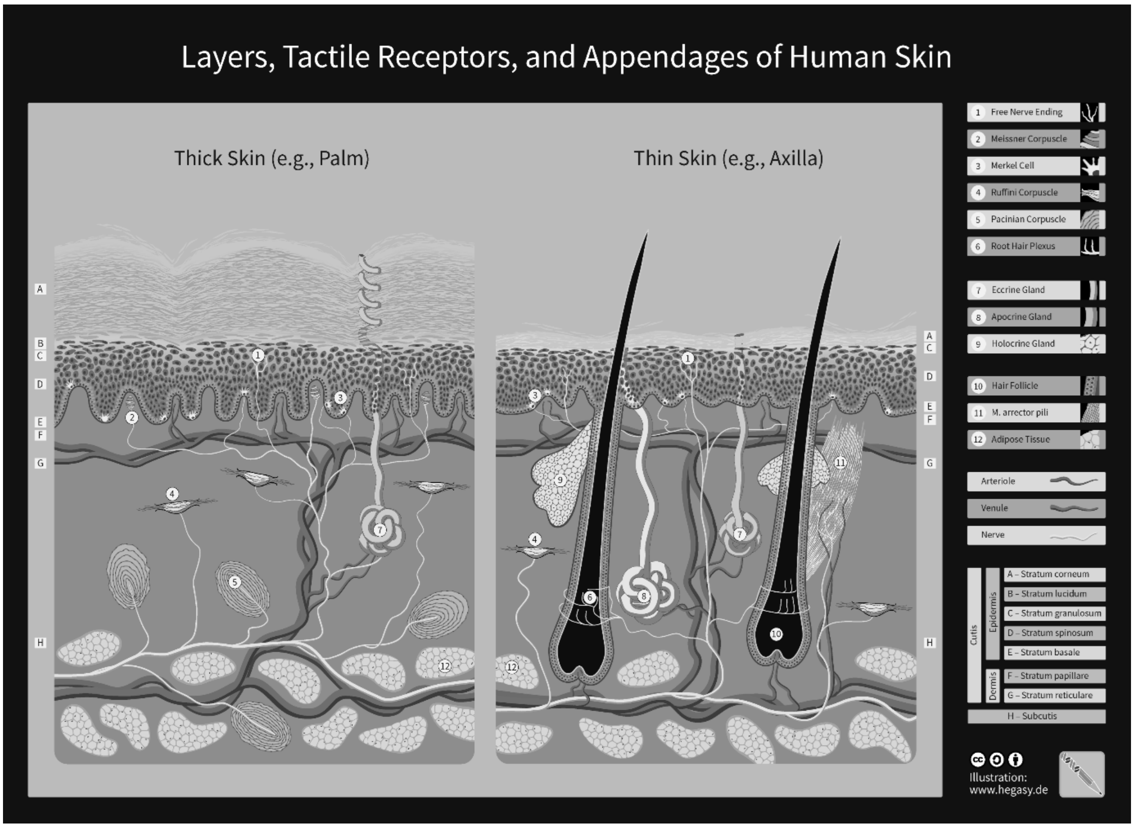

Figure 3-1. Mechanoreceptors within human glabrous and thin skin.

Notice the wider range and greater density of tactile receptors in glabrous skin (thick skin) including Meissner corpuscle (2), Merkel cell (3), Ruffini corpuscle (4), and Pacinian corpuscle (5).

Image copied from:

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3.2 Vibration

Vibration is a mechanical oscillating motion, characterised by the rapid and repetitive movement to and from an equilibrium point (*i.e.* the neutral point). A repetitive oscillation can be represented by a sinusoidal wave (Figure 3-2). A familiar example of an oscillating motion is the swing movement of a pendulum. Vibrations can be linear, circular, periodic or non-periodic, and they can be the intended outcome of a design *e.g.* vibration feedback from the steering wheel in virtual reality car racing games, or the indication of some damage *e.g.* vibration feedback from the steering wheel when driving at speed in a real car and the front tyres are unbalanced.

Linear vibration is achieved by a linear resonant actuator (LRA), a type of vibration actuator that has a small internal mass attached to a spring, which moves linearly up and down when driven. LRAs were widely used in earlier designs of force plates found in gyms but they are now used a lot more in telecommunications and wearable products where a vibration functionality is desired. LRAs provide faster response time and longer lifetime compared to the alternative type of vibration method: the eccentric rotating mass (ERM) motor. Pager motors are an example of ERM motors used in early haptic technology. ERM motors produce vibrations by rapidly spinning a shaft with an off-centre load. The uneven mass distribution around the axis of rotation creates an uneven centripetal force which in combination with the speed at which the shaft spins the unbalanced load results in vibrations. The lack of shaft allows ERM actuators to be exceedingly small, typically 10 mm in diameter and 2 mm in height and easy to mount on the desired surface. Both LRA and ERM vibration motors are controlled by a haptic driver chip and driven by an electronic circuit where a microcontroller dictates the timing and pattern of the vibration.

Vibration can be characterised by amplitude and frequency:

- Vibration amplitude is the magnitude of an oscillating motion over a reference point, or in other words, the severity of the vibration. Vibration amplitude is usually expressed as the peak velocity highlighted by the line ‘a’ in Figure 3-2 or as the peak-to-peak value highlighted by the line ‘b’. An alternative, but less used, definition of vibration amplitude considers the root mean square (RMS) of the velocity amplitude. RMS includes the time of the vibration wave's cycle and gives an amplitude value that is related to the energy content of the vibration.

- Vibration frequency is the number of cyclical occurrences per unit of time, more specifically, the number of motion cycles achieved in one second and is thus expressed in cycles per second or hertz (Hz). Often, manufacturers of ERM actuators only report the motor's revolution per minute (RPM). In such cases the vibration frequency can be calculated by dividing the RPM over 60 seconds *i.e.* Hz = RPM/60.

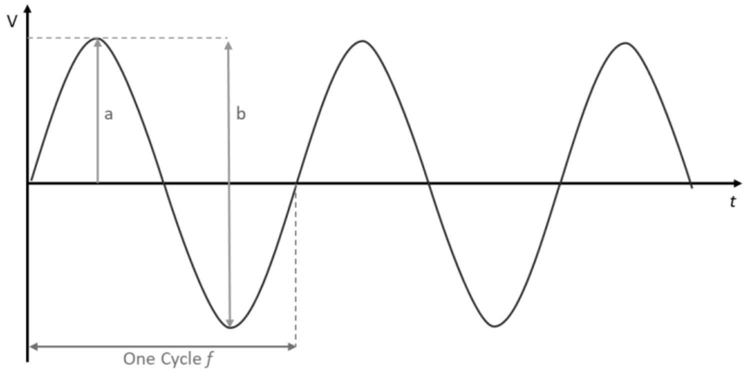

Figure 3-2. A graph of a typical oscillating movement time domain.

A sinusoidal wave represents the time period of a complete cycle (*f*) and can be described by the mathematical formula $V(t) = A * \sin(2\pi f t + \Phi)$, where t = time, A = amplitude, f = frequency (cycles), $2\pi f$ = angular frequency, Φ = phase of the oscillation.

3.3 A haptic reaction test device for Judo

Advances in haptic technology mean that it is now possible to create a low cost, practical, and reliable electronic device to test reactions to a haptic prompt: the stimulus that utilises the same sensory modality used by experienced judoka in training or competition. To the best of our knowledge such a device has never been designed before for Judo or other sports. The device we describe in this chapter is the prototype design we have used in our research in Judo. We have used this device to complete multiple series of data collection from haptic reaction tests.

By integrating haptic technology in a purpose-built reaction testing device (Figure 3-3) we aim to obtain accurate, reliable, and meaningful data on reaction time (RT) and accuracy (percentage of correct responses over the total of responses) in a haptic choice reaction test carried out by experienced judokas. Beyond judo, other applications for this device may include use for tests in visually impaired athletes in any sport or for other research projects unrelated to sports performance where reaction data on haptic stimulus can be of importance.

Figure 3-3. The haptic reaction testing device.

The device is connected to a laptop via USB to transfer raw data after reaction tests were completed. Each grip on the sides has two actuators located in the upper part of the grip (A) and the lower part of the grip (B). The mini joystick (C) is located next to the Liquid Crystal Display screen.

3.4 Design objectives and outcomes

The haptic reaction test device was developed in conjunction with the technician of our research laboratory who provided the expertise and time to design the hardware and develop the source code used to run the tests. The chief investigator gave feedback to the technician at various stages of the device's development to help improve the user-friendliness of the device and the quality of the data collected. Further improvements to the device were carried out following feedback from volunteers who took part in the pilot study described in section 3.7.2. Below, we outline the objectives we had in mind when we set out to design, and produce, the haptic device to test choice RT and accuracy in judokas.

Budget

Perhaps the most common limitation when building a prototype device is available budget. In our case we wanted to build a useful device that could be reproduced, used, and maintained by other researchers or coaches at a low cost. It is reasonable to assume that more people are likely to replicate the device and use it in research or training if it is not expensive to reproduce. We were able to produce a fully functional device for under £100 in 2017.

Low maintenance and running costs

This device has been designed so that it can be easily reproduced, run, and maintained. Other than the inside part of the ERM actuators (where the vibration is generated) there are no moving parts within the device, which makes it more likely to resist wear and tear over time. All of the components are robust designs and are not subject to mandatory upgrades to continue functioning. The device runs on a 5V battery that gives enough power to run multiple tests and can be recharged via a mini-USB cable.

Dynamic test protocols

It is important to have a testing device that can meet the specific requirements of different research projects. Our device can be programmed to allow changes to the number of people tested, the number of reaction episodes per test, the inter-stimulus interval time (the time period between reaction cues), the type of reaction test (simple or choice), the test modality (haptic or visual), the sequence of the tests carried out and other functions. These changes are accessible via simple computer coding.

Test methods variety

We wanted to validate our device against already established RT methods. Thus, it was important that we included alternative test modalities, such as visual reaction tests, in the device alongside haptic tests. We therefore created a device that can offer simple reaction and choice reaction tests in visual and haptic mode.

Unobtrusive

For athletes to integrate a test into a training session or competition, the test needs to be quick to set up through a device that is user friendly to avoid undue inconvenience or disruption to their usual routine. If the test is not perceived as a hindrance, then it is more likely that the athletes will engage in the testing process. It takes just under two minutes to: 1) start up the device, 2) select a username, and 3) complete a test with 20 reaction episodes, with the time taken for the first two steps being several seconds long. There is an option for the investigator to add a step where the user can also select the test mode but the type of test is most likely going to be predetermined and therefore, already set up for the user in most situations.

Sport specific

We can have more confidence in the ecological validity of reaction data collected if the reaction prompt is compatible with the dominant sensory route used. In the case of judoka this route is through the mechanoreceptors in the skin of their fingertips and palms. In addition, the response task should allow enough freedom of movement to be able to replicate sport specific actions. For our specific project the device was designed to be held with both hands to simulate the typical judo grip judoka perform when holding their opponent’s sleeve. In fact, the grip on either side of the device was dressed in the same material the official competition judogi is made of to enhance the sense of familiarity on the grip. Also, the device does not impose the typical task, or location, restrictions seen in other tests that can only be carried out in laboratories or with impractical equipment. By its nature, the device allows for a test to be carried out at any training or competition environment the judoka may be and allows freedom to decide the starting position and the task movement. For our project with judoka this consideration was an important one for a successful test. Of course, the freedom of task movement is subject to the condition that both arms move sharply in the correct direction for a fraction of a second when movement is initiated and on the same plane with the starting point. For example, if in the start position the user holds the device parallel to the ground then the initial sharp displacement of the device should be towards the direction indicated by the location of the actuator that has been activated in the device but still parallel to the ground. The device only records the time it takes to initiate locomotion and the direction chosen, which allows the user freedom to execute sport-specific movements of their choice after the initial movement.

Portable but robust

We wanted a device that was portable, light, and could be used at the dojo (training area for Judo) or at any competition around the World but also to be robust enough during travel and during use by athletes like judoka who tend to have extraordinarily strong grips. Our prototype device weighs under 240g, is small (length = 10 cm, width = 20 cm, height = 4.5 cm), and is robust. Aside from the four ERM motors the device has no moving parts and the electronic components are protected within a durable casing. Our device is light and durable enough to be used without causing physical fatigue or getting damaged during use or transport in hand luggage.

Data

Another important objective was to have a device that can record and store highly accurate data that can be easily transferred to another platform for further analysis. Our device records each response to every reaction stimulus in microseconds (μsec = 10^{-6} of a second) and stores the data in plain text format. Study investigators can transfer the stored data via USB to a computer where a serial port terminal programme (HT Comm) has been installed. The HT Comm is a free software (https://www.hobbytronics.co.uk/ht-comm) that allows text strings to be sent via a serial connection to an attached device. Subsequently, the data transferred to the computer can be saved in different ways but CSV is the preferred format as it allows for data to be transferred to and used by any other software for statistical analysis.

Hygiene

Hygiene considerations were important because we wanted our device to be handheld and to be used by many different judoka in their training environment. We used materials that are easy to clean so that with a little effort in cleaning, the device is unlikely to be a hygiene hazard. More specifically, the cloth around the grips can be removed to be washed and the device’s casing can be cleaned with antibacterial wipes.

3.5 Alternative methods for reaction tests

Even though there are some straightforward ways to turn any modern computer into a reliable reaction test device (Dalrymple-Alford, 1992; Voss *et al.*, 2007), to date several commercial and open-source software packages have been developed that offer an array of reaction tests used in cognitive research such as CANTAB (Cambridge Cognition Inc., UK), DLRT (The University of Edinburgh, UK), E-Prime (Psychology Software Tools Inc., USA), Experiment Builder (SR Research Ltd., Canada), Presentation (Neurobehavioral Systems Inc., USA), and Psykinematrix (Kybervision, LLC, Japan).

- The Deary-Liewald Reaction Task (DLRT), developed by Ian Deary and David Liewald (Deary *et al.*, 2011) is one example of a validated computer-based reaction test. It is a simple test to administer, and the software is freely available via the DataShare webpage of the University of Edinburgh (https://datashare.is.ed.ac.uk/handle/10283/2085).
- The Cambridge Neuropsychological Tests Automated Battery (CANTAB) is a computer-based test that was developed by Trevor Robbins and Barbara Sahakian at the University of Cambridge. CANTAB is now a commercial product of Cambridge Cognition who proclaim it to be the 'Gold standard' in cognitive research (https://www.cambridgecognition.com/what-we-do/gold-standard-cognitive-research/). However, some researchers have recommended caution as CANTAB has been shown to be moderately associated with traditional neuropsychological tests (Smith *et al.*, 2013). Furthermore, CANTAB has considerable cost implications despite the availability of much cheaper, or even free, software products that offer similar functionality.
- PsychoPy, is an open-source programme (Peirce *et al.*, 2019) written in the programming language Python. PsychoPy allows users to set up reaction experiments on a computer to desired specification including parameters such as test stimulus (either visual or auditory), inter-stimulus intervals, response modality *etc.*

Whilst the tasks involved in the tests from these software packages can be user friendly neither is particularly practical as they require a laptop or tablet computer to run their programmes, and neither had haptic tests available at the time of our investigations.

Perhaps the best known but low technology reaction test is the ruler drop. This test is arguably the cheapest and most rudimentary reaction test requiring only a standard ruler and the help of an assistant. For the test, a ruler is dropped for the participant to catch with the dominant arm's index finger and thumb (for a detailed description of the ruler drop test see Eckner *et al.* 2010). Due to its low cost and practicality, this test has been used as an alternative field test to computer tests when assessing athletes' fitness to return to play *e.g.* after sport related concussion (Eckner *et al.*, 2010; MacDonald *et al.*, 2015). Another advantage of this specific test is that unlike computer-based tests there is no technical latency involved as there are no peripheral components through which a signal needs to be relayed; the time estimated is purely the response time. However, the ruler drop test was overly simple for our purposes and did not have ecological validity for Judo specific stimuli. Also, the response time is not measured directly but rather estimated by observing values on the ruler and then using the following formula:

$$t = \sqrt{\frac{2d}{g}}$$

Where t = time in seconds, d = the distance the ruler dropped in meters, and g = the standard gravity of 9.806 m/sec^2. Hence, there are several sources for potential error that can impact on the desired level of accuracy and precision. Sources of error may include the parallax from the observer's chosen viewpoint from which the ruler value is read, typing errors when entering values to the formula, or erroneous calculations.

3.6 Design

3.6.1 Electronic components

A range of electronic components were necessary to build the haptic reaction testing device to meet the desired objectives outlined earlier in this chapter. Each item is described below along with the manufacturer part number (MPN) where applicable.

- Microcontroller
    - The reaction test protocols were run via the Arduino Mega2560 microcontroller (Figure 3-4) Arduino produces open-source boards allowing custom source code to be written and uploaded so the board can control specific components. Arduino code was written by the research team technician to run reaction test protocols as required for the study. The board includes 54x digital I/O pins, 16 analogue inputs, 4x hardware serial ports, 256 KB flash memory, and 16 MHz clock speed. The board is user friendly and can be powered by battery.

Figure 3-4. Arduino Mega2560 microcontroller

- Accelerometer
    - The ADXL335 Accelerometer (Figure 3-5) from Seeed Studio (MPN: 101020051) is a small, thin, low power, 3-axis accelerometer with signal conditioned voltage outputs that measures the static acceleration of gravity in tilt-sensing applications as well as dynamic acceleration resulting from motion, shock, or vibration.

Figure 3-5. 3-axis accelerometer

- Real Time Clock (RTC)
    - The Adafruit DS3231 (Figure 3-6) Precision RTC (MPN: 3013) is a highly precise breakout board with the timing crystal inside the chip. There is a temperature sensor right next to the integrated crystal so that clock ticks can be added or removed to maintain accuracy even when temperature changes. A CR1220 coin cell can keep the clock running for years.

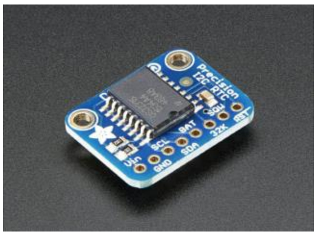

Figure 3-6. Precision real time clock

- Coin vibration motor
    - The tactile stimuli were delivered via coin ERM actuators (Figure 3-7) from Precision Microdrives (MPN: 310-004) with 1.5V operating voltage, 7300 RPM vibration speed, and approximately 122 Hz frequency. This product is a shaftless ERM vibration motor enclosed in a metal coin shape case 10 mm in diameter and 3.4 mm in height (for more information see Appendix A). A pair of motors were placed on each grip and each pair was mounted approximately 80 mm apart, as measured from each motors centre. This arrangement of the actuators allowed to create two distinct vibration sources on each handle grip of the reaction testing device. Thus, vibrations could be localised in the upper part of the user's

grip (through the skin surface of the *pollex,* or thumb) or in the lower part of the grip (through the skin surface of the *digitus minimus manus,* or little finger, and palm area over the hypothenar muscles).

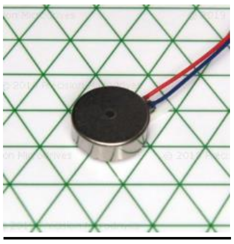

Figure 3-7. Coin vibration motor

- NPN Transistor
    - A transistor is a current-controlled three-terminal device used as an amplifier. NPN transistors are semiconductors, and they have a positive layer ‘P’, also known as ‘base’, fixed between two negative layers ‘N’: the ‘emitter’ and the ‘collector’. A device such as the octal Darlington driver (MPN: ULN2803A), with a 500 mA transistor array of eight NPN Darlington pairs (Figure 3-8), can increase the current gain in a circuit further because each pair of transistors results in a current gain that is equal to the product of their individual current gains. This specific transistor was used as an open collector output *i.e.* a collector that is not attached to anything but rather acts like a switch that turns on to allow a higher current to flow when sufficient power reaches the base of the transistor.

Figure 3-8. NPN transistors

- PNP Transistor
    - PNP transistors have a negative layer ‘N’ fixed between two positive layers ‘P’. The TO92 30V by CDIL (MPN: BC559C) is a general purpose PNP transistor (Figure 3-9) suitable for signal processing, switch and amplification applications and in this project it was used to operate as an ON/OFF type solid state switch.

Figure 3-9. PNP transistor

- Electrolytic Capacitor
    - A capacitor is a two terminal component made up by two conductive plates separated by an insulate material, which can temporarily store electrical charge. Compared to conventional batteries, capacitors can store a lot less energy but can charge and discharge at a much faster rate, which makes them useful components when a burst of energy is required in the integrated circuit. In contrast to ceramic capacitors, electrolytic capacitors are polarised and can only be connected in a specific direction so that the longer lead is used as the positive terminal (cathode) and the shorter lead as the negative terminal (anode). In this project, an electrolytic capacitor was used to maintain a power supply in the electronic components of the device and prevent the loss of data while the device was unplugged from a power source and without a battery for a short time. The capacitor used was the micro miniature radial aluminium electrolytic capacitor (Figure 3-10) by Forever (MPN: 7MM MICROMIN10U16V) that has 10 μF capacitance with 20% tolerance and can withstand up to 16 Volts.

-

Figure 3-10. Electrolytic capacitor

- Signal Diode
    - Diodes are simple semiconductor components that allow current to flow through them in one direction only, like a one way valve. They are often used to prevent reversal of polarity. The semiconductor signal diode (Figure 3-11) by Fairchild (MPN: 1N4148TR) is a standard high speed switching diode with 200mA forward current.

Figure 3-11. Semiconductor signal diode

- Liquid Crystal Display (LCD) screen
    - The Arduino colour thin film transistor (TFT) LCD screen (MPN: A000096) is a backlit screen (Figure 3-12), 45mm diagonal length, with a micro SD card slot in the back that allows for the drawing of images and shapes in 160 x 128 pixels screen resolution.

Figure 3-12. Liquid Crystal Display (LCD) screen

- Mini Joystick

  - A 5-Way tactile switch breakout board module (Figure 3-13) compatible with Raspberry Pi Arduino for a joystick-like interface.

Figure 3-13. Mini joystick

- Micro-USB Breakout Board
  - Breakout boards take pins from an integrated circuit and break out each conductor to a terminal giving easy access to the integrated circuit. This Adafruit USB micro-B breakout board (Figure 3-14) by Adafruit (MPN: 1833) was used to establish a socket through which communication with the microcontroller is enabled and 5V of Direct Current (DC) power can be supplied.

Figure 3-14. Micro-USB breakout board

- Power Supply Charger
  - The Adafruit PowerBoost 1000C (MPN: 2465) is a power supply for 5V portable projects (Figure 3-15). It has a low battery detection facility, more than 90% efficiency, and 700 KHz high-frequency operation. The built-in battery charger has load-sharing that automatically switches over to the USB power when available

Figure 3-15. Power supply charger

- <u>Lithium Cell Batteries</u>
    - CR2450 lithium coin cell batteries (Figure 3-16) by Energizer CR2450 (MPN: 638179) with 620mAh capacity.

Figure 3-16. Lithium coin cell batteries

- <u>Stripboard</u>
    - This 95 x 127mm strip-board (Figure 3-17) by Rapid (MPN: 34-0515) was used as a prototyping board to build the device’s circuit.

Figure 3-17. Stripboard

3.6.2 Shell and Handles

The casing for the device was made using a 3D printer (FlashForge 3D Printer Creator Pro) using acrylonitrile butadiene styrene (ABS) plastic, which is 100% recyclable. On the left and right sides of the device we created a handle grip that the user can use to simulate a typical Judo grip. Each handle was also dressed in judogi material to enhance the sense of familiarity by the judoka who use the device. Another advantage of using this specific type of fabric is that it is durable material designed for heavy duty and can be removed and replaced with ease as needed for cleaning (Figure 3-18). The entire device can be easily cleaned with a simple antibacterial wipe. Attention to hygiene is important for using a device that is most likely going to be passed around many different hands with no guarantee that all hands will be clean enough and without sweat.

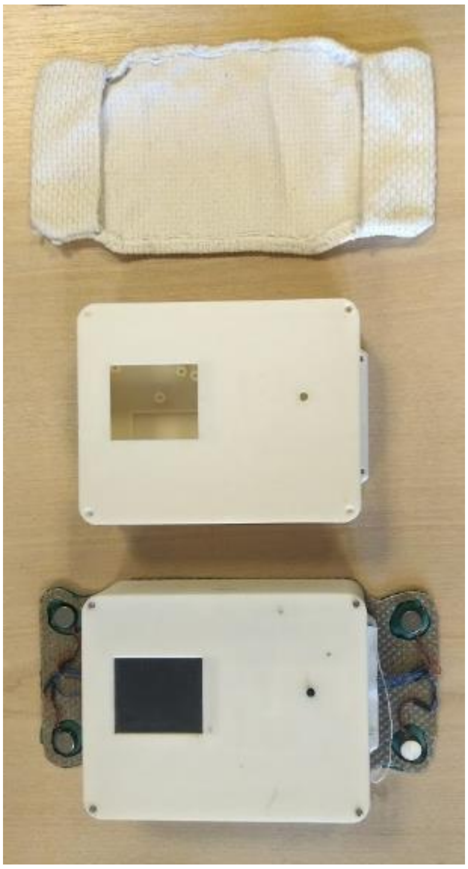

Figure 3-18. The casing of the reaction device.

The judogi material used to cover the grips (top), the ABS plastic casing that housed the integrated circuit (centre), and the reactions device fully assembled before its handle grips are covered with the judogi material (bottom).

3.6.3 Arduino software

Arduino is an open-source hardware, software, and content platform with a worldwide community of over 30 million active users (https://www.arduino.cc/). Any Arduino microcontroller can be connected via USB to a computer where it can be programmed using Arduino code via the open source Arduino Integrated Development Environment (IDE). Arduino code will function on any of the three major operating systems *i.e.* Windows, Mac OS X, and Linux. Code is easily uploaded to the microcontroller via USB and this code is then executed allowing interaction with inputs and outputs as programmed.

A distinctive advantage of using Arduino code is that it is easy to alter and upload to the Arduino microcontroller whenever a change in functionality to the project is required. Additionally, there is a dedicated support network of experienced Arduino users online and a wealth of useful online resources. Arduino code has several built-in libraries, a common feature of most programming platforms, which provide basic functionality. There is also capacity to import other libraries that can expand the Arduino microcontroller capabilities and features. Arduino projects can be designed online through Circuito (Figure 3-19), an application where users can visualise their integrated circuit design, view costs of materials, and test code (https://www.circuito.io/).

Creating code for an Arduino project and maintaining it is free. And although the Arduino language is based on C/C++ there is no need for prior knowledge in programming languages as tutorials for complete beginners are available online. There is also a programming environment available called ArduBlock that is designed for beginners in Arduino projects. In ArduBlock the user can take advantage of a list of code blocks to visually set up a code instead of using a proper programming language making Arduino projects accessible to more people who do not have any technical expertise in programming languages.

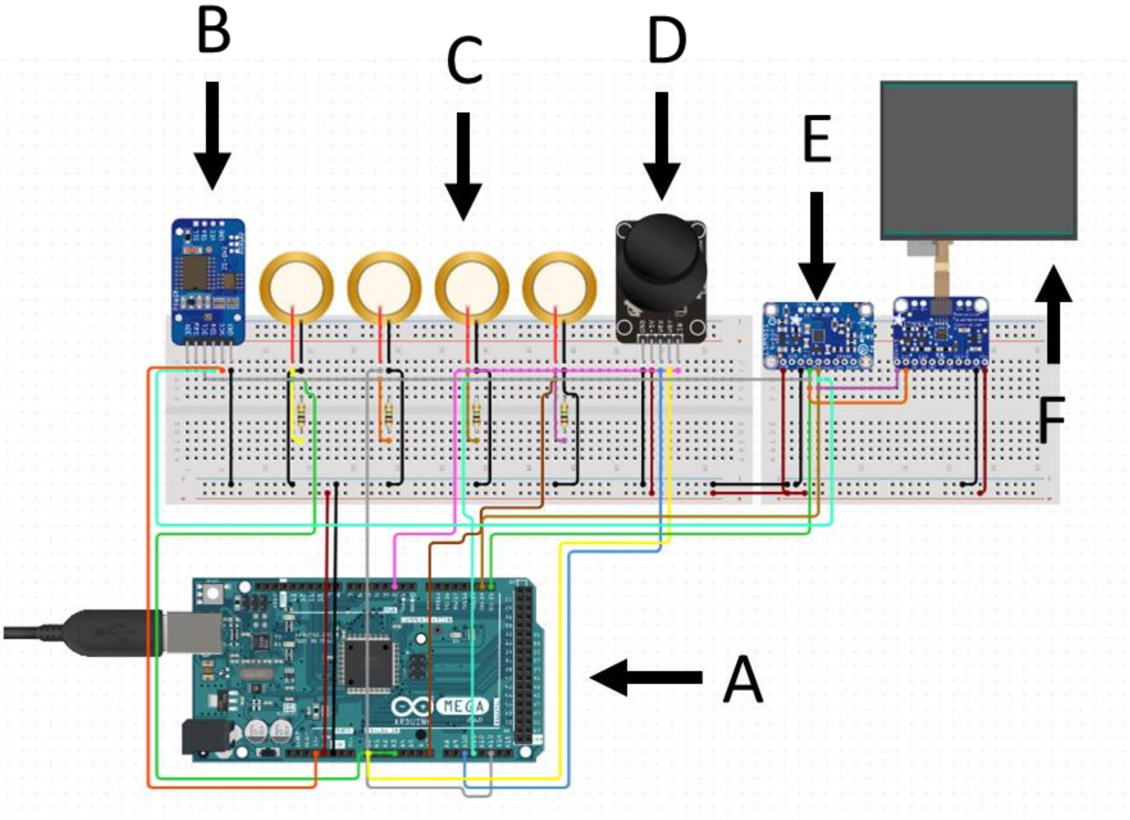

Figure 3-19. A high-level integrated circuit schematic of the reaction device.

Note this is an example of an integrated circuit schematic as viewed on Circuito (https://www.circuito.io/). In this example the Arduino Mega2560 microcontroller (A) is connected to some of the electronic components listed in this chapter: precision timer (B), ERM actuators (C), mini joystick (D), 3-axis accelerometer (E), and LCD screen (F).

3.7 Testing

3.7.1 Latency

An electrical current is needed to provide energy to the ERM coin vibration motor for it to reach its peak RPM, which means that it takes time for the motor to achieve the necessary acceleration to change its RPM from 0 to its maximum value. Hence, we had to investigate the typical latency magnitude of the ERM actuators between the start of the current flow (start of a reaction test episode) and the change in the ERM's amplitude and frequency. We used a standard oscilloscope to run repeated tests on the ERM motors to ascertain their mean latency value (Figure 3-20). After 20 tests the median latency was 60 msec with a 2% coefficient of variation (CV). With such low CV we were confident that 60 msec was a fair representation of the true latency value for any reaction test carried out with these specific ERM motors.

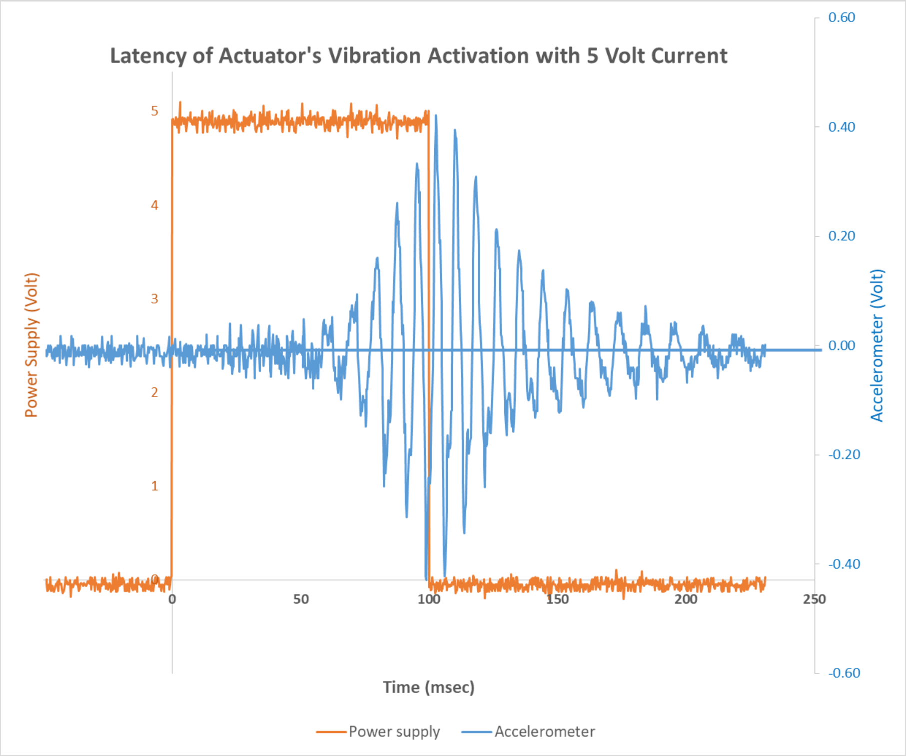

Figure 3-20. Latency of Actuator' vibration activation.

A graph showing 5 Volt power supplied to the motor (orange line) for 100 msec and the ERM motor's response with an acceleration that takes approximately 60 msec to show a distinct change in the amplitude of oscillation (blue line). The peak amplitude values continue to increase up to the point the current flow is stopped at 100 msec after which point the amplitude returns to its resting value within the following 120 msec.

3.7.2 Pilot data

Once the prototype device was put together, we examined how easy it was for the device to be operated by a new user and how convenient it was to carry out a test protocol. We asked six volunteers to test the device for functionality. The test itself was informal and carried out at the University of Stirling by undergraduate students. No information other than usability of the device was collected from these volunteers.

Before each participant started the test a demonstration was carried out explaining how to hold the device, how to turn it on, and how to perform a visual choice reaction test and a haptic choice reaction test (for details on the test procedures see Chapter 4). A trial run on each test was allowed and the participants were free to start the tests when they felt ready to do so. The device was set up in such way that when the user switched it on they just needed to select ‘start’ on the screen by depressing the mini joystick. Once the test was started the user had to carry out 10 responses in the choice reaction mode with a visual cue displayed on the screen (a white arrow against a black background). After a short break, another 10 choice responses followed but the prompt would come from a haptic signal (vibration) instead.

Following the conclusion of the tests all participants reported that they found the device easy to use, comfortable to hold, and light. However, the participants also reported that they could not always differentiate between which one of the two ERM motors in each handle grip was producing the vibration signal. For example, if one of the two actuators in the left handle was activated the participants could sense the haptic signal in their left hand but not the exact location it originated from. After examining the data collected it was immediately apparent that there was an issue with the haptic signal. The error rate for the visual choice reaction test was 0% whilst the error rate for the haptic equivalent test was 63%.

One explanation for the lack of clarity in the vibration signal, and the subsequent extremely high error rate in the results, is that in the original design the actuators were attached on the layer of stripboard that was used to base the rest of the materials on. Thus, when a vibration motor was activated the vibration signal most likely spread across the stripboard area making it very difficult for the user to pinpoint which one of the motors was producing the vibration signal. To remedy this issue small holes were created on the strip-board in each area where previously an actuator was attached (Figure 3-21).

This modification allowed each ERM coin vibration motor to fit in place without being in contact with the stripboard. Instead, the motors were attached to a thin plastic membrane layer underneath. This small adjustment to the internal design of the reaction device led to an improvement in the haptic signal quality. In follow up pilot tests we found that the error rate during a choice reaction haptic test dropped from 63% to around 15%. The participants in this test confirmed that when they made a choice error they were aware that they had done so, which demonstrated their awareness of where exactly the signal came from.

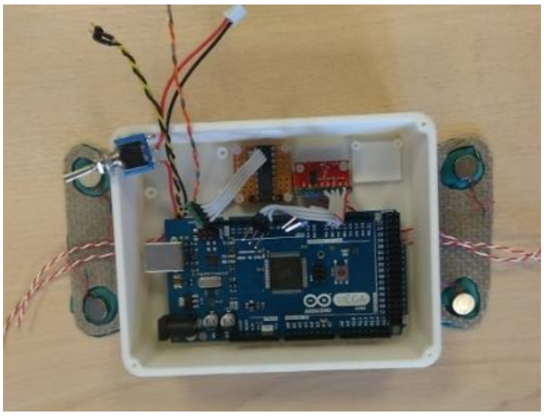

Figure 3-21. Correction of haptic signal from the device.

A hole was made on the stripboard on each area where an ERM vibration motor was placed. Notice that each motor is attached to a thin plastic membrane (green) and has no contact with the thicker and harder stripboard. This small change in the design improved the quality of the vibration signal and made it easier to pinpoint the direction of the haptic stimulus.

From the data collected we were also able to confirm that the intra-stimulus intervals between reaction prompts were at random as was the choice of actuator activation (from the four actuators that could be activated). Thus, we are certain that the likelihood of a user guessing the start of a signal and the correct response in choice reaction tests is practically impossible.

3.8 Conclusion

Reaction tests are widely used to assess information processing ability in people. In performance sports where quick and correct decisions are important for success reaction tests may be used to monitor improvement in execution of tasks (*e.g.* sprint starts) or to help assess readiness for return to play after concussion in contact sports. Historically, all reaction testing methods developed have been based on visual perception or audio perception. In a sport like Judo, where the dominant sensory input is tactile it is sensible to utilise reaction tests based on a more ecologically valid sensory modality such as a haptic signal.

We have produced a novel, judo-grip specific reaction testing device where the reaction stimulus is a haptic signal. The device is portable, light, robust, and inexpensive. This device is easy to reproduce by any electronics enthusiast and it has minimal maintenance and running costs. The RT data are saved in a plain text file and can be transferred with ease to a computer for statistical analysis. Another important advantage of the device's design is that it allows testing to be carried out within a brief time period and wherever the judoka train or compete without disturbing their routines.

3.9 References

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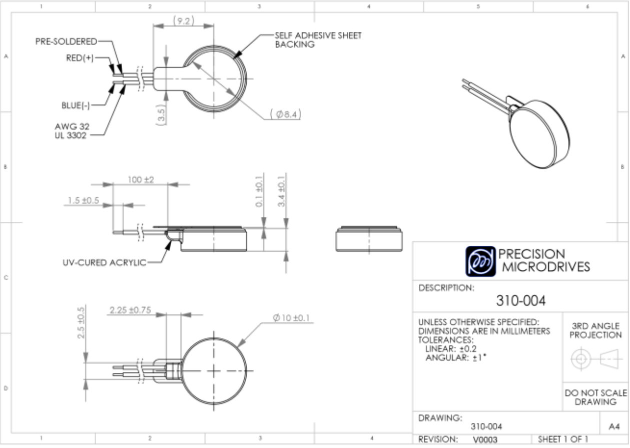
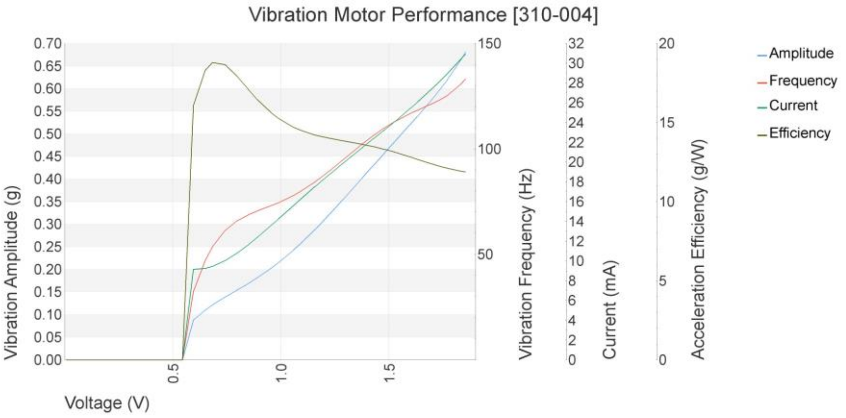
3.10 Appendix A

3.10.1 Coin vibration motor

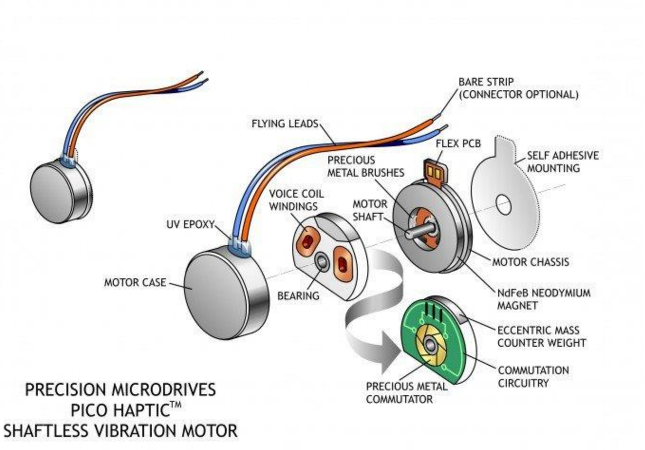
Product Dimensional Specification



Typical Vibration Motor Performance Characteristics



Exploded view of a Coin Vibration Monitor



Source: https://www.precisionmicrodrives.com/vibration-motors/coin-vibration-motors/

Chapter 4: Reliability and Validity of a Novel Haptic Choice Reaction Test Device for Judo

4.1 Introduction

In Chapter 3 we described the development of a haptic choice reaction test device, the components we used to put it together, and the design objectives. In this chapter we describe the battery of reaction time (RT) tests carried out by a cohort of volunteers against a criterion method to examine the reliability and validity of our novel device.

Cognitive performance as manifested by the ability to react rapidly to an opponent’s move, or to any scoring opportunity, is necessary in many sports. Fast reactions are not just advantageous for the performance result but can also help prevent or minimise injuries through better anticipation (Honda *et al.*, 2018). Hence, from racket sports and ball games to sprint races and combat sports, improving RT has become an integral part of most athletes’ training regimens. With the increase in interest in collecting RT data came the need to develop practical, valid, and cost-effective reaction tests that can be carried outside a laboratory and can help assess more accurately competitors’ RT (Eckner *et al.*, 2010; MacDonald *et al.*, 2015).

Beyond the performance driven monitoring of RT, other uses of reaction tests can have a more clinical purpose. For example, RT as well as other cognitive function parameters can be negatively affected following a concussion (Harmon *et al.*, 2013). Changes in RT from baseline can aid in figuring out the necessary time to clinical recovery (Lau *et al.*, 2009). The potential of RT values as a diagnostic tool has led to a growing interest in reaction tests that can be used as part of routine pre-season physical examination in sports with concussion risk (Broglio *et al.*, 2007; Eckner *et al.*, 2011). In some cases, field tests have been developed that are merely a variation of the classic ‘drop and catch’ ruler test (Eckner *et al.*, 2009). These tests appear to be sensitive enough to identify athletes with a concussion in cases where pre-concussion RT results are known (Eckner *et al.*, 2010). Judo is a full contact combat sport and the risk for concussion, although not as common as in sports like rugby or American football (Bakhos *et al.*, 2010), is still a concern. Arguably, by having a judoka’s baseline reaction data from a reliable and ecologically valid test, then if that judoka suffered a concussion the clinical and support staff could have another piece of useful information when trying to reach a conclusion about the progress of recovery and the safe return to training.

In earlier chapters (see Chapters 1 and 3) we have argued that when trying to assess athletes’ RT it is better to choose a method where the type of stimulus used to initiate a reaction is compatible with the dominant sensory modality used in the chosen sport. For example, in athletes who race the 100 m sprint event in athletics, it is preferable to know how quickly they can react to an audio cue given that the start signal is the sound of a gunshot. In the case of boxers, it would be better to know how quickly they can respond to a visual prompt given that boxers have to react to their opponent’s attacks through visual stimuli. In a team sport like basketball, it is perhaps more relevant to understand how quickly the players can capture and process a high volume of visual information given that they have to take a glance during fast play on the court and identify the position of their teammates and the openings available in the opposition’s defence that can be exploited to create a scoring opportunity. In Judo, any studies carried out to investigate RT have not been sport specific in their sensory modality having used images or sounds as the reaction task prompts instead of tactile stimuli (Cojocariu & Abalasei, 2014; Javier *et al.*, 2013; Lima *et al.*, 2004; Supiński *et al.*, 2014; Zukowski, 1989).

4.1.1 A new reactions test paradigm

Judo’s limited demand on visual cues is aptly demonstrated by judoka such as Zvian Gogotchuri, a well-known Georgian judoka who is visually impaired but has competed, successfully, against World class non-visually impaired judokas. Similarly, British judoka Sam Ingram is another highly accomplished Paralympian with visual impairment who has competed at major events against top ranked judoka with no disability. Judoka like Gogotchuri and Ingram demonstrate why the use of a haptic stimulus to test RT in judoka should be of interest; a haptic test will assess RT through the type of sensory stimulus that is more compatible with the dominant sensory input judoka experience when in training and competition.

We need a reliable RT testing method with a sensory modality that is appropriate for judoka and it is practical enough to carry out at a training venue. We should move away from computer-based methods that test RT in response to visual or aural stimuli as such tests do not satisfy a requirement for a tactile stimulus. Furthermore, computer-based tests can result in higher variability in the data due to the latency from the system delays that are inherent in the technology (Kim *et al.*, 2020). We have tried to address the issues described above by designing and manufacturing a reaction testing device that includes haptic technology (see Chapter 3). Although the device was designed specifically to assess RT in Judo it could potentially also be used for the same assessment on any visually impaired athletes or in any other sports where somatosensory perception may be important for performance.

4.2 Methods

4.2.1 Device

The design, manufacture, and operating characteristics of the haptic device used throughout the rest of this project is described in Chapter 3. For the haptic tests, a signal (*i.e.* a vibration) was produced by one of the four actuators at random and to prevent successful anticipation of the next signal the time between signals (*i.e.* inter-stimulus time) was randomised within 1000 to 3000 msec. The frequency of each vibration from the vibration motors used was 122Hz, which we tested in a pilot study and found it to be sufficient for the users to detect the source of the vibration when holding the handle grips.

4.2.2 Participants

We recruited 10 healthy, fully mobile, and physically active volunteers, three females and seven males, with an average age of 27.6 ± 6.5 years (Table 4-1). The study was approved by the School of Sports Research Ethics Committee of the University of Stirling (NICR 16/17) and all participants gave written informed consent prior to taking part in the study. Data from each participant was associated with a code generated at the time of recruitment to ensure anonymity. Four of the participants were students who trained regularly and were competitive in Judo and the rest were fulltime staff from the Scottish Institute of Sport who trained and competed in sports such as cycling, running, football, and Taekwondo.

Cohort	Female	Male	Age (SD)	BMI (SD)	Judo	Non-Judo
10	3	7	27.6 years (6.5)	22.6 Kg/m^2 (1.9)	4	6

SD = Standard Deviation, BMI = Body Mass Index

Table 4-1. Reliability Study Participants.

There were four exclusion criteria for the study:

- Being under 18 or over 40 years old.
- Engaging in habitual physical exercise less than once weekly.

- Being clinically obese (defined as having Body Mass Index > 30 Kg/m^2 and waist circumference >= 88cm and >= 102 cm for females and males respectively).
- Being pregnant or suspecting pregnancy.

4.2.3 Overall procedure

Each participant was asked to attend the Exercise Physiology laboratory at the University of Stirling on five occasions: one visit prior to testing plus four visits to perform the reaction tests. At the initial visit, each participant was asked to complete a confidential health questionnaire and was then given detailed information about the study. At the same visit, they were also given the opportunity to familiarise themselves with the RT tests on the prototype device and two validated RT tests on a laptop computer. Following the conclusion of their initial visit, all participants had at least two days to consider their decision to take part in this project. Any subsequent testing was carried out only after written consent was obtained. Testing was completed over four morning visits at the Exercise Physiology laboratory within a two-week period.

4.2.4 Experimental condition

In order to increase our confidence in the validity of our novel method we repeated the measurements (*i.e.* A *Vs* B) under two conditions of hydration status (*i.e.* No dehydration *Vs* Dehydration). It is not uncommon for judoka to purposefully dehydrate prior to a competition in order to enter a lower weight class (Artioli *et al.*, 2010). We opted for a mild level of dehydration (2-3%) for the experimental condition because we thought this magnitude of dehydration could be achieved by all our participants without having to overexert themselves. If the criterion method was sensitive enough to detect a difference in RTs between the two conditions, then we would expect our method to be equally sensitive.

4.2.5 Experimental procedure

A battery of tests was carried out using the prototype device and the Deary-Liewald Reaction Time Tester (DLRT) software running on a laptop computer. The DLRT software and testing procedure details have been described elsewhere (Deary *et al.*, 2011). In total there were six reaction tests for the participants to complete at each visit:

- A simple reaction test with a visual cue (laptop)
- A simple reaction test with a visual cue (device)
- A simple reaction test with a haptic cue (device)
- A choice reaction test with a visual cue out of four choices (laptop)
- A choice reaction test with a visual cue out of four choices (device)
- A choice reaction test with a haptic cue out of four choices (device)

The test which we were interested in evaluating was the haptic choice reaction test. We used the validated DLRT method (see section 4.2.7) as benchmark and we added the simple reaction tests in the experimental procedure to allow a more extensive analysis of the device's performance.

Each one of the six tests was carried out by every participant in a random sequence within the same session, under two different conditions (Dehydrated and Not dehydrated) and on four separate occasions to replicate the 'test-retest' model (session A and session B). The order of the four testing conditions *i.e.* Dehydrated session A and session B, and Not-dehydrated session A and session B, was also randomised to minimise any learning effect. Before the start of the tests on every visit at the laboratory participants were allowed a practice run on each test to ensure that they felt fully familiar with the details of each testing procedure. Once the participant indicated they were ready to begin the tests then 10 reaction episodes were recorded for each test. In the choice reaction tests the number of reaction episodes was fixed irrespective of the number of errors committed.

As part of the preparation procedure for the tests, all participants were asked to have their dinner before 8 pm on the night preceding the test and to have no further food or drink beyond that time prior each visit to the laboratory on the following morning. Participants who were taking part in the 'No dehydration' protocol were told to continue having non-caloric fluids to thirst. The participants were also instructed to record their nude body mass before going to bed and to make sure that they had emptied their bladder and opened their bowels before stepping on the scales. A set of calibrated digital scales was loaned to each participant for this purpose. The participants were also asked to refrain from eating anything on the morning of each test until the end of the testing procedures. Those who were on the ‘Dehydration’ protocol were also asked to avoid taking any fluids until the end of the tests. Those who were on the ‘No dehydration’ protocol were advised to consume fluid to thirst, or more if they wanted, in order to stay hydrated.

Upon arrival at the laboratory participants were weighed and those who were assigned to the ‘Dehydration’ condition (mild dehydration of 2-3% body weight) would begin the dehydration protocol for the amount of time necessary. Those who were assigned to the ‘No dehydration’ condition would seek to replace the weight lost overnight with flavoured water before starting the tests.

Upon completion of the tests participants were offered a selection of cereal bars, porridge, bananas, mineral water, and hypotonic drinks.

4.2.6 Dehydration protocol

For the dehydration protocol participants were told that they would need to drop their body mass by 2-3% compared to the weight recorded the evening before. Some exercise of moderate intensity on either a treadmill or a static bike were the options available to the participants to use for this purpose. We expected that all participants should be able to reach the body mass target within less than 60 minutes of easy to moderate intensity exercise.

All participants chose running on a treadmill as the exercise mode to lose the required amount of weight. The room temperature in the laboratory was set at 23^{o} Celsius and participants run with long sleeves and trousers on to induce more sweat. All participants run regularly as part of their fitness training or sport, so they had more than adequate fitness to complete a low intensity run on a treadmill of less than 60 minutes duration. The running pace was dictated by each participant’s perception of an ‘easy’ run. The investigator was by their side controlling the speed of the treadmill and maintaining the speed at a point where each participant could still have a conversation without any heavy breathing. All participants were told that they could stop the exercise if they felt uncomfortable.

4.2.7 Reaction tests protocol

There were four reaction tests set up on our handheld device:

1. Simple Reaction Haptic (SRH) test
2. Simple Reaction Visual (SRV) test
3. Choice Reaction Haptic (ChRH) test
4. Choice Reaction Visual (ChRV) test

In the SRV test, the participant had to hold the device with both hands so that the device's liquid crystal display (LCD) screen was facing up and the mini joystick, which was located next to the screen, was directly under and in contact with their right thumb (see Figure 3-3 for an image of the device). A large white solid circle against a black background would appear at random intervals on the screen. The participant was instructed to depress the mini joystick as soon as the white circle appeared on the screen (Figure 4-1). The RT was recorded and stored in the device's mini Secure Digital (SD) card. The time unit used to record all RTs on the device was microseconds (µsec, 10^{-6} of a second) and converted to milliseconds (msec, 10^{-3} of a second) for later analysis.

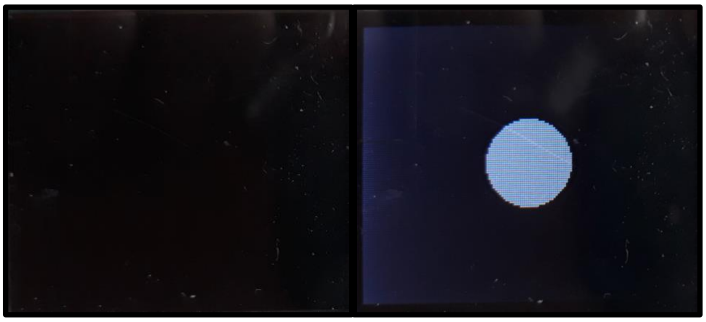


Figure 4-1. Screenshot of the visual simple reaction task on the device.

A black screen at the start of each trial (*left*) and a white dot on black background serving as the visual cue (*right*).

In the ChRV test, the participant had to hold the device in the same way as in the SRV test; with both hands so that the LCD screen was facing up and the mini joystick was directly under, and in contact, with their right thumb. A large white solid arrow against a black background would appear at random intervals pointing either Up, Down, Left, or Right (Figure 4-2) and the mini joystick had to be pushed in the direction indicated by the arrow on the screen. The random inter-stimulus intervals and arrow direction made it practically impossible to guess the timing and the direction of the arrow.

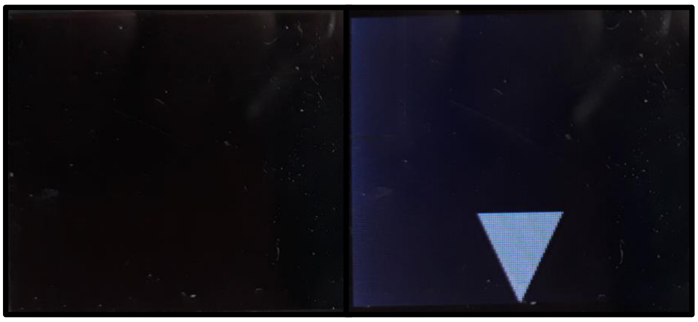


Figure 4-2. Screenshot of the visual choice reaction test on the device.

A black screen at the start of each trial (*left)* and a white arrow on black background serving as the visual cue (*right)*. In this example the participant would have been expected to shift the mini joystick towards their body.

In the SRH test, the participant had to hold the device with both hands so that the LCD screen was facing up and the mini joystick was directly under, and in contact, with their thumb. However, with their left hand, the participant held the left handle grip of the device so to be able to detect the haptic signal from the actuators housed in the handle. The participant was instructed to depress the joystick with their right thumb as soon as they felt the haptic signal from the vibration motors in the left handle.

In the ChRH test, the participant had to hold the device using the handle grips so that the LCD screen was facing up with the mini joystick most proximal to the right hand. It did not matter at which plane, in relation to the coronal or transverse planes, the participant moved the device during the test as long as they tried to keep the movements on the same plane. By keeping the movements closer to two dimensional parameters, instead of three dimensions, we removed any potential uncertainty about the direction in which the participant chose to initiate movement at each response. During the ChRH test each signal was relayed in a randomised order from one of the four actuators housed in the handles of the device. The participant was instructed to push or pull the device sharply in the direction they thought the vibration came from and return it to the start position. In the interest of clarity we suggested to each participant they consider the front of the device pointing an imaginary North and the device placed in the intersection of the North-South and West-East line. The response to the top left actuator would be a move in Northwest direction, bottom left in Southwest direction, bottom right in Southeast direction, and the top right in Northeast direction. As in the ChRV test, the sequence and the timing of the vibration motor triggered was randomised making it practically impossible to successfully guess the timing and correct location of the haptic signal during the test.

All the test results on the handheld device were automatically recorded on the mini SD card within the device and subsequently transferred to a computer via USB for storage and later analysis. The data from each test included: test performed, date of test, participant’s name, reaction order (from the total of reaction episodes), and reaction time. For the choice reaction tests the information generated also included: the direction expected at each trial, the actual direction the participant moved the device to, and whether each trial was a success *i.e.* the actual direction of the device movement matched the expected one.

We used the Deary-Liewald Reaction Time task (DLRT) as a validated, open-source computer-based test (https://www.ccace.ed.ac.uk/news-events/latest/reaction-time-task-new) to collect RT data and to compare with the data from our novel reaction testing device. To ensure consistency in the testing process the software was downloaded to a Dell Latitude E6430 laptop computer (Intel Core i5 3210M 2.5 GHz Processor, 8 GB RAM, Windows 10 64-bit Operating System) with a screen vertical refresh rate of 60 Hz. The same laptop was used to collect data from all participants for all the computer-based tests. Also, every response in the DLRT tasks was carried out using the laptop’s integrated keyboard (QWERTY configuration for English language) thus minimising the potential variability in latency from using different peripheral devices *e.g.* external keyboard or mouse.

There were two visual reaction tests in the DLRT:

- Simple Reaction Visual Deary-Liewald (SRV-DL) test
- Choice Reaction Visual Deary-Liewald (ChRV-DL) test

In the SRV-DL test, participants were instructed to get into a comfortable position standing or sitting with the laptop resting on a solid base (*e.g.* table) and their hands resting on the laptop. Their preferred finger or thumb was to be positioned directly over and in contact with the keyboard space bar. During the test, the laptop screen displayed a white square fixed in position approximately in the centre of the screen and against a blue background. The participants were instructed to depress the space bar as soon as a diagonal cross appeared within the white square (see left panel in Figure 4-3). The time unit used to record, analyse and report all data was in milliseconds (msec).The inter-stimulus time was randomised between 1000 and 3000 msec, which was the same range we set for the prototype device. All RTs were automatically recorded to a file on the laptop’s hard drive alongside the inter-stimulus interval for each trial.

In the ChRV-DL test, participants were instructed to repeat the setup as described above for the SRV-DL test procedure except that four fingers had to be in contact with specific keys on the keyboard. The index and middle fingers on the left hand were in contact with the keys ‘Z’ and ‘X’ respectively. And the index and middle fingers on the right hand were in contact with the keys ‘,’ and ‘.’ respectively. During the test, the laptop screen displayed four white squares in a row with equidistant spaces between them and fixed in position approximately in the middle of the screen and against a blue background (see right panel in Figure 4-3). The sequence of the squares corresponded to the sequence of the keys programmed for the test so that the far most left square corresponded to the key ‘Z’, the next square to the key ‘X’, the following one to the key ‘,’ and the far most right square to the key ‘.’. The participants were instructed to depress the appropriate key that corresponded to the white square within which a diagonal cross appeared as soon as that cross appeared. Again, the inter-stimulus time was randomised between a range of 1000 and 3000 msec. And as was the case with the SRV-DL test procedure the RTs were automatically recorded to a file alongside the inter-stimulus intervals between trials, the key pressed, and whether the trial was a success *i.e.* the correct key was pressed.

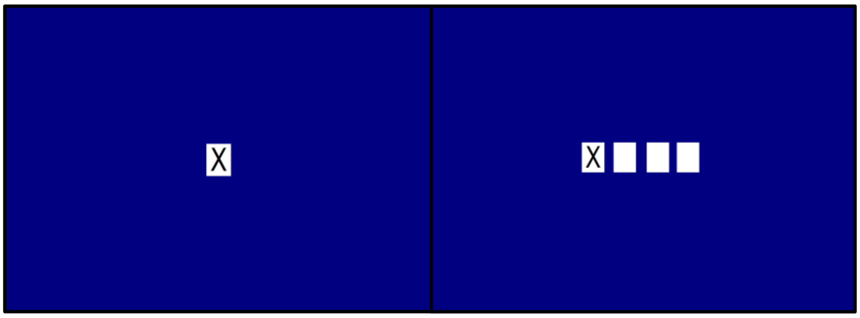


Figure 4-3. Screenshots of the Deary-Liewald task.

The simple reaction time task *(left panel)* and the choice reaction time task *(right panel).* During the simple reaction test an X would appear in a blank white box at which point the participant had to press the keyboard's space bar. During the choice reaction test an X would appear in one of the four blank white boxes at a random sequence at which point the participant had to press the correct key.

4.3 Statistical analyses

All raw data from the haptic reaction testing device were transferred to a laptop computer via USB and stored as comma separated values (CSV). Data processing (data wrangling) was carried out in R, version 3.6.1 (R Core Team, 2019) using the *tidyverse* package, version 1.2.1 (Wickham, 2017), and all the plots were designed with the *ggplot2* package, version 3.2.1 (Wickham, 2016). Descriptive statistics and Pearson’s product moment correlation coefficient were computed using the *stats* package included in R. Test-retest reliability was assessed by the intraclass correlation coefficient (ICC) with functions from the *psych* package, version 1.8.10 (Revelle, 2018). Bland-Altman plots were used to assess method agreement between tests, and they were produced with the *BlandAltmanLeh* package, version 0.3.1 (Lehnert, 2015).

We have used the ChRV-DL test as the validated benchmark against which to determine the validity of the novel ChRH test. A fourfold process was followed: 1) a visual comparison of the mean RT and Standard Error of the Mean (SEM) for each one of the four testing sessions, 2) a comparison of the overall coefficient of variation (CV) between the two tests, 3) a computation of the Pearson’s product-moment correlation coefficient (r) of the data between the two tests, and 4) an examination of the level of agreement between the data from the same two tests on a Bland-Altman plot.

In order to complete the latter two steps, we grouped the RT values from the ChRH test (the haptic choice reaction test under investigation) and the ChRV-DL test (the validated visual choice reaction test) by participant, test, condition, and order of testing and paired the counterpart values in ascending order. Any RT value from one test that could not be paired with the equivalent value from the other test was omitted.

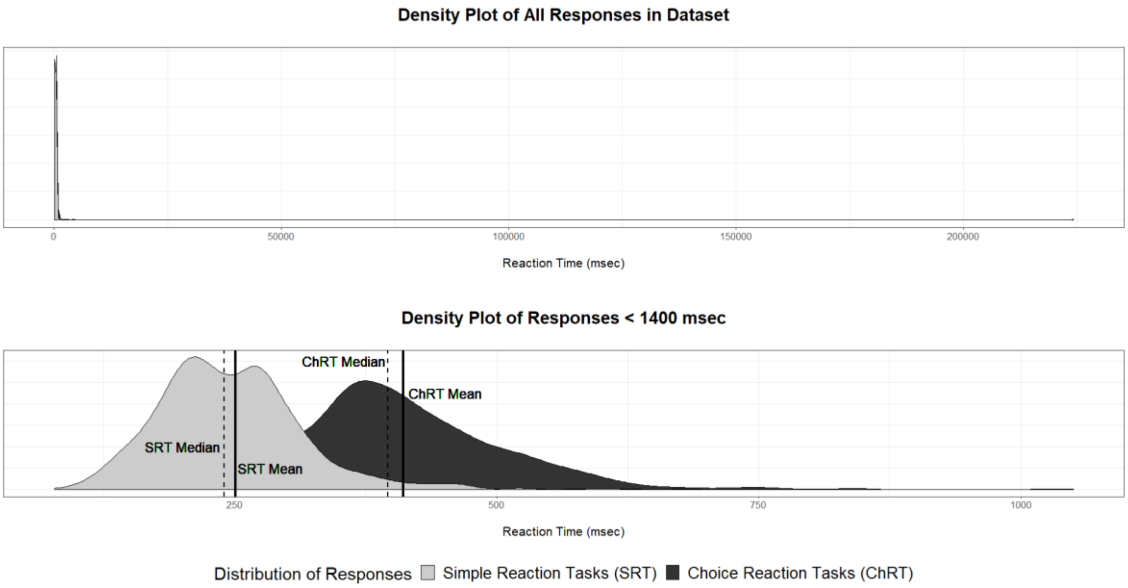
We have used the ICC to examine the test-retest reliability of the ChRH test and the ChRV-DL test. The reason for examining the test-retest reliability of the latter was to determine the level of reliability we should deem acceptable for the former method. To complete the test-retest analysis we paired the RT values each participant registered in the first session with the equivalent RT values in the follow up session for the same method and under the same condition (*e.g.* ChRH test ‘Not dehydrated’ session A *Vs* ChRH test ‘Not dehydrated’ session B). As described in Chapter 2, the specific ICC model we chose was the single rater measurement, absolute-agreement, two-way mixed-effects model (ICC [2, 1]). Following the test-retest analysis the ICC results were interpreted based on the description by Koo & Li (2016): ICC values <0.5 indicate poor reliability, values between 0.5 - 0.75 indicate moderate reliability, values between 0.75 - 0.9 indicate good reliability, and values > 0.9 excellent reliability.

4.4 Data inclusion range

In total, 2400 reaction responses were collected from the 10 participants who carried out the battery of six reaction tasks. Each test had 10 reaction episodes (trials) carried out on two separate occasions (*i.e.* A and B) under conditions of no dehydration and two separate occasions under conditions of mild dehydration (*i.e.* ‘Not dehydrated’ A and B, ‘Dehydrated’ A and B), which resulted in 600 observations over six tests for each one of the four conditions.

We sorted the RT values in descending order, and we were able to identify ten results (78 msec and 1422 to 224158 msec) that we considered unrealistic and unlikely to be genuine RTs. Most of these RTs were likely the result of machine error or malfunction. Seven out of the nine invalid responses were generated by the haptic device in the simple reaction test mode supporting our suspicion of a machine malfunction. These observations made up 0.4% of the original data pool and were discarded prior to further analysis.

A density plot of the RT values was created (Figure 4-4) to expose the effect a few rogue values could have in the overall distribution of the data. Figure 4-4 (upper panel) demonstrates the considerable influence of the extreme values on the overall distribution of the data. However, even after removing the extreme values a positive skew remained (lower panel) and indicated atypically long responses were present, potentially influencing the measurements of central tendency.


Density Plot of All Responses in Dataset

Density Plot of Responses < 1400 msec

Figure 4-4. Density plot of all reaction time values.

The responses are grouped by simple reaction and choice reaction tests, before any filters were applied (upper panel) and when only values under 1400 msec were accepted (lower panel). The solid vertical black lines (lower panel) indicate the mean RT of all simple reaction tests (SRT) and all choice reaction tests (ChRT). The black dashed vertical lines before each solid black vertical line displays the median RT for the same sets of data. Note the bimodal nature of the SRT distribution, which is due to the differences in RT results between the three different simple reaction testing methods.

After we removed the obvious invalid RT values we used the median absolute deviation (MAD) with a very conservative factor of 3. Filtering on MAD is a robust statistics' method to eliminate outliers that could bias the comparisons between test conditions and test mode (Leys *et al.*, 2013). Our acceptable range for data inclusion was determined as the median ± 3 x MAD and this filter was applied to sets of data grouped by participant, test, and condition. This filter removed another 141 values before further analysis. In total, nearly 6% of the remaining 2391 observations were trimmed off. More specifically, 101 from simple reaction tests (SRH = 36, SRV DLT = 28, SRV = 37) and 40 from choice reaction tests (ChRH = 8, ChRV DLT = 13, ChRV = 19). Analysis of density plots for each test revealed distributions that were still somewhat positively skewed but were more likely to reflect the true RT parameters (Figure 4-5).

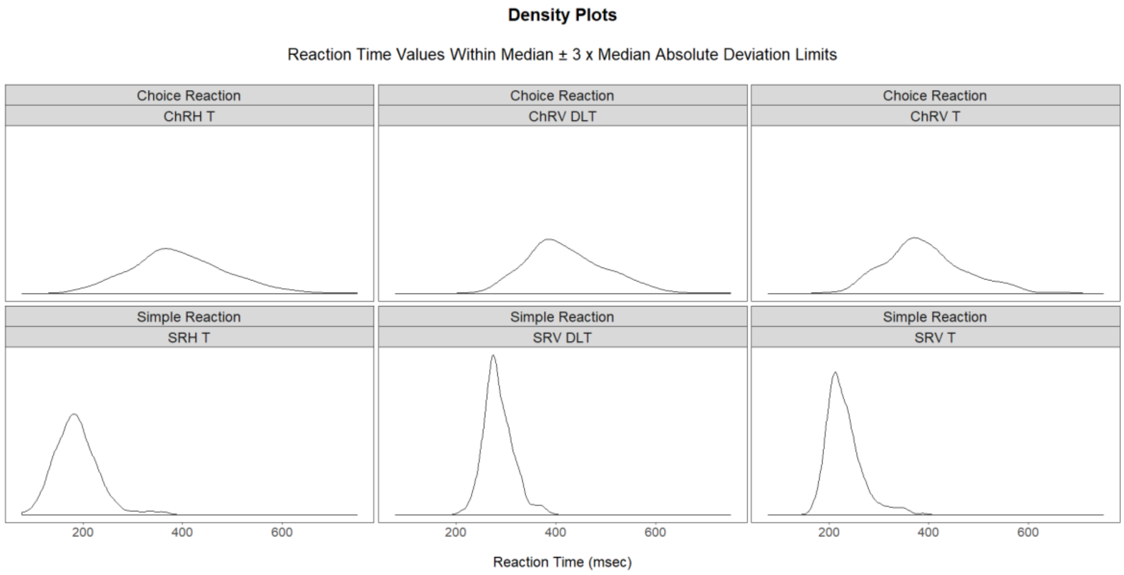


Figure 4-5. Density plot of reaction time values with MAD filters applied.

RT values within MAD limits for each test performed (ChRH T = Choice Reaction Haptic Test, ChRV DLT = Choice Reaction Visual Deary-Liewald Test, ChRV T = Choice Reaction Visual Test (handheld device), SRH T = Simple Reaction Haptic Test, SRV DLT = Simple Reaction Visual Deary-Liewald Test, SRV T = Simple Reaction Visual Test (handheld device).

After application of filtering we then proceeded to correct the recorded RT values for any known latency that was included in the original data. A fixed value of 60 msec was subtracted from all data points that were recorded with the haptic device for the latency of vibration feedback (for more details see section 3.7.1). A fixed value of 17 msec was subtracted from all DLT trials recorded on the laptop for the latency of the screen refresh rate (60 Hz). There were no known latencies for which to adjust the data from the visual tests on the handheld device.

4.5 Results

4.5.1 Participants

All 10 participants who volunteered for the study completed successfully all trials. None of the participants needed to perform a lengthy run on the Dehydration condition as they had already lost considerable weight overnight and were closer to the expected 2-3% body mass loss. Typically, most participants, only had to drop around 1% or less of their body mass with some moderate physical effort, which typically lasted no longer than 30 minutes before they reached the expected body mass loss for the test.

On average, in the ‘No dehydration’ condition, the participants’ body mass was approximately 0.3% lower, on the morning of the tests, when compared to their body mass recorded the day before. On the other hand, when on the ‘Dehydration’ condition the participants’ body mass was 2.3% lower by the start of the reaction tasks compared to the previous day (Figure 4-6).

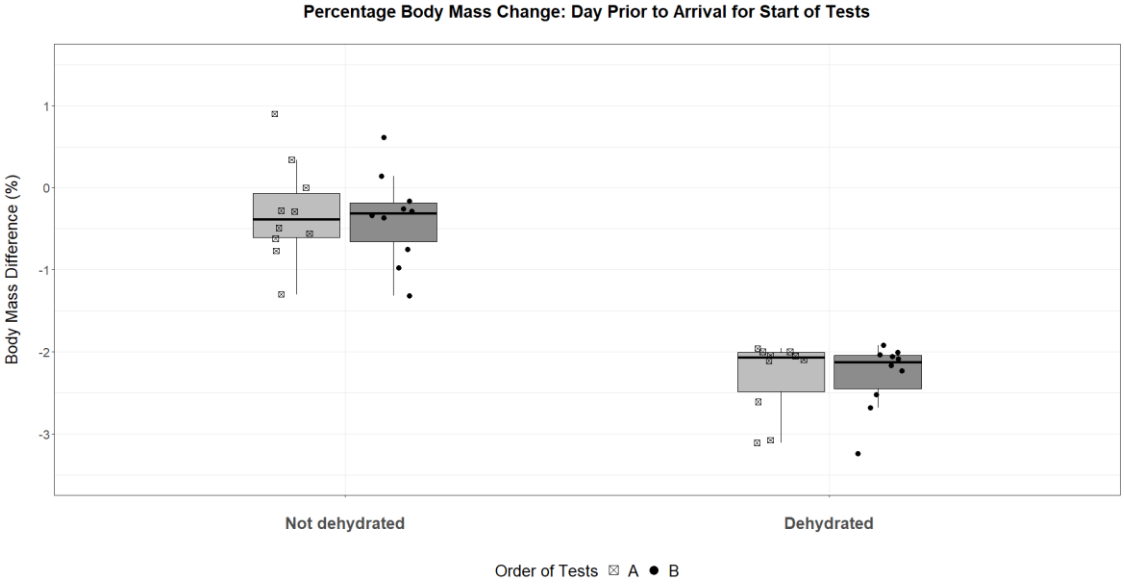


Figure 4-6. Participants’ body mass difference.

Percentage body mass difference from previous day to the morning of tests in the ‘No dehydration’ condition (left side of the chart) and ‘Dehydration’ condition (right side of the chart). Each boxplot and corresponding data points represent one of the two visits (A and B) to the laboratory under each test condition (*i.e.* ‘Not dehydrated’ and ‘Dehydrated’).

4.5.2 Visual reaction tests

In the SRV-DL test, the validated simple reaction test on the laptop, we collected data from 400 trials but after filtering out values outside the MAD borders approximately 7% of the variables were discarded and 372 observations remained. The overall mean value and standard error of the mean (SEM) were 281 (8) msec.

In the SRV test, the visual simple reaction test on the handheld device, we collected data from 400 trials, but one value (1518 msec) was discarded as unlikely to reflect a true response to the simple reaction task. Following the application of the MAD limits around 9% of the data were filtered out and 362 observations remained with an overall mean (SEM) of 224 (10) msec.

In the ChRV-DL test, the validated choice reaction test on the laptop, about 3% of the data were discarded, 387 out of 400 observations remained following the application of the MAD filter. The mean (SEM) value was 409 (22) msec. There is an additional parameter of interest in choice reaction tests over simple reactions tests and that is the accuracy achieved as expressed by the number of correct responses over the total number of trials. In the ChRV DLT the participants achieved mean (SEM) accuracy of 93 (1.04) %.

In the ChRV test, the visual choice reaction test on the handheld device, 381 observations remained after approximately 5% of the 400 trials beyond the MAD limits were removed. Overall, the mean RT (SEM), was 390 (22) msec and the accuracy of the responses was 97 (1.30) %.

Summary statistics of the means across each test, grouped by participant and test mode, is available on Table 4-2.

Test	Test Type	Mean (SEM)	Accuracy (SEM)
ChRH	Choice reaction	386 (23) msec	85 (1.76) %
ChRV DL	Choice reaction	409 (22) msec	93 (1.04) %
ChRV	Choice reaction	390 (22) msec	97 (1.30) %
SRH	Simple reaction	183 (12) msec	NA
SRV DL	Simple reaction	281 (8) msec	NA
SRV	Simple reaction	224 (10) msec	NA

ChRH= Choice Reaction Haptic, ChRV DL= Choice Reaction Visual Deary-Liewald, ChRV= Choice Reaction Visual, SRH= Simple Reaction Haptic, SRV DL= Simple Reaction Visual Deary-Liewald, SRV= Simple Reaction Visual, SEM= Standard Error of the Mean, NA = not applicable.

Table 4-2. Mean (SEM) reaction time per test method.

4.5.3 Haptic reaction tests

In the SRH test, the device based haptic simple reaction test, we collected data from 400 trials but seven values (78, 1422, 1646, 2561, 2940, 3088, and 4195 msec) were ignored as unrealistic or machine errors. After the invalid responses were cleared almost 9% of the remaining data were found outside the MAD parameters and were filtered out. The mean (SEM) value was 183 (12) msec.

In the ChRH test, the device based haptic choice reaction test, we collected data from 400 trials, but two responses (1454 and 224158 msec) were believed to be the result of machine malfunction and were discarded. Only 2% of the remaining 398 observation were out with the MAD boundaries leaving 390 responses available for further analysis. In this test the mean (SEM) was 386 (23) msec and the average accuracy was 86%.

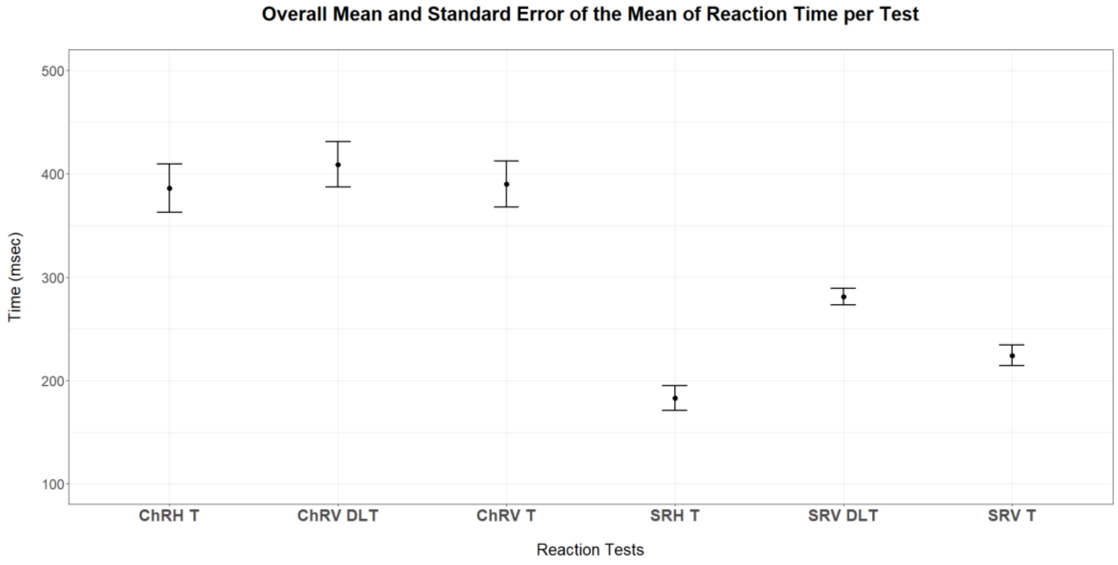


Figure 4-7. Mean reaction time per testing method.

Mean and standard error of the mean (error bars) of all reaction times across each test. The three choice reaction tests are shown in the first half of the x axis and the three simple reaction tests in the latter half. Note that all three simple reaction tests have produced lower mean RT values and narrower SEM intervals to those of any of the three choice reaction tests.

Figure 4-7 displays of the overall mean RT and SEM data from each reaction test method listed in Table 4-2. In the Deary-Liewald tasks the choice reaction resulted in higher mean RT and wider SEM intervals than the simple reaction task. The same pattern was replicated between the simple reaction tests and the choice reactions tests of the prototype handheld device.

4.5.4 Validity

The mean RT and standard error of the mean (SEM) collected from the ChRV-DL test revealed some faster responses under the ‘Dehydration’ condition when compared to the condition of ‘No dehydration’ (Figure 4-8). This pattern of slightly faster mean RT under the condition of dehydration was repeated by the results obtained from the ChRH test. We also see that the SEM for each one of the four ChRV-DL tests were of comparable size to each other indicating a degree of agreement between them in relation to the extent of uncertainty about the value of the true mean. This pattern of similarity between the SEM values from each one of the four test results was repeated in the case of the ChRH test. It is clear from Figure 4-8 that the SEM values from the four ChRH test results were consistently higher than the SEM values from the ChRV-DL test, which indicates a higher degree of uncertainty about the value of the true mean from our haptic derived RT values compared to that from the Deary-Liewald results. A further noteworthy observation is that the slopes of the lines *i.e.* the difference between the means of the repeated tests (A and B) were similar between the two tests modes in respect to the absolute value of the difference (not the direction), which indicates a similar amount of variability (‘noise’) in the data between test and retest sessions. In fact, the overall CV for the ChRV-DL test was computed to be 6.7%, which was almost identical to the 6.3% CV for the ChRH test.

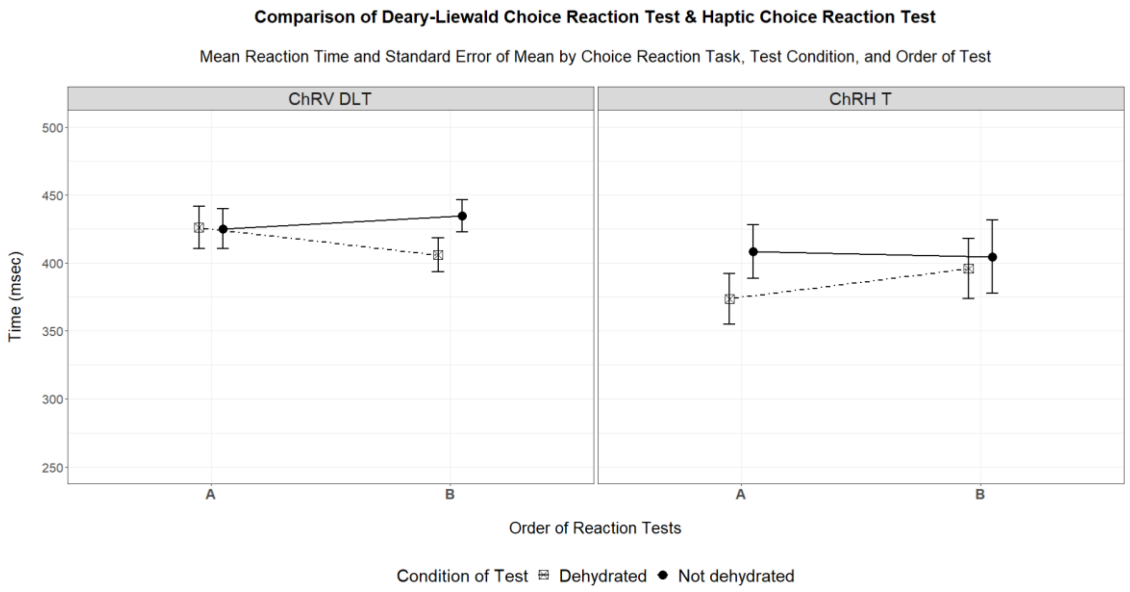


Figure 4-8. Deary-Liewald Vs Haptic choice reaction test.

Mean and standard error of the mean of participants' reaction times in Deary-Liewald choice reaction test (left panel) and the novel haptic choice reaction test (right panel) at all four testing sessions (*i.e.* Not dehydrated A and B, and Dehydrated A and B).

We computed the Pearson's product-moment correlation coefficient (r) with the level of statistical significance at α = 0.05 (Table 4-3) and found the RT results from the DLRT and Haptic choice tasks to be moderately and positively correlated r = 0.68, at a statistically significant level ($p < 0.001$).

Visual	**Haptic**	**Pearson's correlation (r)**	**95% Confidence Interval Limits**		**t stat.**	**Sign.**
Deary-Liewald	Haptic device	0.68	0.62	0.73	18.05	$p < 0.001$

t stat= *t* statistic, Sign = Significance

Table 4-3. Pearson's correlation of Deary-Liewald test and Haptic test. Correlation between the validated visual choice reaction test (ChRV-DL) and the haptic choice reaction test (ChRH) using a two-way random effect, mean of k measurements of absolute agreement.

After we paired each RT value from the ChRH test against the equivalent value from the ChRV-DL test we plotted the data on a Bland-Altman plot (Figure 4-9). The mean difference between the two methods was 28 msec and the limits of their agreement were found to be between -108 and 164 msec (critical difference = 136 msec). The line of equality on the Bland-Altman plot was not within the confidence interval of the mean difference, indicating significant bias: the responses recorded with the handheld haptic device were more likely to yield lower RT values compared to responses using the Deary-Liewald choice reaction task.

When we looked at the RTs grouped by participants who practice Judo and those who train in other sports, we noted a more consistent performance by the judokas. Indeed, we found that on average judoka’s responses in the haptic choice reaction task were consistently faster under both conditions when compared to non-judokas’ responses (Figure 4-10). In the case of the Deary-Liewald choice task the difference in mean RT was not as clear between the two groups. The judoka’s ability to respond faster to a haptic stimulus was supported further by the yet again consistently faster mean RT they produced compared to non-judokas in the simple reaction haptic task (Figure 4-11).

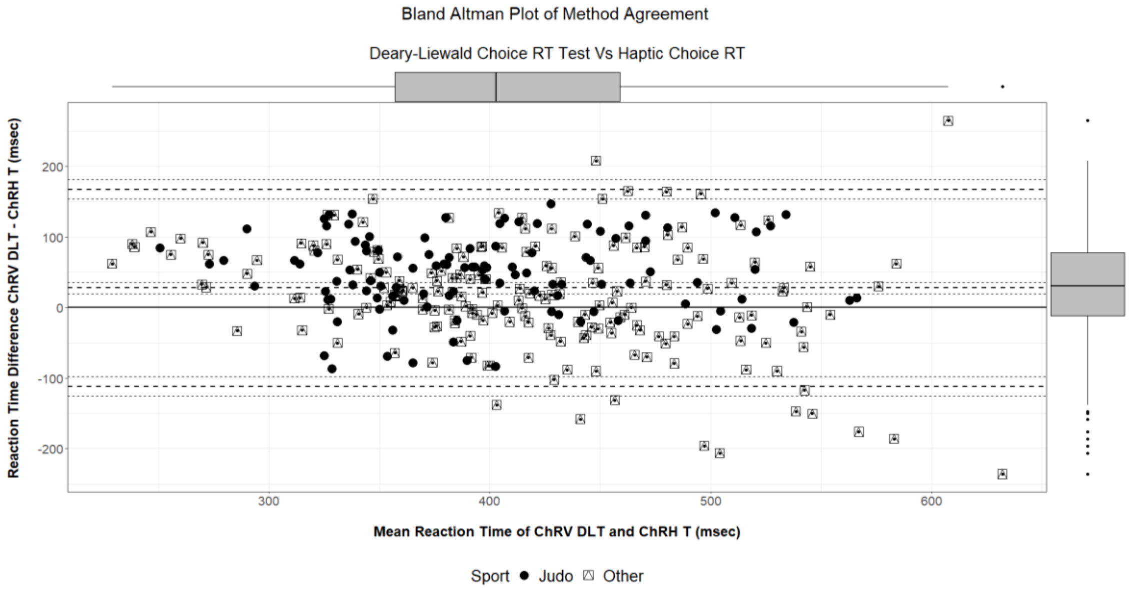


Figure 4-9. Bland-Altman plot of method agreement.

Examination of agreement between the Deary-Liewald visual choice reaction task (ChRV DLT) and the haptic choice reaction test (ChRH T). Note that judoka’s results (black dots) appear more consistent than the results of non-judokas (squares).

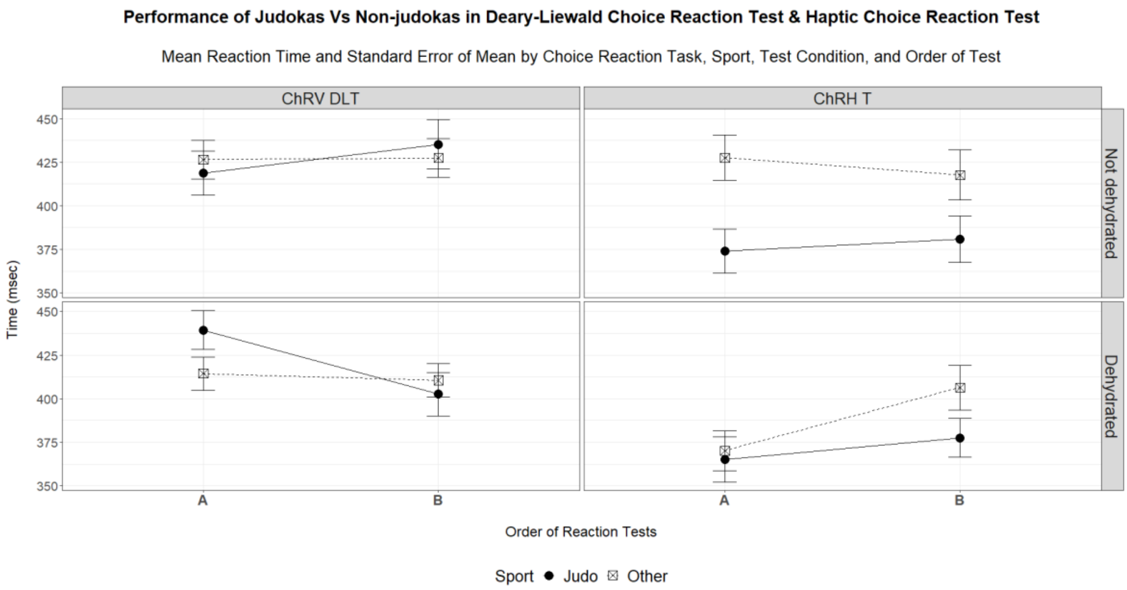


Figure 4-10. Visual and Haptic choice reaction time; judoka vs non-judokas.

Participants' mean reaction times in the Deary-Liewald choice reaction test (left panel) and the novel haptic choice reaction test (right panel) at all four testing sessions (*i.e.* Not dehydrated A and B, and Dehydrated A and B) grouped by sport (*i.e.* judoka Vs non-judoka). Note that on average judoka (black dots) were consistently faster in the haptic mode than non-judokas (squares), with no clear difference between them in the visual mode.

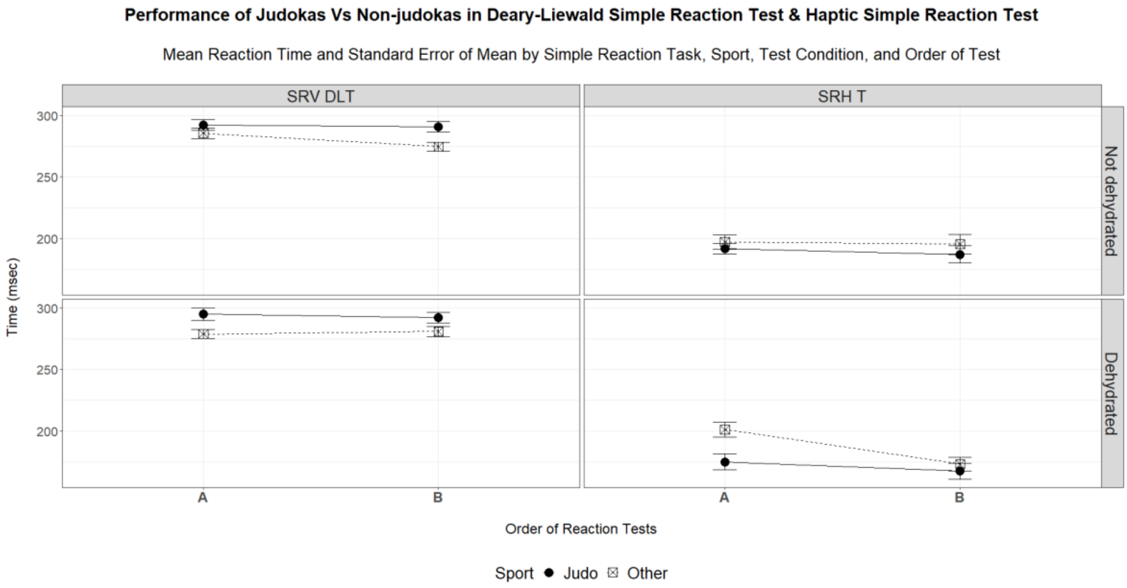


Figure 4-11. Visual and Haptic simple reaction time; judoka vs non-judokas.

Participants' mean reaction times in Deary-Liewald simple reaction test (left panel) and the novel haptic simple reaction test (right panel) at all four testing sessions (*i.e.* Not dehydrated A and B, and Dehydrated A and B) grouped by sport (*i.e.* judoka Vs non-judoka). Note that on average judoka (black dots) were consistently faster in the haptic mode and consistently slower in the visual model than non-judokas (squares).

4.5.5 Test retest reliability

We computed the ICC between the first and second testing sessions under each condition and for each test (Table 4-4). The ICC of the validated ChRV DLT method under the 'No dehydration' condition was 0.82 with the 95% Confidence Interval between 0.80 - 0.90. Based on the ICC result the reliability of this method is 'good' (Koo & Li, 2016). The ICC of the same method under the 'Dehydration' condition was 0.76, with the 95% Confidence Interval between 0.64 - 0.84 indicating 'moderate' to 'good' reliability.

The ICC of the ChRH T method, under the 'No dehydration' condition was 0.79 with the 95% Confidence Interval between 0.71 - 0.86 indicating that the reliability of this method is 'moderate' to 'good'. The ICC of the novel haptic choice reaction method under the 'Dehydration' condition was 0.77 with the 95% Confidence Interval between 0.55 - 0.87 indicating the reliability is 'moderate' to 'good'.

Test	**Order**	**Condition**	**ICC**	**95% CI limits**		***F* stat.**	**Sign.**
ChRV-DL	A Vs B	Not Dehydrated	0.82	0.80	0.90	14	*p* <0.001
ChRV-DL	A Vs B	Dehydrated	0.76	0.64	0.84	7.7	*p* <0.001
ChRH	A Vs B	Not Dehydrated	0.79	0.71	0.86	8.7	*p* <0.001
ChRH	A Vs B	Dehydrated	0.77	0.55	0.87	9.9	*p* <0.001

ChRH = Choice Reaction Haptic, ChRV-DL = Choice Reaction Visual Deary-Liewald, A Vs B = test-retest data, ICC = Intraclass Correlation Coefficient, CI = Credible Interval, *F* stat = *F* statistic, Sign = Significance.

Table 4-4. ICC for visual and haptic choice tasks.

Intraclass correlation coefficients (ICC) among the test-retest conditions of the visual choice (ChRV-DL) and haptic choice (ChRH) reaction time tasks using a two-way fixed effect, mean of k measurements of consistency.

4.6 Discussion

In this study we set out to examine the validity and test-retest reliability of a novel haptic choice reaction device. Following from the data analysis we are confident that our device's performance is comparable to that of a validated reaction test, and it does produce reliable results.

One fundamental difference expected between the types of tests carried out is that the mean RT from a simple reaction task should be shorter to that of a choice reactions task (Hick, 1952). Our device would have failed its validity assessment if the results from a simple haptic reaction could not be distinguished from the results recorded from a choice haptic reaction. Our first reassurance about the quality of the handheld device's performance comes from the fact that, after invalid data were removed, outliers filtered out, and response times were adjusted for the relevant latency the descriptive statistics on the remaining observations revealed the mean RTs of the simple reaction tests on our device to be shorter than the choice reaction ones (Figure 4-7).

An important observation from Figure 4-7 is that from the two Deary-Liewald tasks (*i.e.* simple reaction vs choice reaction) the choice reaction test has not only produced higher mean RT but also wider SEM intervals, which makes sense considering that there are fewer variables at play in a simple reaction task. Again, this same pattern of higher mean RT and wider SEM intervals when comparing choice and simple reaction tests was replicated in the results gathered from our device.

Another interesting point from Figure 4-7 is that the simple reaction version of the Deary-Liewald task produced a higher mean RT than the device based visual simple reaction test. This observation was somewhat surprising as one would expect two tests of the same type, same reaction stimulus, and similar task to have produced near identical results. One explanation for the difference in the mean RT values between these tests is the difference between them in the digits used to respond. It is possible that response times in keyboard-based reaction tasks can be affected by participants who may had simply used different fingers or hands (Hayes & Halpin, 1978) between test sessions. When the participants carried out SRV-DL test they were instructed to use their preferred finger or thumb to hit the space bar and were encouraged to keep their initial choice of finger or thumb throughout the experiments. However, no record was kept of their initial choice, so it is possible that there was an inconsistency in the digit or hand side chosen at each session the SRV-DL test was carried out. In contrast, in the simple reaction task on the haptic device only the right thumb could be used to depress the mini joystick on either the visual simple reaction test or the haptic reaction test. Another point is that although we have tried to make the comparisons between tests fair by cutting known latency values, we were not able to check the latency between depressing the space bar on the computer keyboard and registering a response.

It has been argued that humans react faster to an audio stimulus compared to a visual one (Diederich & Colonius, 2004; Jain *et al.*, 2015; Shelton & Kumar, 2010) and response times to tactile stimuli have also been found to be shorter than responses to visual prompts (Forster *et al.*, 2002). The above suggested order though has been challenged by Diederich & Colonius (2004) who in their study of RT tasks reported the rank order of the sensory stimulus that can produce the fastest mean RT to be: audio first, then visual, and then tactile. However, the visual stimulus used in their study was a flash (250 lux) projected onto a screen whilst the tactile stimulus was delivered by an oscillation exciter (vibration). Unlike flashlights, a latency exists in all oscillators from when an electrical current is supplied to the point when the stated frequency is reached (see 'Latency' in Chapter 3). In their paper Diederich & Colonius make no suggestion that they made the necessary adjustments to the raw data from haptic tasks in order to correct for the latency of the vibration machine used in their study. Forster *et al.* (2002) on the other hand, in their study of RTs, found responses from tactile reaction tasks to be consistently quicker to ones measured in visual tasks. A major difference in the latter study design is that the tactile stimuli were produced by non-noxious electrical pulses with a device that is commonly used by clinicians in the management of chronic pain (Johnson, 2007). Unlike haptic technology, the device used by Forster *et al.* does not involve a noteworthy latency factor. Others have argued that in fact it is through tactile tasks that the quickest responses can be observed, not just when compared to visual tasks but even when compared directly with similar aural reaction tests (Godlove *et al.*, 2014;

Ng & Chan, 2012; Zbigniew, 2008). Our findings agree with most earlier studies that have found responses to be faster to a haptic stimulus than a visual one.

Although the difference in accuracy between the two visual choice reaction tests was small (Table 4-2) it is still worth noting that the highest accuracy came with the test that needed the least coordination of movement. It is perhaps self-evident that the ChRV test should result in higher accuracy when we consider the slightly higher complexity of the computer-based ChRV-DL test. The latter method required participants to use two fingers from each hand on a keyboard as opposed to the ChRV test set up where the right thumb was required to control a mini joystick as per the direction of the arrow displayed on the screen. In the same vein, as the complexity of the response task increased further with the ChRH task, where the participants had to determine the source of the signal and then coordinate both hands in the correct direction, a further drop in accuracy was noted.

The drop in accuracy from the Deary-Liewald task to the haptic task was double the drop in accuracy from the device based visual task to the Deary-Liewald task (8% Vs 4% respectively). We remain unsure whether the differences in the task complexity between the haptic and visual tests can account for a twofold difference in accuracy loss compared to the accuracy lost from one visual test to another. One argument to explain the considerably lower accuracy in the haptic test might be that the vibration was not intense enough to deliver a clear signal. It has been shown that the intensity of a stimulus can affect the rate of information processing in the sensory pathway (Brown *et al.*, 2008; Nissen, 1977). Our concern of a possible weak haptic signal was addressed in a pilot study were we wanted to establish that the device was user friendly, and the haptic prompt was detectable (see Chapter 3). By the end of the pilot study, we were confident that the haptic signal of the device was powerful enough to be detected. Evidence of the quality of the haptic signal comes from the fact that both in the pilot study and the study presented here the users of the device knew when they moved the device in the wrong direction. A blunted signal would have not allowed for the user to be able to distinguish the exact location of the signal and know that they had moved the device in the wrong direction. We consider the positive correlation observed between lower accuracy and higher task complexity as an indication towards the validity of our method.

We used the Pearson's product-moment correlation coefficient to evaluate the criterion validity of our haptic choice reaction method with the Deary-Liewald choice reaction task. We found that the correlations between RTs from the two subsets of data revealed a positive and moderate relationship that was statistically significant. Further analysis with the Bland-Altman plot revealed that the haptic task was likely to produce faster RTs and that the limits of agreement were too high to make the two reactions test methods equivalent. However, considering that these two tests are completely different in sensory modality and task requirements a wide range in the limits of agreement is not surprising.

One observation worth highlighting from the Bland-Altman plot (Figure 4-9) is that when we split the data by Judo participants versus other sport participants, we found the variability across the data was more consistent for the judokas. This outcome encouraged us to compare RT results based on the participants' sport and we found that, on average, judoka appeared to respond faster to the haptic signal in both choice reaction (Figure 4-10) and simple reaction (Figure 4-11) tests when compared to non-judokas. These results were consistent with our expectation of judoka being more conditioned to tactile feedback. We also found that on average, judoka responded consistently slower than non-judokas in the visual simple reaction task (Figure 4-11). In a different study judoka were reported to respond slower than boxers in a visual simple reaction task (Badau *et al.*, 2018). Perhaps, the above observations support the ecological validity of our device but at this stage the participants and the data are not enough for us to make firm conclusions on this suggestion. However, we anticipate the overall variability of the results and the test-retest reliability to improve if the haptic tests were carried out by a cohort of judoka or other athletes who regularly challenge their tactile sensory routes.

We used the ICC to determine the test-retest reliability of our haptic choice reaction method. We found the ICC results to consistently indicate a 'moderate' to 'good' reliability that was statistically significant and in agreement with the ICC results obtained from the already validated Deary-Liewald choice reaction task.

Thus, we have shown that the test-retest reliability of our device is on par with that of the criterion method. We believe that we have demonstrated reasonable evidence to accept our novel haptic choice reaction device as a valid and reliable method to collect haptic RT data. But before we close this chapter, we feel it is important to describe the rationale and methods we used to rid the raw data from unrealistic values.

On our first step of the raw data processing, we tried to eliminate unrealistic values from the choice RT datasets so that any RT values over 1400 msec were removed. Arguably, the upper cut-off point that we set for true responses could have been lower than 1400 msec. But, when the 2400 reaction times were put in ascending order a clear pattern emerged where every next value on the list was 0-30 msec higher than the value before. That pattern was interrupted abruptly towards the end of the list where a near 400 msec jump was found between two neighbouring values (from 1050 to 1422 msec). This atypical gap, and at such a high reaction time, was either a machine error or the result of an operator mishandling the device. Indicative of a technical error was a single recorded RT of nearly four minutes. These rogue values made a very small proportion of the raw data and filtering them out was unlikely to have compromised the size of the remaining data pool but most likely has enhanced the quality of the statistical analyses that followed.

Unlike simple RT to audio prompts, there is no universally accepted minimum limit that can serve as a cut-off point for unrealistic choice RT values. In a study carried out to establish the fastest response possible to an auditory simple reaction task it was shown that young adults can react in as fast as 85 msec following an audio cue (Komi, 2009; Pain & Hibbs, 2007). We could not find studies that have determined humans' limits for the lowest RT possible to a visual or haptic signal. As a result, we have accepted the value suggested by Pain & Hibbs (2007) as the lower cut-off value for our data. This minimum limit set for realistic responses filtered out only one simple reaction value and had no effect on choice reaction data, as the lowest value recorded was 178 msec. This value is clearly very low for a choice RT when compared to the mean but we still do not have enough evidence to exclude it as an impossible true response.

Another approach often used in chronometry research is to set fixed cut-off points so that any values over a predetermined threshold, usually over 1000 msec, are ignored. Such approach would have been unsuitable in our study considering that we collected reaction values from six testing methods with different types of reaction (simple reaction and choice reaction), with different sensory modalities (visual and haptic), with different tasks (keyboard strikes and mini joystick control), and with 10 different people taking part. We were not in position to predetermine a suitable fixed cut-off value and had we done so we would have introduced strong biases that could have resulted in spurious conclusions. For example, as shown on the density plots in Figure 4-5 the RT values from simple reaction tests concentrate in a narrower range on the x axis and closer to zero compared to the RT values from choice reaction tests, which tend to have a much wider spread on the x axis. Thus, the reliance on a fixed cut-off value to eliminate outlier values would have been inappropriate.

With the above in mind, we used the robust statistical approach of filtering on a multiple of the median absolute deviation (MAD), in the same way the more common method of standard deviation around the mean has been used (Leys *et al.*, 2013). We applied a conservative MAD multiple of three as described by Leys *et al* (2013) and filtered data that were perhaps not representative of true responses but could bias comparisons between test conditions and test modes. With the MAD limits in place, we were able to preserve nearly 94% of the raw data, which is an acceptable level of raw data retention following filtering as recommended by Ratcliffe (1993).

Finally, in order to make the comparison between laptop based and device-based methods fair we had to take the technical latency of the equipment used into consideration. Latency is a factor that is often not measured in mental chronometry studies, yet it can influence the variability of the results, especially when different electronic devices are used (Kim *et al.*, 2020). We have already described in Chapter 3 how we determined that it would take 60 msec for the user of the haptic device to sense the vibration signal generated from one of the ERM motors in the handles. A fixed value of 60 msec was deducted from every RT registered on a haptic test. Similarly, 17 msec was deducted from every RT value recorded in the laptop based tests to account for the latency of the computer’s screen refresh rate. In the haptic device the refresh rate of the screen was not a factor as the dot, or arrow in the case of the choice reaction test, was drawn by the software on a blacked out screen before the screen was lit to reveal the shape. (Figure 4-1 and Figure 4-2).

4.7 Conclusion

It is well understood that fast reactions and quick information processing are important qualities for most elite athletes. It is also understood that different sports have different demands on the sensory modality for response yet most methods available to assess reactions tend to be computer-based and make use of visual or audio prompts. We argue that athletes in sports with stronger kinaesthetic elements like Judo should have access to haptic based reaction tests to match the sensory route they utilise the most during performance.

We have built a novel handheld device to test haptic choice reactions and to the best of our knowledge there is no similar device already available to make a direct comparison with. Therefore, our first step was to test the performance of the device comparing responses against a reference standard and to then determine its test-retest reliability. We used the validated Deary-Liewald reaction task as the benchmark method to compare between simple and choice reaction data. We have shown that the level of performance of our novel haptic reaction testing device is comparable to that of the criterion method. We are satisfied from our device’s validity and reliability results.

We are confident that our device can be utilised for research in Judo or other tactile sports and could become a meaningful tool to assess cognitive performance parameters around training and competition.

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Chapter 5: Typical Haptic Choice Reaction Data in a Group of Elite Judoka

5.1 Introduction

In Chapter 4 we demonstrated that our novel haptic reaction device can record reliable and valid data. In the study described in this chapter our aim was to determine the typical baseline cognitive performance parameters, such as mean reaction time (RT) and accuracy (the number of correct responses over the total number of responses) to an ecologically valid stimulus (tactile) in a group of elite judokas.

In order for Judo competitors (judokas) to excel at Judo they need to achieve high standards in lean body composition and muscular physique (Quintero *et al.*, 2019) and to have the necessary physiological attributes such as strength, power, flexibility, and good aerobic capacity (Franchini *et al.*, 2011), technical skills (Ishii *et al.*, 2018), tactical skills (Bianca *et al.*, 2012), mental resilience (Masashi *et al.*, 2017), and quick reactions (Zukowski, 1989).

It is self-evident that the ability to react fast is a particularly important quality for judokas. It is generally accepted that athletes can react faster than non-athletes (Bańkosz *et al.*, 2013; Christenson & Winkelstein, 1988; Vera *et al.*, 2017; Youngen, 1959), possibly due to the brain’s plasticity and the long term perceptual and motor training in sports that lead to the necessary adaptations (Nakata *et al.*, 2010). These adaptations include modulations in neural function as well as in grey and white matter structure (Draganski *et al.*, 2004; Driemeyer *et al.*, 2008; Huelsduenker *et al.*, 2018). Even within a cohort of athletes from the same sport, experts may perform better in sport specific reaction tasks compared to novices as the former are more likely to have developed better attention and anticipation capacity than the latter (Fontani *et al.*, 2006; Savelsbergh *et al.*, 2002).

In Judo research attempts have been made to understand the relationship between competitive performance and RT. In one study it was reported that judoka responded slower to a visual reaction test compared to Kung-Fu and Taekwondo fighters (Javier *et al.*, 2013). In another study, when compared to boxers, judoka were found again to respond slower in a visual simple reaction test (Badau *et al.*, 2018). In the same study by Badau *et al.* (2018) judoka performed better than boxers in a choice reaction test, but the method was designed to measure cognitive flexibility (figuring out the correct pairing of items on a screen) as opposed to responding rapidly to a prompt. In a different battery of visual simple reaction and choice reaction tests no difference was found in response times between a group of judoka and a group of Physical Education students from a variety of other sports (Cojocariu & Abalasei, 2014).

It has been argued that amongst judo competitors those who are more successful are also the ones who can respond the fastest in simple and choice reaction tests with visual or audio stimuli (Lech *et al.*, 2011; Zukowski, 1989). Interestingly, in a study of motor abilities between different age groups, cadet judoka (age 15-16 years) performed better than senior judoka (age 20-23 years) in audio and visual reaction tasks (Sterkowicz *et al.*, 2012). However, the outcome in this study may reflect the standard of judoka tested as in a different study, with more experienced judokas, it was shown that National team level judoka with the longest training history achieved faster responses and higher accuracy in visual choice reaction tests compared to other judoka with less experience who took part (Supiński *et al.*, 2014).

The effect of rapid weight loss, as seen typically prior to tournaments (Artioli *et al.*, 2010), on RT in experienced judoka has also been examined. The method used was based on visual choice reaction tests and the results suggested that rapid weight loss leads to slower responses compared to progressive weight loss (Morales *et al.*, 2018).

In a more competition-specific study it was shown that under conditions that raise blood lactate concentrations and thus simulate the physiological conditions of an intense Judo bout, judoka can maintain their reaction speed in a visual choice reaction test but at an increased error rate (Lima *et al.*, 2004).

The main criticism that can be levelled against the studies described here is that the chosen reaction stimuli for each test conducted were either audio or visual. Judo is mostly a kinaesthetic sport and judoka receive most of the sensory input through their hands when they grip their opponents. In support of this view, one study concluded that reaction tests with visual stimuli have no relevance in Judo practice and performance in such tests does not improve with Judo either (Cojocariu & Abalasei, 2014). Elite judoka usually spend years conditioning their somatosensory system by learning to respond to tactile cues from interaction with their opponents to force them off balance. It is undeniable that knowing how fast sprinters react to an audio signal is more relevant to them than knowing how fast they react to a visual signal, yet in the case of judoka their primary sensory input has been ignored in current research. Our novel haptic choice reaction test utilises the dominant sensory route in competitive Judo.

By trying to determine the typical baseline cognitive performance parameters a group of elite judoka is capable of in a haptic choice reaction test, we can contribute useful information to the academic literature, and we could provide coaches and the wider support team of sports science practitioners a yardstick against which to measure deviations in cognitive performance under different conditions (*e.g.* after high volume training blocks or following extreme weight making efforts prior tournaments).

5.2 Methods

5.2.1 Participants

The study was approved by the School of Sports Research Ethics Committee of the University of Stirling. Ten healthy judoka (Table 5-1) who compete at international level and participate at World ranking tournaments volunteered for this project and gave written consent after the purpose and details of the study were explained to them (see section 2.1 in Chapter 2 for further details). All participants knew that they could withdraw from the study at any point if they wished to do so without having to provide any explanation.

Judokas	**Total**	**Age (SD)**	**Mass (SD)**
All	10	21.2 (1.8) years	68.2 (9.7) Kg
Female	4	21.3 (2.2) years	62.3 (8.5) Kg
Male	6	21.2 (1.6) years	72.2 (8.3) Kg

SD = Standard Deviation

Table 5-1. Judo haptic reactions study participants.

5.2.2 Test

We asked each participant to carry out a series of haptic reaction tests over a period of nine weeks using a novel bespoke handheld haptic reaction testing device (for details see Chapter 3). During the weeks when reaction tests were carried out there were no competitions scheduled for the judoka involved in this project. By not including a period with major tournaments we were able to avoid any impact on cognitive performance from dehydration or other weight management techniques typically used in weight controlled sports when athletes try to drop their weight for competition (Artioli *et al.*, 2010).

All the tests were carried out on the Judo mats at the Performance Centre of Scottish Judo and took place just before the judoka started warm up and on training sessions where they practiced randori (Judo sparring). We had four identical devices built and available for use. Every judoka had multiple opportunities to use one of the haptic devices during a familiarisation period to acquaint themselves with the overall process of the haptic choice reaction test and with the operation of the device prior to the period of the baseline tests. Furthermore, because we recognised that reaction tests can be monotonous and tedious, we introduced a competition (a weekly league table for best RT and accuracy) in an attempt to make the tests more interesting and enjoyable for the participants and to help motivate them to sustain their attention (for details see Chapter 6). A single test involved 20 reaction episodes and it took just under two minutes to complete. Each reaction episode assessed the reaction to a haptic signal (vibration) that was generated from one out of four available actuators housed in specially designed handles that allowed judoka to apply a judo grip on the handles in the same way they grip the sleeve of their opponent's Judo jacket (for details on the haptic choice reaction test see Chapter 3).

5.2.3 Statistical Analyses

Upon completion of the tests, all raw data were transferred from each device's memory card into a password protected Comma Separated Values (CSV) file for subsequent analysis. All the data processing (data wrangling) and data analyses were carried out in R, version 3.6.1 (R Core Team, 2019) using the *tidyverse* package, version 1.2.1 (Wickham, 2017) and all the plots were designed with the *ggplot2* package, version 3.2.1 (Wickham, 2016).

We have used descriptive statistics for the data analysis in this chapter as we were interested in summarising the data that describe our cohort's baseline levels and we have made no inferences based on these data. For some of the data visualisation we used the local polynomial regression model to fit a smooth curve between the variables of interest, a procedure that was developed in the late 1970s for scatterplot smoothing (Cleveland, 1979). In R, this method of data visualisation is available through ggplot2, a data visualization package included in the collection of packages in *tidyverse*. We used the LOESS (LOcally Estimated Scatterplot Smoothing) method to compute the regression analysis and produce the smooth line for the figures.

5.2.4 Data filtering

We excluded RT values above 1000 msec because: 1) it is a common threshold in RT studies that can improve the power of analysis of variance (Ratcliff, 1993), and 2) from our data presented in Chapter 4 we found that after we filtered unrealistic values all choice RTs were under 1000 msec. We did not set a filter for short RTs because unlike simple reaction tasks where minimum response time can be determined empirically or mathematically (Hsu, 2005; Pain & Hibbs, 2007) the same is not true for choice reaction tasks. Although we can be certain that the minimum choice RT cannot be shorter than, or as short as, the minimum simple RT (see section 1.5.1) we remain unsure as to the exact lower cut-off value we should set. This uncertainty stems from the fact that the minimum latency between a signal presentation and the initiation of a response in a choice reaction task is conditional on more variables such as cognitive processing of the information input (*e.g.* signal differentiation) and task complexity (*e.g.* number of available options and method design). We removed one RT value of 1 msec that we considered impossible and most likely a machine error. In fact, such low RT would even be a stretch for the calanoid copepod, a planktonic aquatic invertebrate known to have a RT between 1.5-3 msec (Lenz & Hartline, 1999). The next shortest RT for a correct response was 195 msec, which we considered acceptable. It was important that we filter out unrealistic data because it only takes a few extreme values, which may be the product of factors unrelated to the testing procedure (*e.g.* a distraction of sorts), to have a disproportionate influence on the results (Harald Baayen & Milin, 2010; Miller, 1991; Ratcliff, 1993).

5.3 Results

On average, each judoka completed approximately nine tests over a time period of nine weeks. A total of 1780 responses were collected from 89 tests, but 88 data points were discarded because they were registered as ‘technical error’ by the software indicating a machine malfunction. Together with one more response that was considered a technical error too due to its extremely low value (1 msec), 5% of the raw data were removed as machine errors. From the 1691 data points that were left, another 36 values (2%) were discarded because they were over 1000 msec and were considered too slow to be true reactions to the haptic signal. Overall, 7% of the raw data were removed from further analysis.

From the remaining 1655 responses, the judoka reacted correctly to 1287 of them. The overall mean accuracy and standard error of the mean (SEM) was 78 (3.66) % and the mean RT (SEM) of the correct responses across the group was 359 (18) msec. Between the sexes, a small difference in mean choice RT was observed with the female judoka’s mean RT at 362 (46) msec compared to the male judoka’s mean RT of 357 (11) msec. The shortest RTs recorded came from a female judoka whose mean RT at 244 msec was nearly 70 msec lower than the shortest mean RT recorded by male judoka (Figure 5-1).

While the overall mean accuracy from our cohort was 78 (3.66) %, the female judoka’s mean accuracy was around 74 (8.11) % and the male judoka’s mean accuracy (SEM) was around 81 (3.15) % (Figure 5-2). For the judoka with the lowest mean RT a low mean accuracy rate was noted as well, approximately 63%, which ranked second lowest and was around 15% lower than the group mean accuracy.

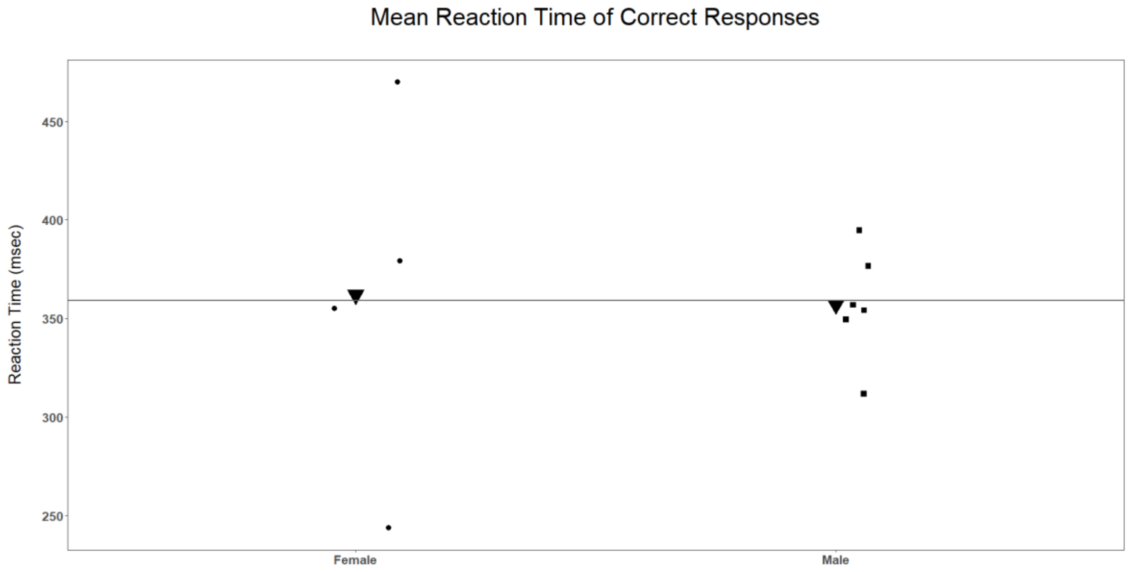

Figure 5-1. Mean reaction time of female and male judokas.

The mean reaction time of correct responses for each judoka is represented by the dots and squares. The overall group mean reaction time is represented by the black line parallel to the x axis. The group mean RT of the female and male judoka is represented by the black triangles.

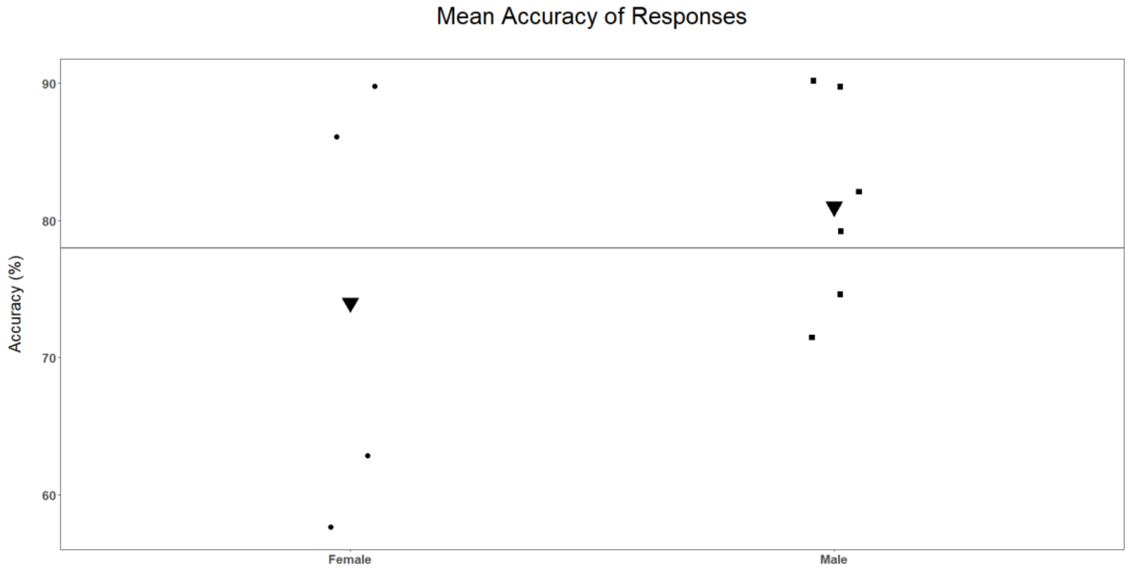

Figure 5-2. Mean accuracy of female and male judokas.

The mean accuracy rate across all choice reaction tests for each judoka is represented by the dots and squares. The overall group mean accuracy is represented by the black line. The group mean accuracy of female judoka and male judoka are represented by the black triangles.

We examined the group's distribution of RT and accuracy across each of the 20 reaction episodes in the haptic choice reaction test. A smooth local regression model (LOESS) fitted over all the data points revealed that the average response time for correct responses across the sequence of the 20 reaction episodes was consistently faster than the average response time for erroneous responses (Figure 5-3), with no difference in this pattern found between the sexes.

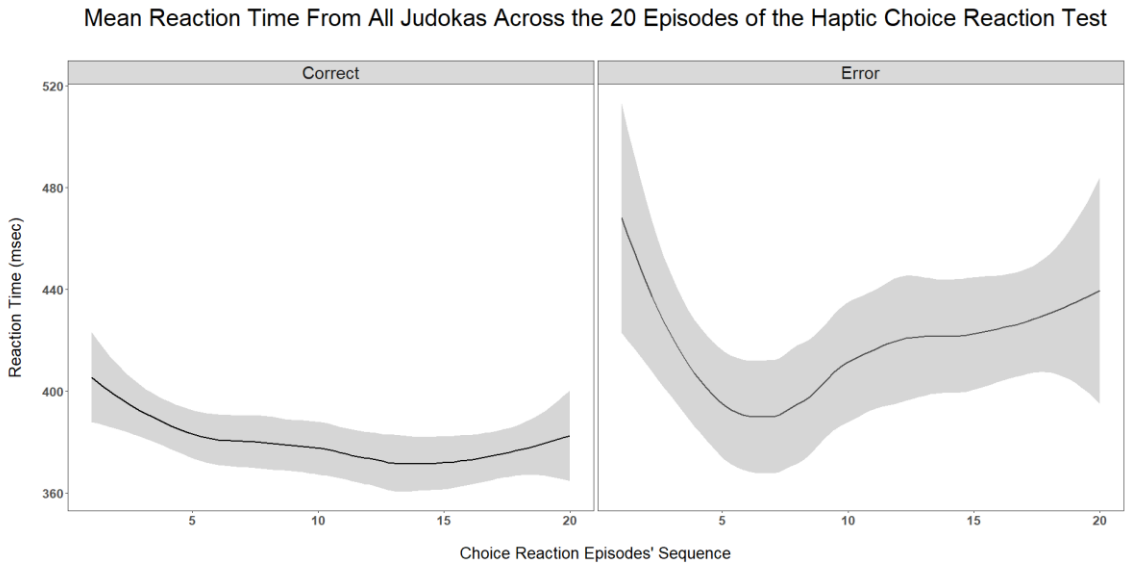

Figure 5-3. Reaction time pattern across all 20 episodes; group.

A LOESS smooth curve (local polynomial regression) revealed that the judoka's mean reaction time of correct responses (black line in left panel) at each episode in the testing sequence in all the haptic choice reaction tests was faster and more consistent compared to the mean reaction time of erroneous responses (grey line on right panel). The shaded grey area above and beneath the lines denotes the standard error of the measurements.

We fitted the LOESS model over all the data points recorded from the judoka who had the lowest mean RT and we found that the average response time for correct responses across the sequence of the 20 reaction episodes was consistently slower than the average response time for erroneous responses (Figure 5-4).

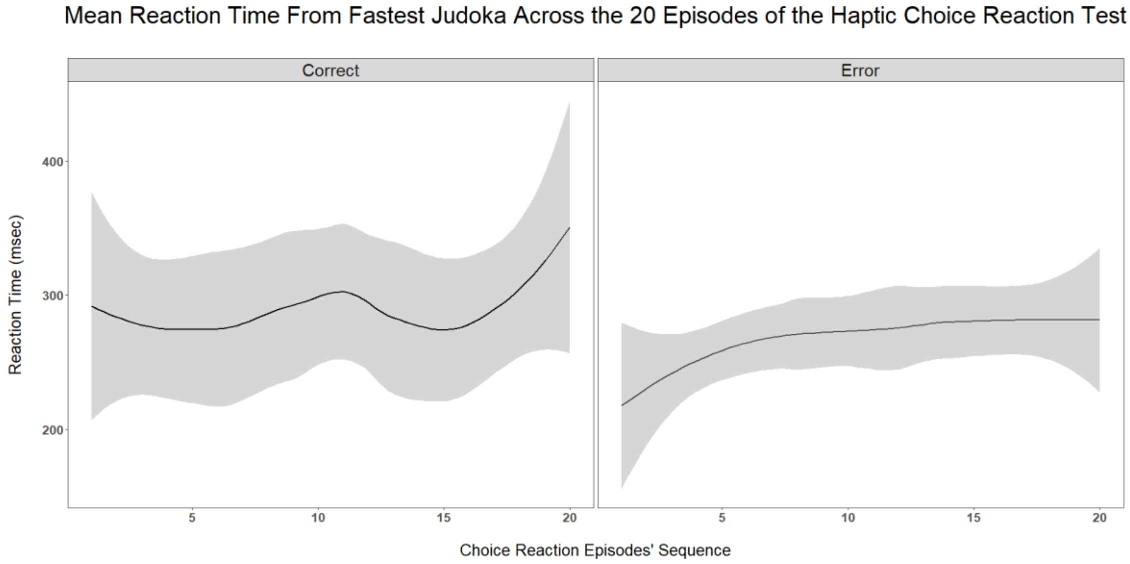

Figure 5-4. Reaction time pattern across all 20 episodes; fastest judoka.

A LOESS smooth curve (local polynomial regression) revealed that for the judoka with the lowest response times the mean reaction time of correct responses (left panel) at each episode in the testing sequence of the haptic tests was slower when compared to the mean reaction time of erroneous responses (right panel). The shaded grey area above and beneath the lines denotes the standard error of the measurements.

The LOESS curve was also used to visualise the distribution of the group's mean error rates at each one of the 20 reaction episodes of the haptic choice reaction test (Figure 5-5). It appears that both female and male judoka displayed a bimodal pattern in their error rate distribution over the duration of the tests. In both cases the error rate appears to have increased progressively to its first peak followed by a fluctuation for the most part of the test and then followed by an improvement by the end.

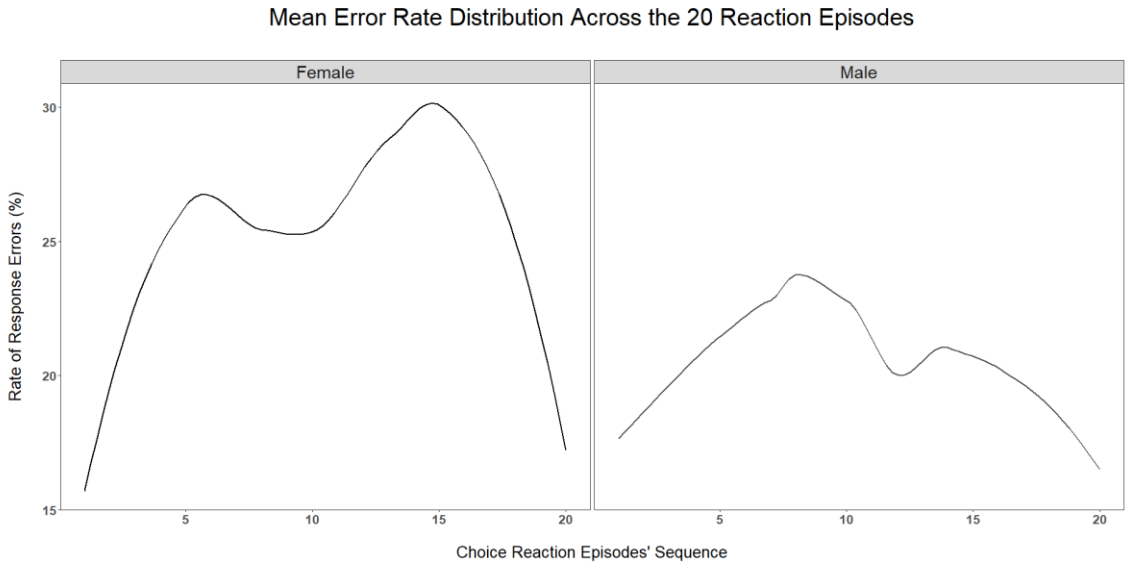

Figure 5-5. Error rate pattern across all 20 episodes; group.

A LOESS smooth curve (local polynomial regression) revealed that the female judoka's mean error rate (black line on left panel) at each episode in the testing sequence of all the haptic choice reaction tests was somewhat higher but of a similar pattern to the male judoka's error rate (grey line on right panel).

With the use of simple data visualisation methods, we can identify the best RT performers within our cohort of elite judoka (Figure 5-6). Using a vertical black line on the x axis to denote the group mean RT, a horizontal black line on the y axis to denote the cohort mean accuracy value, and with the proper scale on the two axes we partitioned the data into four quadrants. From the bottom left quadrant (where the x and y axes are nearest to zero) and moving clockwise we considered each quadrant representing an area in the chart as follows:

- First quadrant; faster reactions and lower accuracy.
- Second quadrant; faster reactions and higher accuracy.
- Third quadrant; slower reactions and higher accuracy.
- Fourth quadrant; slower reactions and lower accuracy.

Four judokas, including three males and one female, appeared to have clustered in what would be considered the ideal quadrant: the top left quadrant of the chart with the faster responses and higher accuracy.

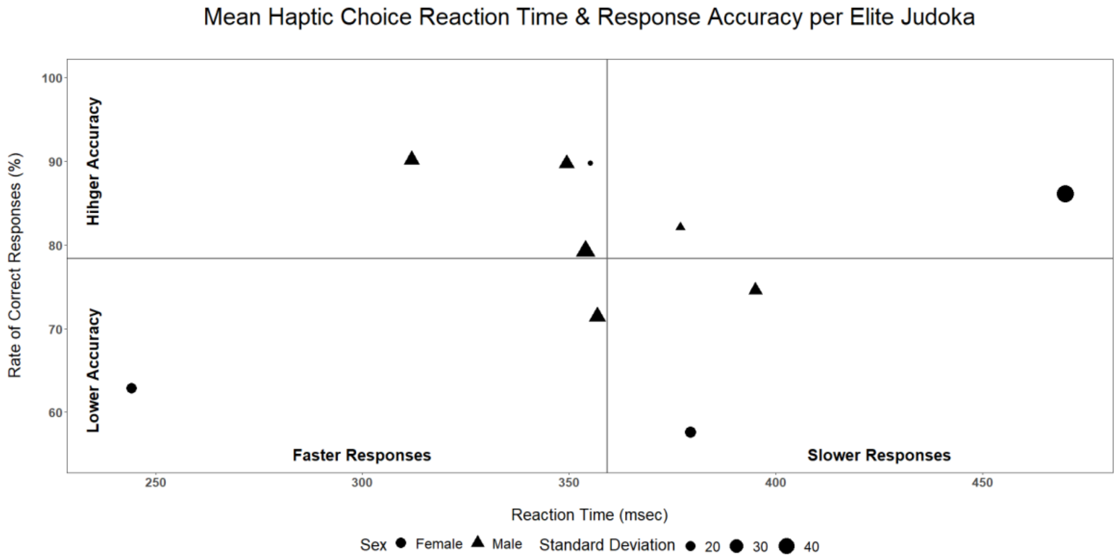

Figure 5-6. Mean accuracy over mean reaction.

The vertical black line on the x axis is placed at the point of the group mean reaction time. Responses on the right side of the line are slower than the group's average while those on the left are faster. Equally, the horizontal black line on the y axis is placed at the point of the group mean accuracy. Results below the horizontal line indicate more errors than the group average while those above indicate fewer errors. The dots and triangles represent the position of each judoka on the chart based on their individual reaction time and mean accuracy. The size of each shape represents the standard deviation of the responses by each judoka.

To compare RT data between left hand and right hand side signals we computed the mean RT and SEM from correct responses to haptic signals generated from the two vibration motors housed in the left handle and the two actuators housed in the right handle of the haptic device (Figure 5-7). We found that the haptic signals from the right hand side handle led to overall shorter mean RT (SEM) of 346 (17) msec compared to the mean RT following haptic signals from the left hand side handle, 369 (19) msec. The mean RT was shorter for both the higher and lower placed actuators in the right handle when compared to either of the two placed in the left handle.

Figure 5-7. Mean reaction time and SEM by hand side.

The mean reaction time of correct responses for each one of the four directions in the haptic choice reaction test is represented by the dots. The standard error of the mean (SEM) is represented by the error bars on each dot. The mean reaction time on the right hand side was consistently shorter than that on the left hand side.

5.4 Discussion

This study is the first to report mean RT of correct responses and mean accuracy for a haptic choice reaction test from a group of elite judokas. We have excluded RTs from erroneous responses for two reasons: 1) The RT a judoka is capable of is only relevant if the choice of action is correct *i.e.* we are not interested in how fast elite judoka can make erroneous decisions but rather how fast they can make correct decisions after processing relevant information, and 2) The inclusion of RT values from erroneous responses would likely dilute the true mean RT as it could potentially add data influenced by factors other than what was being measured *e.g.* lapse of concentration.

Earlier results reported from other mental chronometry studies in Judo have involved vastly different methods that make any meaningful comparison with our study difficult. For example, Morales *et al.* (2018) reported mean baseline RT (SD) of 380 (40) msec for a group of judokas. Although this result does not appear much different to the mean RT reported here, Morales *et al.* (2018) have used a visual simple reaction model. In their test the participants had to step forward 20 cm from a standing stance onto a contact platform in response to a light signal. This set up explains the rather long RT for a simple reaction test as it includes the time necessary for a participant to move their preferred foot 20 cm forward. In another example, Cojocariu & Abalasei (2014) reported mean RT (SEM) of 404 (11) msec for the dominant hand in a cohort of judoka who used a computer-based choice reaction test in which they had to press one of four keys on a computer keyboard corresponding to one of four dots lighting up on the computer monitor. Although both the computer-based test and ours had four available options, and both were set up in a way to minimise necessary movement to register a reaction (thus minimising the degree of motor learning required to complete the task successfully), the mean RT we have reported is considerably lower than the mean RT reported by Cojocariu & Abalasei, most likely due to the different test method and the different sensory modality used. In one study the judoka's reported mean RT in a choice reaction test was practically identical (362 msec) to the one we have reported here (Lech *et al.*, 2011). However, Lech *et al.* (2011) provide no details on the actual test procedure, they do not clarify whether the stimulus for the complex reaction task was visual or auditory, and they do not indicate whether they computed the mean RT from all responses or from correct ones only.

We did not use haptic simple reaction tests in this study as it can be argued that simple reaction tasks lack practical relevance for an open skill sport like Judo where the need to defend, or the opportunity to score, against an opponent does not have a predetermined pattern. Multiple cues to defend or attack can be presented to a judoka concurrently or consecutively in rapid succession. Rapid presentation of different reaction stimuli can result in a phenomenon known as psychological refractory period (PRP). In brief, PRP occurs when two reaction stimuli are presented in rapid succession; as the interval between the stimuli is reduced the response time to the second stimulus lengthens (Pashler, 1994). It is not within the scope of this study to investigate PRP in judoka but its existence highlights the complexity behind real life reaction choices in a combat sport and the importance of understanding elite judoka’s capacity for processing information rapidly. In a simple reaction test a person’s ability for quick decision making is not challenged as the input information stream and response task are fixed (*e.g.* the sprinter who only needs to push off the starting block at the sound of the start gun). Hence a choice reaction test, albeit more intricate than a simple reaction test, is more relevant to elite judoka’s cognitive performance.

To the best of our knowledge, this study is the first to investigate the response-by-response RT and accuracy pattern across the temporal sequence of reaction episodes in a choice reaction test in a group of elite judoka (Figure 5-3 & Figure 5-5). Humans cannot fix their response time or accuracy to a specific level and have to make conscious efforts to sustain their attention on a task over periods of time (Smilek *et al.*, 2010). Moment-to-moment fluctuations in sustained attention was explored in a different study where a specially designed continuous performance task with visual prompts was used (Esterman *et al.*, 2013). In their study Esterman *et al.* (2013) had participants watch pictures of mountain or city scenes transitioning every 800 msec for eight minutes and instructed the participants to press a button for each city scene but ignore any mountain scenes. The results showed that the participants gradually made more erroneous choices across the eight-minute run and that their correct responses became slower. Esterman *et al.* (2013) used an innovative analysis procedure to reveal two attentional states: a less error prone state with lower variability in RT or “in the zone,” and a more error prone state with higher variability, or “out of the zone.” Our method was quite different to that reported by Esterman *et al.* (2013), and with different objectives. And although we would not expect a similarity in the response-by-response data pattern (due to the differences in the study design) it is worth highlighting that our results too revealed the variability in RT to be lower for correct responses than incorrect ones (Figure 5-3).

As shown from the smooth curves in Figure 5-3 the response-by-response mean RT over the sequence of 20 reaction episodes was shorter when the judoka made correct decisions. This finding suggests that quick responses were not achieved by sacrificing accuracy. It could be argued that the slower responses when the choices were wrong is evidence of some degree of lapse in concentration, which led to the errors. In Figure 5-4 we presented the response-by-response mean RT from a judoka who reacted consistently faster than any other in the group but whose superior RT was achieved at the expense of accuracy. In this case, unlike the trend we saw by the group, the variability in RTs was higher for correct responses. Perhaps the lower variability of inaccurate RTs compared to accurate ones reflects persistent attempts from this judoka to guess the correct response in order to register shorter RTs.

We also see a downward trend of the smooth curves for the first five reaction episodes (Figure 5-3). It is as if the judoka were ‘easing into’ the test. In competitive Judo the pace can be intense from the very first few seconds and a match can be lost or won on the first exchange of moves between judokas. It follows then that elite judoka must be able to begin a fight with the necessary levels of cognitive arousal from the opening seconds and for the duration of the match. It is conceivable though that this seemingly slow start would not have been present if the judoka had completed some exercise prior the tests to raise their levels of physiological and psychological arousal.

It has been suggested that it is best to test judoka’s RT after a warm up as their RT reduces post warm up (Zukowski, 1989). Indeed, studies outside Judo, support the idea that an improvement in RT can be realised after exercise (Draper *et al.*, 2010; Rattray & Smee, 2013). Acute exercise has been shown to have a stimulating effect on the central nervous system (Oberste *et al.*, 2019), which might result in enhancing performance in the haptic choice reaction test. However, we were interested in exploring elite judoka's limits on a haptic choice reaction test at rest (baseline) and without the potential influence of any cognitive stimulation by physical exercise. One example of how baseline parameter values in cognitive performance could potentially be used is in the event of a head injury. Medical staff could use baseline RT results to consider a judoka's readiness to return to training or competition following a concussion (Eckner *et al.*, 2009). Hence, we remain confident that the baseline for mean RT and accuracy in elite judoka should be determined at rest and without the potentially stimulating effect of acute exercise on the central nervous system.

Our cohort of participants was almost equally split between male and female (60% male judoka and 40% female judokas) and we found the mean RT from these two subgroups to have been nearly identical. As shown in Figure 5-1, the individual mean RT of the male judoka appears clustered tightly around the overall group mean RT while in the case of the female judoka we see two extreme points away from the centre and at opposite directions. It would seem that in this subgroup we have managed to get the judoka with the fastest and slowest mean RT in the group. In true serendipity though these two extreme values have not affected the overall mean value as they cancelled each other out. Indeed, when we recalculated the mean RT from our cohort with these two extreme values excluded there was no difference in the result.

Several well conducted studies have shown that, on average, females tend to have slower responses than males (Der & Deary, 2006; Engel *et al.*, 1972; Fozard *et al.*, 1994; Noble *et al.*, 1964). Data from sprint events in athletics too appear to support the belief that female competitors have slower response time to the firing of the starter's gun than male competitors (Babic & Delalija, 2009; Paradisis, 2013). However, data showing male sprinters post faster RTs than female sprinters have been put to question. It has been argued that female and male sprinters' RT to the starter's gun at the 2008 Beijing Olympic Games would have been similar if the force threshold on the starting blocks was lowered by 22% for female sprinters, which would have accounted for their lower weight and strength (Lipps *et al.*, 2011). The idea that there is some innate difference between females and males in their ability to react fast has been challenged with three main arguments (Silverman, 2006): 1) The participation of females in sport only started to increase a few decades ago, 2) Since participation in sport can reduce RT it follows that the mean RT of females in the general population should drop too, and 3) Many studies in reaction performance include a higher number of male participants, a greater proportion of whom are more likely to regularly take part in sport and consequently skew the results.

Athletes can react faster than non-athletes (Bańkosz *et al.*, 2013; Christenson & Winkelstein, 1988; Vera *et al.*, 2017; Youngen, 1959) and RT can improve with practice (Ando *et al.*, 2002; Taniguchi, 1999). Therefore, there is validity in the argument that past data showing females to be slower in their responses compared to males may be partly explained by the fact that historically fewer women regularly engaged in activities that challenged their reactions *e.g.* competitive sports or driving.

There are no major studies in Judo research to have examined the difference in mean RT between female and male judokas. In a recent study investigating the effects of rapid weight loss on RT in a group of female and male elite judoka the results were reported without considering differences by sex (Morales *et al.*, 2018). Perhaps such approach to the reporting of the results by authors indicates that if any difference in RT between sexes existed, they were of no practical significance or consequence. Our cohort was too small to allow us to draw firm conclusions but the evidence we have obtained suggests no reason to assume that elite female judoka could not match the mean RT typical of elite male judokas.

It has been argued that the most successful and most experienced judoka are also likely to respond faster in simple and choice reaction tests compared to less successful and less experienced judoka (Lech *et al.*, 2011; Zukowski, 1989). But no explanation has been offered as to how judoka with better skill levels can outperform less skilled judoka in tests that are not Judo specific *i.e.* computer-based tests with audio and visual cues. We compared the overall cognitive performance (RT and accuracy) of each judoka against the rest of the group (Figure 5-6). We split the chart area in Figure 5-6 into four quadrants based on faster or slower RT (x axis) and higher or lower accuracy (y axis). Interestingly, the female judoka in the top left quadrant (faster RT and higher accuracy) was the most competitively successful amongst the females in the group and two out of the three male judoka in that same quadrant were the most competitively successful amongst the male judokas. However, our cohort is too small for us to reject the possibility that any positive correlation that may exist between the participants' cognitive performance in the haptic test and competition success is purely coincidental.

When we examined the RT data based on which side the haptic signal was generated from, we found that the mean RT from the right hand side was shorter than the mean RT from the left hand side (Figure 5-7). In a study where differences in RT between left and right hand responses were studied across a variety of computer-based visual tests in a group of judokas, the authors found responses to be consistently faster with the dominant hand although at not a statistically significant level (Cojocariu & Abalasei, 2014). In each one of our devices all four actuators housed in the handle grips were identical in design, they produced the same vibration frequency, and they were placed at symmetrical points to each other and from the centre of the device. Consequently, the design of the haptic device cannot explain the discrepancy between the left side and right side responses. Most people have a manual asymmetry and the vast majority favour their right hand for manual tasks that require dexterity or simply for most of their daily tasks (Buckingham & Carey, 2015). In the reaction task every single response recorded by the judoka was done with them holding the device with both hands and moving their hands in unison whenever they displaced the device in response to the haptic cue, which does not explain the difference in mean RT based on their manual asymmetry alone. A more likely explanation for the difference is attentional bias. According to the attentional bias hypothesis, attention is biased toward the right hand, in right hand dominant people (Buckingham & Carey, 2015). Our cohort was made of judoka all of whom were right hand dominant. We had no way of testing whether left hand dominant judoka can respond in an equivalent way as none were available in our study.

In future studies it would be useful to repeat the haptic choice reaction tests on a larger cohort of elite judoka and perhaps, over time, develop a clear understanding of the true cognitive performance standards for this population of athletes and whether a correlation exists between judoka who perform well in the haptic test and judoka who perform well in Judo competition. It would also be interesting to use the haptic choice reaction test to determine whether athletes from sports where the primary sensory input is from tactile feedback (*e.g.* Judo, Olympic Wrestling, and Brazilian Jiu-Jitsu) have an advantage to such sensory modality against athletes from sports where tactile feedback is minimal or non-existent (*e.g.* Boxing, Clay Pigeon Shooting, and Sprint).

5.5 Conclusion

We have reported the mean RT and mean accuracy in a novel haptic choice reaction test from a cohort of elite judoka who are active at international standard competitions. In addition, the device used to collect data from choice reaction tests has arguably a much stronger ecological validity compared to other methods reported previously in the literature as it has allowed for the collection of haptic reaction data within real life Judo training conditions.

To the best of our knowledge this is the first study to report typical mean response times and mean accuracy rate from a haptic choice reaction test in Judo. It is also the first study to show a response-by-response pattern in the variability of mean RT and accuracy in a choice reaction task carried out by a group of elite judokas.

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Chapter 6: The Use of Competitiveness in Haptic Choice Reaction Tests for Elite Judoka

6.1 Introduction

In Chapter 5 we described the typical baseline cognitive performance parameters, such as mean reaction time (RT) and accuracy to a haptic choice reaction test in a group of elite judokas. Due to fact that the haptic tests were carried out on multiple occasions we considered it important to minimise the potential ‘noise’ in the data from factors unrelated to the test *e.g.* boredom. In this chapter we describe how we used competitiveness to make the testing procedure more interesting for the judoka and motivate them to engage fully in the tests. We describe people’s innate inability to sustain attention and other factors such as motivation and distraction, which can influence a person’s ability to stay focused on a task. We also show how the competitiveness element to the testing procedure affected some of the judoka’s responses.

There are thousands of studies carried out in sports science looking at a plethora of distinct factors that can affect the performance of athletes during competition. But most of these studies, including ones on Judo, are observational or intervention studies carried out within controlled environments such as University laboratory facilities (Cojocariu & Abalasei, 2014; Javier *et al.*, 2013; Lima *et al.*, 2004; Lopes-Silva *et al.*, 2014). Often, researchers may opt for tests in their studies that do not necessarily reflect the actual demands of the sport *e.g.* designing a reaction test with visual prompts for sports where most of the sensory input is tactile. Thus in sports like Judo there is a gap in knowledge relating to the specific somatosensory demands of the sport. To address this knowledge gap in Judo we have designed a bespoke reaction testing device (see Chapter 2). One aim in developing this novel device was to establish baseline measurements to determine a reliable estimate of the typical reaction time (RT) and accuracy of response to a haptic signal in a group of elite judokas.

During the initial stages of the haptic reaction data collection, acute improvements in measurement values can be observed as participants acquaint themselves (learning effect) with the process of the new task (Raglin, 1992), which can confound baseline measurement. Familiarisation is therefore an important phase before we attempt to estimate baseline parameter values. But even once all participants are fully accustomed to how the device works, and comfortable with the task, the data collected may still not reflect accurately the true values. The demands of the test on participants' attentional resources may exceed their motivation to use their best efforts if they perceive the reaction test as too monotonous or boring. In fact, it has been shown that during a sustained attention task less motivated participants were more likely to get distracted (Seli *et al.*, 2015). Hence, there is a risk of participants disengaging from a test procedure which, in our case, is fundamentally important to elucidate the typical cognitive performance parameter values in a group of elite judokas.

It is fair to assume that athletes in high performance sport are more physically robust and more motivated (Keegan *et al.*, 2010) to push their limits than the average person: they have to be if they are to compete at high level. But even elite athletes need to find ways to maintain their motivation to regularly complete extreme physical efforts outside competition, whether in training or during physiological testing (Laukka & Quick, 2013), unless a motivational component or variable is introduced such as: the promise of training adaptations that will enhance performance in competition, the achievement of a qualification standard for a major event, or the promise of some other desirable reward.

In our project we had no monetary awards to entice people to apply their best efforts during the test nor could we promise them any immediate gains from the study. There can be many different factors that motivate people (Deci & Ryan, 2000) however, a strong driver for motivation in high performance athletes is their competitiveness (Tusak, 2000). Of course, competitiveness is not exclusive to sporting arenas. In a workplace experiment, researchers demonstrated an improvement in employees' performance over time when employers introduced competition incentives by systematically rewarding workers who outperformed their co-workers (Benndorf & Rau, 2012). It has been suggested that competition is an effective way to increase motivation and interest in physical education classes participation among University students (Ivanova & Korostelev, 2019).

We believe that the best way to motivate our cohort during the tests is to introduce a competition element to the test. In the following sections we describe in more detail attention and motivation within the context of cognitive performance.

6.2 Sustained attention

Attention is believed to be a collection of mechanisms used by the brain to process selective information from the environment and prevent the potential sensory overload from all the information that can be received simultaneously (Fiebelkorn *et al.*, 2018). Attention of course is critical for performance in any reaction task but studies on spatial attention have revealed that attention is not the product of some continuous process, instead, there are neural oscillations that cause rhythmic cycles in attention, which in turn lead to an increase or a decrease in perceptual sensitivity (Fiebelkorn *et al.*, 2018). In essence, humans have an inherent inability to sustain attention.

Human inability to sustain attention during prolonged tasks has been studied since the Second World War when the Royal Air Force tried to determine the maximum length of time airborne radar operators could stay on submarine watch before their detection accuracy deteriorated (Mackworth, 1948). Mackworth found that after 30 minutes of continuous observation radar operators detection accuracy could drop by up to 15%. Mackworth's was the first study to unequivocally show that over time, during a repetitive task, there is an increasing degree of 'vigilance decrement', which means that sustained attention weakens. The same findings have been confirmed in similar studies since (Fortenbaugh *et al.*, 2017).

Sustained attention has been defined as: "…the ability to self-sustain mindful, conscious processing of stimuli whose repetitive, non-arousing qualities would otherwise lead to habituation and distraction to other stimuli." (Robertson *et al.*, 1997). In essence, sustained attention is a person's capacity to focused attention on a task and is arguably the main limiting factor in cognitively demanding tasks such as lengthy choice reaction tests, which do tend to have "non-arousing qualities", simply put: they can be boring. Of course, a task does not need to be lengthy to lead to a decline in sustained attention. There have been various methods developed to capture and quantify the magnitude of sustained attention decrement.

Robertson *et al.* (1997) developed a reaction test, the Sustained Attention to Response Task (SART), which was designed to measure the ability to sustain attention to a dull but demanding task. In this computer-based test, which was just over four minutes long, subjects were instructed to press a key on the computer's numeric keypad every time a digit appeared on the computer screen but to withhold response when a pre-specified digit was displayed. It was theorised that such a test would demand subjects to sustain their attention and that the test would expose any lapse in concentration without taxing other cognitive processes *e.g.* memory, planning, and overall cognitive effort. SART is used in psychology practice as a validated behavioural index of sustained attention in patients with traumatic brain injury (TBI), people with attention deficit hyperactivity disorder (ADHD), or other neuropsychological conditions (Smilek *et al.*, 2010). However, whether the SART method can adequately challenge sustained attention in healthy individuals has been questioned (Esterman *et al.*, 2013).

More recently, Esterman *et al.* (2013) developed an alternative reaction test to study sustained attention: the Gradual Onset Continuous Performance Task (gradCPT). In a gradCPT study, subjects were placed in a magnetic resonance imaging (MRI) scanner and they were shown grayscale photographs of mountain scenes and city scenes at aperiodic intervals through a goggle system. The images gradually transitioned from one to the next and the subjects were instructed to press a button for each city scene but withhold responses to mountain scenes. By having subjects carry out the gradCPT in an MRI scanner the researchers were able to observe the activity of two important brain networks: 1) the dorsal frontoparietal attention network (DAN), which shows more activity during goal oriented attention, and 2) the default mode network (DMN), which appears more active at rest rather than during task performance. Esterman's research team did not favour one brain network over the other and they pointed to the lack of agreement in studies carried out to find out whether higher activity of DAN or DMN is preferable. Instead, they argued that optimal performance may be the product of the balance between the DAN and DMN activities. With the help of the MRI data this research group were able to show the existence of two attentional states: 1) a less error prone state, which they described as 'in the zone' state, and 2) a more error prone state, which they described as 'out of the zone' state. The authors concluded that in tasks that may be perceived as easy and potentially performed more automatically errors follow elevated DMN activity. In contrast, in tasks that may require more effort any errors may be due to incomplete activation of the DAN region.

It is clear then that achieving consistent results in a reaction test is very difficult as the mind has a tendency to wander over time. Humans cannot fix their attention to a constant level and variability in moment-to-moment responses always exists (Esterman & Rothlein, 2019; Fiebelkorn *et al.*, 2018). People’s inability to prevent mind wandering during a task has been known since antiquity and philosophical schools of thought such as Stoicism and Buddhism are known for meditation methods that encourage their followers to control mind wandering (Davis & Sharpe, 2013).

We know that during a cognitive task the quality of sustained attention declines over time and such deterioration manifests in slower detections of reaction signals and lower accuracy (Parasuraman *et al.*, 1987) thus increasing the probability of attentional failure or errors. It is easy for most of us to recollect examples of attentional failures with a varying degree of consequences, from quite innocuous to disastrous slips of action such as: forgetting that pair of red shocks in the white wash, filling up the car with the wrong fuel (according to the British Insurance Brokers’ Association (BIBA, 2007), every year as many as 150,000 drivers in the UK accidently put wrong fuel in their cars), or distracted motorists who cause traffic incidents with human fatalities. Beyond the obvious consequence from lapse of attention during a task *i.e.* making mistakes, the ability to sustain attention is considered critical for academic readiness (Isbell *et al.*, 2018) and it has been a topic of research investigation for decades (Fortenbaugh *et al.*, 2017). It has been estimated that people’s minds wander 47% of the time during waking hours (Killingsworth & Gilbert, 2010). But it is believed that there may be an advantage to mind wandering as it is conducive to planning for events in the future or problem solving. However, at the same time the cost of mind wandering is high [for a review see (Mooneyham & Schooler, 2013)].

6.3 Motivation

One common concern in mental chronometry research is that participants may be too eager to perform well in reaction tests. Indeed, often the underlying hypothesis may not be revealed to test volunteers at the start so that they do not produce false positives as they try to be ‘good’ participants (Seli *et al.*, 2015). In our study we made clear to the participants from the start that our intention was to find out how fast and how accurately they could respond each time they performed the haptic reaction test. Given the above relating to sustained attention our concern was not whether the judoka would be overzealous but whether they would be motivated enough to concentrate on the test as well as they could and do so on multiple occasions.

It has been long recognised that for a person to complete a task and apply their best efforts on that task their motivation is a crucial factor (Ericsson *et al.*, 1993). Indeed, self-motivation has been repeatedly highlighted as an important quality of high achievers in academia and other fields (Button, 2011). Such is the importance of motivation for training and competition in high performance sport that it has been argued that when talented athletes are identified at the early stages of their sporting careers as having the potential to excel, then the ones selected should be those who appear to be the most motivated to carry out deliberate practice (Hodges & Baker, 2011). In mental chronometry research it has been shown that motivated participants are less likely to engage in task unrelated thoughts (*i.e.* mind wandering) during a response task compared to less motivated participants (Seli *et al.*, 2015). Thus, a motivational constraint exists that directly impacts on execution of a task and it would be unwise to assume that the participants in our study would be motivated enough to do well in the response task whenever we handed them over one of the haptic reaction devices.

Obviously, we cannot expect or even assume that our participants will have the necessary motivation to complete the RT tasks in our research to the best of their abilities when there are no tangible benefits to them for doing so. When we consider that the tests need to be repeated on multiple occasions it becomes clear that we need to introduce some factor in the testing process that will motivate our judoka to maximise their engagement and attention, so that we can have more confidence that the data collected are a true reflection of what our cohort of judoka is capable of. It would be impractical to find out, and impossible to satisfy, all the intrinsic and extrinsic factors that may maximise each participant’s motivation (Deci & Ryan, 2000) to deliver their best efforts at each test episode but we are perhaps able to identify a common denominator.

Before we move on to consider ways to motivate our cohort to fully engage in the reaction tests we should outline other conditions necessary to optimise the level of performance by each individual at each test. Ericsson *et al.* (1993) have argued that, besides motivation, the task we expect individuals to learn and perform should take into account:

1) Prior knowledge of that task. Participants who are not familiar with the testing protocol should be given the appropriate instruction and as many times as may be necessary to ensure their correct understanding of what is expected of them. Although all of the participants were familiar with the concept of ‘Reaction Test’ none had the opportunity to experience the use, or see, our novel haptic choice reaction test device before it was shown to them by us. If a judoka’s perceived ability to meet the demands of the task was low only because they had not been explained the task adequately then their self-efficacy could have been low and lead to anxiety (Panayiotou & Vrana, 2004). However, we believe that the set up and use of the device for the test and the testing procedure itself are both straightforward and easy enough for people to understand and execute correctly. With an easy testing procedure in place we can be more confident that the quality of the data we obtain is not subject to having participants with high self-efficacy. In fact, it could be argued that the combination of the repeated practice runs of the tests and the simplicity of the test are likely to promote a level of mastery of the task that can only enhance any participant’s sense of self-efficacy and confidence to complete the test well (Bandura, 1978).
2) Feedback to the individuals on their performance. It has been shown that positive feedback can improve motivation and performance (García *et al.*, 2019). Our reaction devices were not set up to give feedback immediately

after each response or even at the end of the test run. However, following the completion of each test the data were automatically saved in the device's memory and collated at a later point on the day of the test. The data collected were used to update individualised graphs that where shared with each participant on the following week and before their next reaction test. In the chart, the participants could see how their overall performance compared to that of the group and how their most recent results compared with their own previous results. This information was shown to the participants as a point of reference and way of encouragement, and not as a qualitative outcome *i.e.* there were no 'good' or 'bad' results.

3) Repeated practice of the task. 'Deliberate practice' is a common term used in high performance sport to describe the practice of specific activities executed by experts on a regular basis and with purpose, with the main objective being to improve competition performance (Mascarenhas & Smith, 2011). Our cohort of elite judoka were fully aware of the importance of practice on the device in order to fully acquaint themselves with the way they needed to respond to the device's reaction cues. All judoka were offered a practice run of the test before starting the actual test, but they all felt that the task was simple enough to not require any practice before testing.

Ericsson *et al.* (1993) have stated that when the above conditions are in place then it is highly likely to see the accuracy and speed of performance improve on cognitive, perceptual, and motor tasks.

Another variable that can influence an individual's motivation to maximise their commitment to repeated efforts in a given task is self-investment. In other words, people are more likely to 'buy in' if they believe that there is a personal gain to be had from their effort. In an attempt to maximise the 'buy in' factor, when we first described the study to the participants we also explained to them the purpose of the tests as well as the potential longer term benefits they may get out of it *e.g.* use data to establish baselines that can later help identify cognitive fatigue and inform coaching decisions that in turn may help maximise the learning effect or training adaptations from each training session.

6.4 Distraction

It can be argued that even well motivated judoka who are determined to achieve perfect results in the haptic reaction task can still make mistakes or execute slower responses due to some source of distraction. It has been shown that distractions such as low intensity background noise can lead to slower response times (Trimmel & Poelzl, 2006) and it has been claimed that perceived stress too may in itself be a source of distraction as it can degrade judgment and decision making skills (Staal, 2004). On the other hand, it has been said that distractions can be resisted by highly focused individuals (Folk *et al.*, 1992), which may explain to some extent why judoka do not appear to get distracted by the loud noises around them during a competition. Of course, judoka are better placed to resist the potential distractions specific to a typical competition environment as those are primarily sound related yet the response queues between two judoka during their match are by and large kinaesthetic; it would be inconceivable for a 100 m sprinter to be expected to react fast to the sound of the start gun if at the same time there were loud noises made by the crowd watching the event.

It is because of the above we opted to take the haptic reactions test device to the judokas, in their usual training environment, and ask them to complete the reaction task with no intervention against the typical sources of distraction that may had been present (*i.e.* other judoka chatting or loud music in the background). Arguably, in spite of the potential sources of distraction, a reaction task carried out in the judoka’s actual training environment can enhance the ecological validity of the method.

6.5 Challenge Point Framework

One potential issue with any novel method that requires participants to execute a motor task is that the same task can be perceived as an easier or a more difficult challenge amongst performers with different abilities (Guadagnoli & Lee, 2004). According to Guadagnoli & Lee (2004) there are three areas that can influence the potential of an individual to learn a motor task including: the environment within which the motor task is executed, the skill level the individual possesses, and the complexity of the motor task.

All judoka performed the tests in their familiar environment of the Scottish Judo centre with all the usual distractions they encounter during a typical training session. We made no attempt to alter the environment within which the tests took place. Our cohort of elite judoka was fairly homogenous in their skill level and competition experience. It is implausible that any of these highly skilled individuals have found the haptic task (see Chapter 2) difficult to learn.

Regardless of how simple the haptic reaction task was, we would still anticipate our participants to demonstrate notable improvement in their RT results within the first few tests, as is typically the case during task acquisition (Raglin, 1992). Besides, it is well accepted that practice is important to improve any skill (Salmoni *et al.*, 1984). It could be argued however that after having learnt the motor task, and due to its rudimentary nature, the task may had been perceived as too easy by the judoka and could have allowed their attention to shift away from the task.

The signal intensity of the ERM actuators we used was 122 Hz and not at the optimum vibration sensitivity for the surface of the palm, which is thought to be at around 250 Hz (Cholewiak & Collins, 1991; Scheibert *et al.*, 2009). At practically half of the optimum frequency the haptic signal generated was not as easy to detect accurately but still clearly detectable with focused attention. A deliberate approach to make the tests more interesting for the judoka and motivate them to sustain their attention was the competition we introduced in the testing procedure.

6.6 Competition

One would expect a group of young elite judoka who aspire to a place in the Olympic Games and the top levels of the World rankings to have a competitive nature in common. With assumed competitiveness as the common denominator in our cohort we expected a higher level of engagement from them in a method that is more likely to pique their interest compared to a task they may think of as dull. Therefore, in order to entice the participants to engage in the testing process and commit to delivering credible performances we decided to introduce a competition element in the testing process.

We created four ‘events’ and awarded points to the top five individuals with the:

1) Quickest correct response
2) Lowest mean RT on correct choices
3) Most consistent RT on correct choices (*i.e.* the lowest standard deviation)
4) Highest accuracy rate (*i.e.* number of correct responses over the sum of responses)

The top performer in each category was awarded 10 points followed by 7, 5, 3, and 1 point awarded to the judoka placed from 2nd to 5th respectively. A league table was generated and each week, once the results were collated, the league table was updated and the ‘Leaders’ in each category were announced.

An alternative approach to investigating the haptic choice reaction performance could have been to collect data for a few weeks, without a competition element in the process, and then analyse the data points to reveal the learning effect and find the area beyond which the overall RT showed no further improvement. In our study though we wanted to repeat the tests on multiple occasions with the same cohort of elite judoka before trying to determine their baseline mean RT and mean accuracy in a haptic choice reaction test. Without external factors to motivate people to perform their best *e.g.* payment, we decided that the introduction of competition to the test would probably place the results closer to the true parameter values. One consequence of competition though is that it can cause a level of anxiety that can be beneficial to performance or destructive.

6.7 Performance anxiety

The purpose of introducing competition to the testing procedure was to motivate the judoka to apply their best efforts in every test and minimise the risk of collecting data from disengaged participants. However, we cannot assume that the added expectation to outperform others can be purely facilitative and only associated with positive outcomes. In fact, competition increases the importance of performing well and leads to added pressure, and performance under pressure may result in ‘choking’ – a performance decrement under pressure (Baumeister, 1984), as perceived stress can degrade judgment and decision making skills (Staal, 2004).

Performance anxiety is thought to be one of the most important factors in the outcome of a sporting event (Palazzolo, 2020) and it has been described as: “an unpleasant psychological state in reaction to perceived threat concerning the performance of a task under pressure” (Cheng *et al.*, 2009). There is no consensus within the scientific community on a single model to describe accurately the relationship between anxiety and performance (Palazzolo, 2020). Cheng *et al.* (2009) acknowledged that anxiety is complex and not always correlated with negative effects. These authors have proposed a conceptual framework of three main dimensions of anxiety (cognitive *e.g.* worry and self-focused attention, physiological *e.g.* autonomous hyperactivity and somatic tension, and regulatory *e.g.* perception of one’s capacities to be able to cope and attain goals under stress) that they believe better reflects the complexity of anxiety (for more details see Cheng *et al.* 2009).

It is not within the scope of our method or that of the wider study to examine the performance–stress dynamics or to disentangle the factors behind the inconsistent results of the research carried out in this area. Our intention with this specific section is to highlight that performance anxiety affects different athletes in different ways (Palazzolo, 2020). By having introduced competition we may have potentially made the testing procedure more fun and interesting for most judoka but not for all. Crucially, if the competition element of our method has led to some degree of pressure on judoka to perform better then, we could argue that such approach has added to the ecological validity of our method.

6.8 Methods

6.8.1 Participants

This study was approved by the School of Sports Research Ethics Committee of the University of Stirling. Ten healthy, elite level judoka (Four females aged 21.3 ± 2.2 years; weighing 62.3 ± 8.5 Kg; and six males aged 21.2 ± 1.6 years; weighing 72.2 ± 8.3 Kg) who compete at international level and participate at World ranking tournaments volunteered for this project and gave written consent after the purpose and details of the study were explained to them. All participants knew that they could withdraw from the study at any point if they wished to do so without having to provide any explanation (see section 2.1 in Chapter 2 for further details).

6.8.2 Pre Testing

With the need to address factors beyond the mediating variable of motivation in mind, we carried out the following actions before trying to establish a baseline for our cohort's abilities in the haptic choice reaction test:

1) We explained to the judoka the testing protocol and demonstrated how to use the handheld device before letting them have one or two runs of the test without recording any data.
2) We made sure that individualised reports of each judoka's results were generated, the data individually shared and explained to each one so that they could monitor their own progress and be encouraged to continue to seek improvement.
3) We made sure to keep the time length of the test short (just under 120 seconds) to encourage participation and to minimise loss of concentration.
4) We reminded each judoka before the start of every test episode that they could have a practice run of the test prior to recording any data if they wanted to do so.
5) We encouraged repeated tests under similar conditions in order to increase our confidence that any learning effect has been eliminated and could not influence the results that were eventually used to establish baseline values in choice RT and accuracy.

6.8.3 Study Design

The data collection to establish the baseline cognitive performance of elite judoka in a haptic choice reaction test took place nearly over four months and outside their competition season. Not including major tournaments within the study time period meant that we were able to avoid any impact on cognitive performance from dehydration or other weight management techniques typically used by judoka and other athletes who try to make weight for competition (Artioli *et al.*, 2010). Each test was carried out on repeated occasions during regular training hours at the High Performance centre of Judo Scotland. We selected two distinct periods for data collection:

- For the ‘Familiarisation’ measurements the data were collected over a period of nearly two months and just before the start of the judoka’s warm up on sessions. Prior the test, feedback was given to each judoka regarding their results from the previous test (*i.e.* shortest RT, mean RT of correct choices, and accuracy rate). In the Familiarisation condition our intention was to provide sufficient time for our cohort to get familiar with the test protocol and the use of the haptic device. These tests also served as an opportunity for the investigators to identify any potential issues with the testing procedure or the devices used.
- For the ‘Baseline’ measurements the data were collected over a period of almost two months and under the exact same conditions as with ‘Familiarisation’. However, the extra step in this case was that the results from each test were used to award ranking points and update the weekly leader board, which was displayed on the noticeboard of the dojo and showed the top five performers in each category (see section 6.6).

6.8.4 Statistical Analyses

In this chapter we have used Bayesian inference for the statistical analyses. We have used Bayes Factors (BF) to compare paired means from the two conditions of interest *i.e.* Familiarisation and Baseline. We have used Cohen’s effect size (d) calculation to report the magnitude of the mean difference between the groups (see section 2.3 in Chapter 2 for the principles and rationale behind Bayesian Statistics and Bayesian analysis tools such as BF and Credible Intervals).

Cohen's effect size (d) was used with its conventional interpretation (Cohen, 1988):

- Small effect = 0.2
- Medium Effect = 0.5
- Large Effect = 0.8

Data filtering was carried out as described in section 5.2.4. All data processing (data wrangling) was carried out in R, version 3.6.1 (R Core Team, 2019) using the *tidyverse* package, version 1.2.1 (Wickham, 2017). Bayes factors were used for hypothesis testing and to run the correct models and simulations we used the statistical functions available in *BayesFactor* package, version 0.9.12-4.2 (Morey & Rouder, 2018) and more specifically the *bayes_inference*( ) function from the *statsr* library. All the plots were designed with the *ggplot2* package, version 3.2.1 (Wickham, 2016).

6.9 Results

6.9.1 Learning effect

We examined the data from the Familiarisation period and were able to reveal a learning effect as indicated by the steady reduction in the group's RTs over the number of tests completed (Figure 6-1). From the second haptic reaction test onwards there was an increase in faster responses and a reduction in variance of the data. Fewer outlier values were present by the fourth test indicating that by that point the judoka had worked out how to achieve faster and more consistent results than what they were able to achieve at their first test (Figure 6-1).

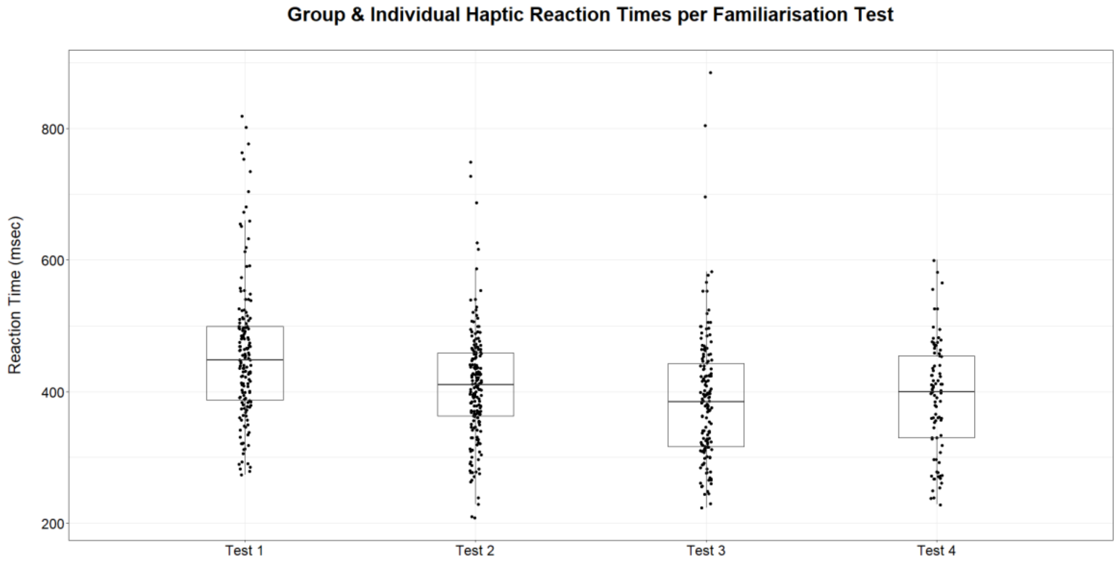

Figure 6-1. Individual responses in Familiarisation tests.

Boxplot of correct individual responses to haptic choice in sequential test order with raw data overlaid as points.

A second approach to examine the learning effect during the Familiarisation process was to split the data recorded from each judoka into two sections. In the first section we included data from the first half of the participant's total number of test sessions (Familiarisation 1st Half). Whereas the second section was comprised of data from the latter half of the total number of test sessions completed by each participant (Familiarisation 2nd Half).

The mean RT and standard error of the mean (SEM) was 425 (24) msec and 373 (20) msec for the Familiarisation 1st and 2nd half respectively (Table 2-1).

Test Condition	Mean RT (SEM)	Accuracy (SEM)
Familiarisation 1st Half	425 (24) msec	82.2 (4.1)%
Familiarisation 2nd Half	373 (20) msec	81.4 (3.3)%
Familiarisation all data	397 (19) msec	82.1 (2.5)%
Baseline	359 (18) msec	78.4 (3.7)%

RT= Reaction Time, SEM= Standard Error of the Mean

Table 6-1. Mean reaction and accuracy; Familiarisation & Baseline.
Descriptive statistics of the group's mean reaction time and accuracy at Familiarisation and Baseline. Note that the Familiarisation data were split into first half and the second half.

The $BF_{H1/H0}$ result (Table 6-2) provides strong evidence that the alternative hypothesis ($\mu_{diff} \neq 0$) was almost 34 times more likely than the null hypothesis ($\mu_{diff} = 0$). The 95% Credible Interval (CI) suggests that true mean difference in RT between the first half and the second half of the Familiarisation data was between 22-73 msec, which supports a belief that the mean RT in the second half of the Familiarisation period was shorter than the mean RT in the first half (Figure 6-2). The effect size (d) was 0.64, which suggests a medium effect of time (learning effect).

Hypothesis (H)	Prior (H)	Posterior Probability (H|data)	$BF_{H1/H0}$	95% Credible Interval on μ_{diff}
$\mu_{diff} = 0$ (H0)	0.5	0.03	33.62	21.7 – 73.1
$\mu_{diff} \neq 0$ (H1)	0.5	0.97		

Table 6-2. BF analysis of RT; 1st Vs 2nd half of Familiarisation.

Bayes factor analysis for the hypothesis that the mean reaction time over the first versus the second half Familiarisation is different from zero.

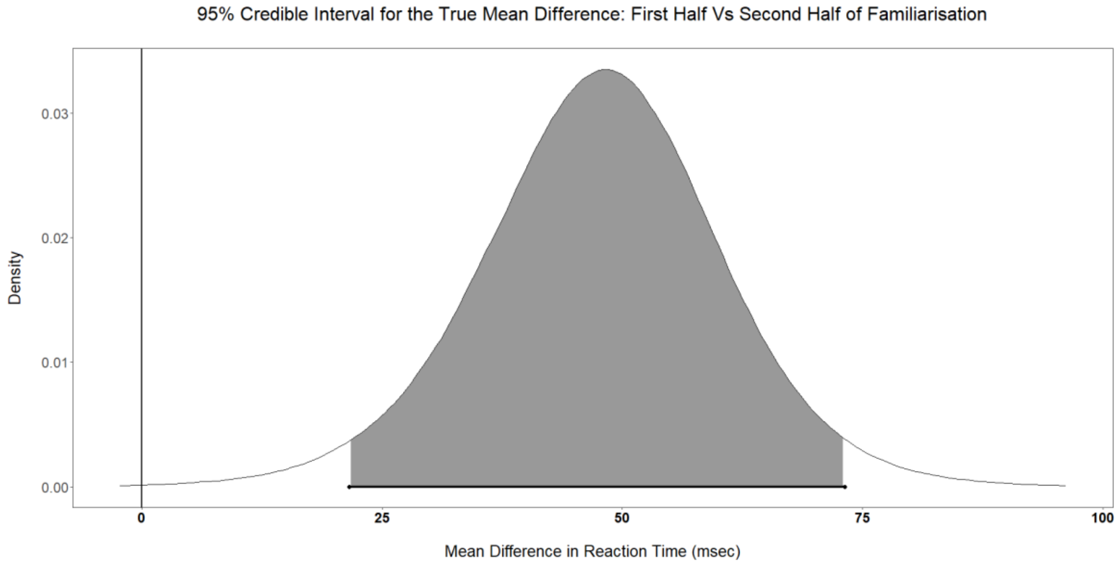

Figure 6-2. Mean RT difference 95% CI; 1st Vs 2nd half of Familiarisation.

The 95% Credible Interval for the mean reaction time difference between the first half and the second half of the Familiarisation data.

After the initial analysis of the RTs, we then turned our attention to the accuracy rates between the two same split conditions of Familiarisation. Accuracy values were calculated as the number of correct responses over the total number of responses for each individual. For the first half and the second half of the Familiarisation condition we found that the mean accuracy (SEM) was 82.2 (4.1) % and 81.4 (3.3) % respectively.

Hypothesis (H)	**Prior (H)**	**Posterior Probability (H|data)**	**BF$_{H0/H1}$**	**95% Credible Interval on μ$_{diff}$**
$\mu_{diff} = 0$ (H0)	0.5	0.80	3.90	-13.01 – 8.68
$\mu_{diff} \neq 0$ (H1)	0.5	0.20		

Table 6-3. BF analysis of accuracy; 1st Vs 2nd half of Familiarisation.

Bayes factor analysis for the hypothesis that the mean accuracy rate over the first versus the second half Familiarisation is different from zero.

The BF$_{H0/H1}$ was 3.9 (Table 6-3) providing support for the hypothesis of no difference in mean accuracy rate between the first half and the second half of the Familiarisation period. There was 95% probability that the true mean difference in accuracy between the first half and the second half of the Familiarisation data was within -13% and 9%, supporting a belief that the mean difference is not different from zero (Figure 6-3). The 95% CI was nearly balanced around 0 and it suggests the lack of bias in the result. Further confirmation comes from the effect size (d) result that was calculated to be -0.06 indicating a trivial effect of time on accuracy.

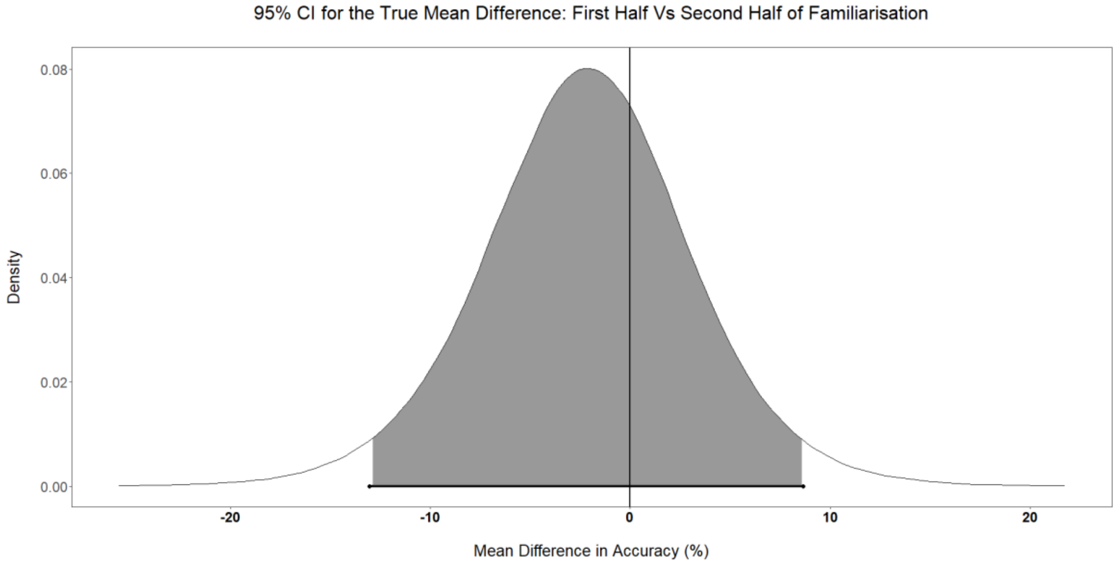

Figure 6-3. Mean accuracy difference 95% CI; 1st Vs 2nd half of Familiarisation.

The 95% Credible Interval for the mean accuracy difference between the first half and the second half of the Familiarisation data.

6.9.2 Familiarisation Vs Baseline

We continued with the same Bayesian model to examine the effect on correct responses of Familiarisation versus Baseline conditions. In this context Baseline indicates the introduction of a competitive element to the RT testing (see section 6.6). The mean RT (SEM) for the Familiarisation and Baseline conditions were 397 (19) msec and 359 (18) msec respectively.

Hypothesis (H)	**Prior (H)**	**Posterior Probability (H|data)**	**BF$_{H1/H0}$**	**95% Credible Interval on μ$_{diff}$**
$\mu_{diff} = 0$ (H0)	0.5	0.04	20.09	14.10 – 55.15
$\mu_{diff} \neq 0$ (H1)	0.5	0.96		

Table 6-4. BF analysis of RT; Familiarisation Vs Baseline.

Bayes factor analysis for the hypothesis that the mean reaction time over Familiarisation versus Baseline is different from zero.

The $BF_{H1/H0}$ result (Table 6-4) provides strong evidence to support the alternative hypothesis ($\mu_{diff} \neq 0$), which is 20 times more likely than the null hypothesis ($\mu_{diff} = 0$). The 95% CI for the true mean difference in RT between the Familiarisation and Baseline data was within 14-55 msec, supporting a belief that the mean difference was not zero. In particular, the evidence suggests that the Baseline mean RT was shorter than the Familiarisation mean RT (Figure 6-4). The effect size (d) was 0.52, suggesting a moderate effect of competition leading to an improvement in mean RT.

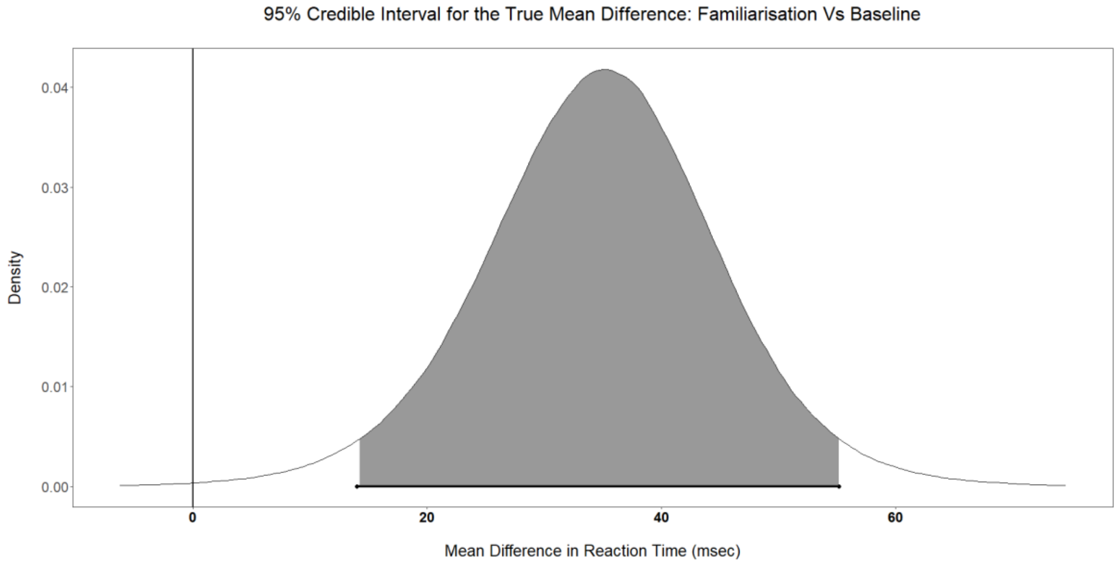

Figure 6-4. Mean RT difference 95% CI; Familiarisation Vs Baseline.

The 95% Credible Interval for the mean reaction time difference between the Familiarisation and Baseline conditions.

The mean accuracy rate (SEM) in the Familiarisation and Baseline conditions was 82.1 (2.5%) and 78.4% (3.7%) respectively.

Hypothesis (H)	**Prior (H)**	**Posterior Probability (H|data)**	**$BF_{H0/H1}$**	**95% Credible Interval on μ_{diff}**
$\mu_{diff} = 0$ (H0)	0.5	0.75	3.02	-5.19 – 11.85
$\mu_{diff} \neq 0$ (H1)	0.5	0.25		

Table 6-5. BF analysis of accuracy; Familiarisation Vs Baseline.

Bayes factor analysis for the hypothesis that the mean accuracy rate over Familiarisation versus Baseline is different from zero.

The $BF_{H0/H1}$ was 3.02 (Table 6-5), supporting the hypothesis of no difference in mean accuracy rate between Familiarisation and Baseline. The 95% CI for a true mean difference in accuracy between Familiarisation and Baseline was within -5% and 12%, which supports the belief that the mean difference was not different from zero (Figure 6-5). The effect size (d) was calculated at approximately 0.31, suggesting a weak effect of competition on accuracy.

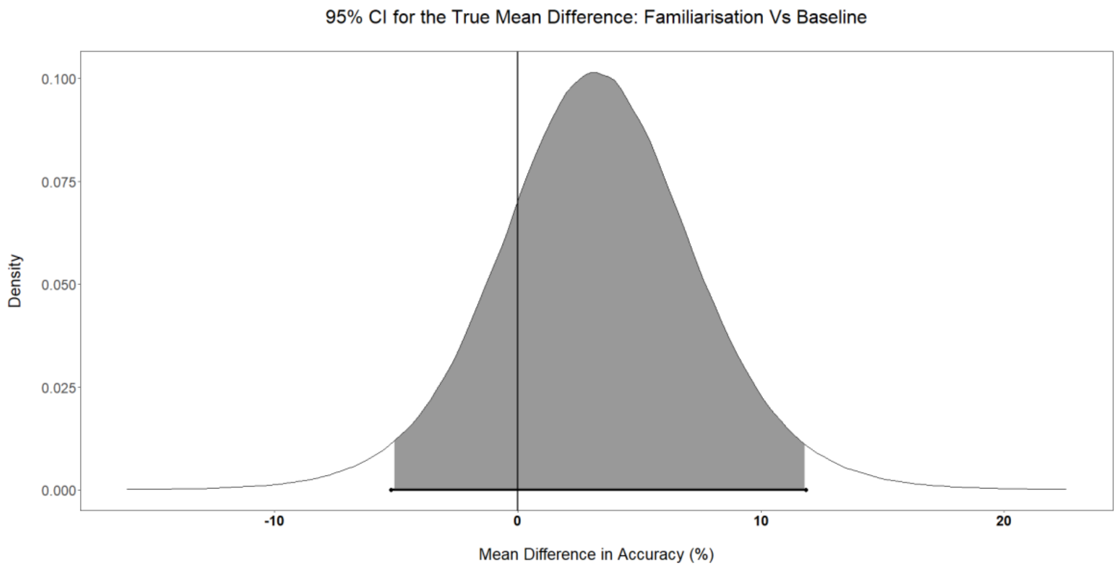

Figure 6-5. Mean accuracy difference 95% CI; Familiarisation Vs Baseline.

The 95% Credible Interval for the mean accuracy difference between Familiarisation and Baseline.

6.9.3 Familiarisation (second half data set) Vs Baseline

We were interested in the effect of competition on the haptic choice RT parameters but the comparison of Baseline against the full Familiarisation data set reported earlier is unfair because, as reported in section 6.9.1, the Familiarisation data set contains significant changes in RT secondary to a learning effect. We have removed the first half of the Familiarisation data, where most of the learning effect was seen, to make the comparison between Familiarisation and Baseline fairer.

Hypothesis (H)	**Prior (H)**	**Posterior Probability (H|data)**	**$BF_{H0/H1}$**	**95% Credible Interval on μ_{diff}**
$\mu_{diff} = 0$ (H0)	0.5	0.71	2.45	-12.6 – 37.4
$\mu_{diff} \neq 0$ (H1)	0.5	0.29		

Table 6-6. BF analysis of RT; Familiarisation 2nd half Vs Baseline.

Bayes factor analysis for the hypothesis that the mean reaction time over the latter half Familiarisation versus Baseline is different from zero.

The $BF_{H0/H1}$ was 2.4 (Table 6-6) giving weak support for no difference between Familiarisation and Baseline mean RT once we exclude data from the early half of Familiarisation. The 95% CI was between -13 to 37 msec (Figure 6-6). This 95% CI suggests a small but not significant bias in favour of a lower mean RT Baseline (competition) conditions. The effect size d was calculated at approximately 0.34 and is consistent with the evidence showing a weak effect of competition on RT once we account for a learning effect in the Familiarisation data.

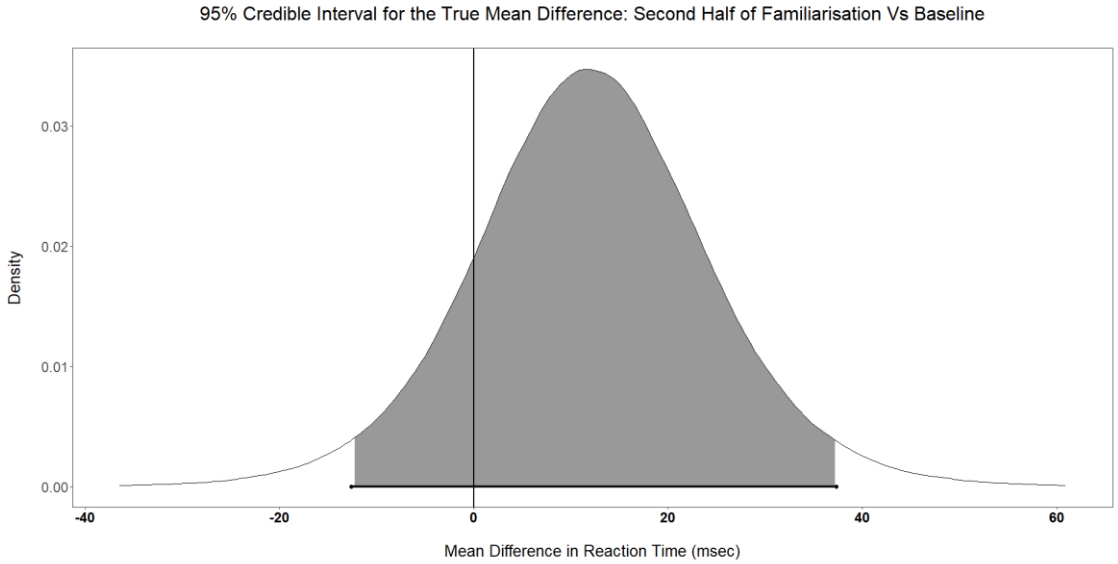

Figure 6-6. Mean RT difference 95% CI; Familiarisation 2nd half Vs Baseline.

The 95% Credible Interval for the mean reaction time difference between the latter half of Familiarisation and Baseline.

Hypothesis (H)	**Prior (H)**	**Posterior Probability (H|data)**	**BF$_{H0/H1}$**	**95% Credible Interval on μ_{diff}**
$\mu_{diff} = 0$ (H0)	0.5	0.73	2.68	-4.99 – 13.26
$\mu_{diff} \neq 0$ (H1)	0.5	0.27		

Table 6-7. BF analysis of accuracy; Familiarisation 2nd half Vs Baseline.

Bayes factor analysis for the hypothesis that the mean accuracy rate over the latter half Familiarisation versus Baseline is different from zero.

The BF$_{H0/H1}$ was 2.7 (Table 6-7) giving weak support for the null hypothesis of no difference between Familiarisation and Baseline mean accuracy once we exclude data from the early half of Familiarisation. The 95% CI of -5% to 13% (Figure 6-7) suggests a small but not significant bias in favour of a drop in mean accuracy rate under competition conditions. The effect size of 0.36 is consistent with a weak effect of competition on accuracy rate.

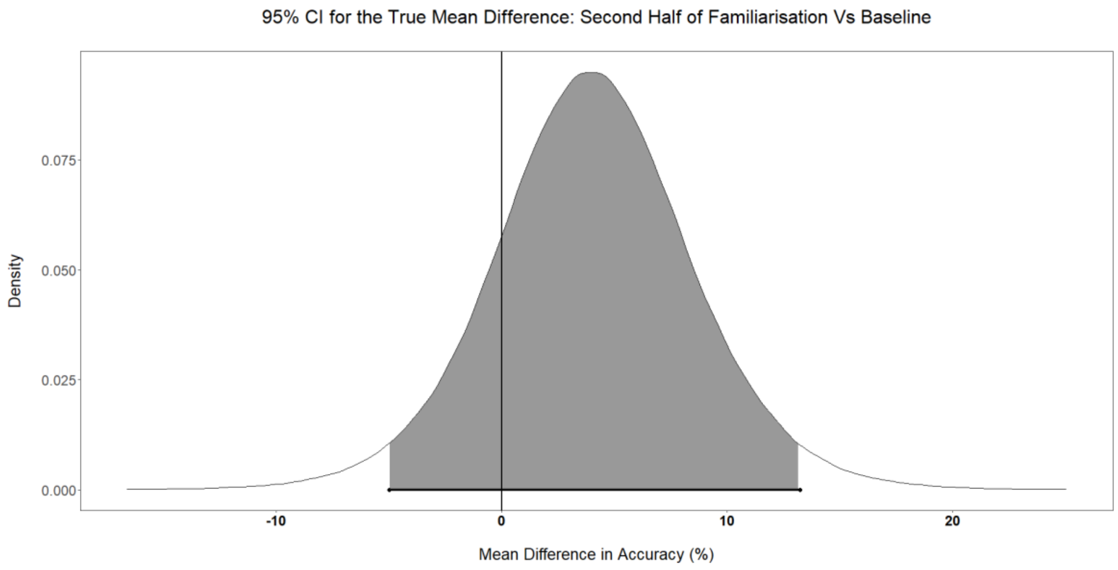

Figure 6-7. Mean accuracy difference 95% CI; Familiarisation 2nd half Vs Baseline.

The 95% Credible Interval for the mean accuracy difference between the latter half of Familiarisation and Baseline.

In summary, the results presented here suggest that there is a learning effect in the Familiarisation data for mean RT but not for accuracy. A moderate effect of competition, with an improvement in mean RT, was noted between Familiarisation and Baseline but not for accuracy. The effect of competition on RT became weaker once we accounted for a learning effect in the Familiarisation data with no significant difference in accuracy.

6.9.4 Individual differences

We examined how individual judoka's mean RT and accuracy changed from Familiarisation to Baseline (Figure 6-8). A closer inspection of the data in each condition revealed that one of the individuals appeared to have become slower and less accurate when the haptic reaction tests were performed under the competitive conditions at Baseline (dotted line in Figure 6-8, both panels; RT increases, accuracy drops steeply). In contrast, we also identified an individual who improved their RT despite already being faster than anyone else in the group (long dashed line Figure 6-8, left panel). However, this improvement came at the cost of a drastic drop in accuracy: from around 80% to just over 60% (long dashed line Figure 6-8, right panel). All of the remaining eight judoka managed to improve their RT with half of them improving their accuracy too and the other half showing lower accuracy.

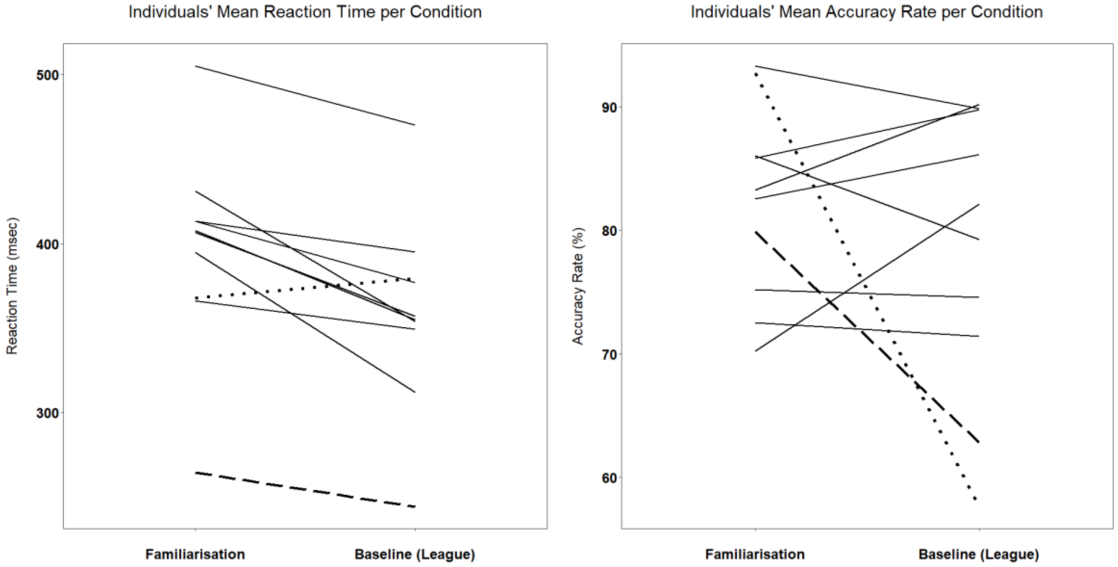

Figure 6-8. Individual changes in RT and accuracy.

Changes in reaction time (left panel) and accuracy (right panel) between Familiarisation and Baseline conditions. Individual differences in mean RT are represented by the black lines. The dotted line highlights the person who was slower in the post Familiarisation test. The long dashed line represents the person who registered the shortest reaction times.

6.10 Discussion

We used our novel haptic choice reaction test device to collect RT data from a group of elite judoka under real life training conditions. To enhance the engagement from each judoka in the testing procedures we introduced a competition amongst the participants on the haptic reaction task. We believe that by introducing a competition element to the tests we have been able to: 1) motivate the judoka's to perform well during the choice reaction tests, and 2) add to the ecological validity of the haptic task by providing a source of stress during the test that may be a closer match to real life Judo competition conditions (*e.g.* competition pressure).

It is typical during task acquisition to observe a remarkable improvement in the early stages of learning a task followed by a decline to that rate of learning, to the point where no further improvement is made (Raglin, 1992). We compared the mean RT and accuracy between the first half and second half of the Familiarisation period and found a learning effect in the Familiarisation data for mean RT but not for accuracy. We expected to observe similar evidence for a difference between the full set of Familiarisation and Baseline. Indeed, we found 96% probability that the mean RT values were different between the two conditions (Table 6-4). But most of the difference in the means was mostly due to the early tests in the first half of the Familiarisation sessions. This conclusion was reached by examining the difference of the means in RT between the second half of the Familiarisation sessions and Baseline where we found nearly 30% probability that the mean difference was not zero (Table 6-6). Although we did not find a substantive difference in the latter comparison, we did note a marginal drop in mean RT and a small effect of competition on RT as suggested by the effect size d (0.34). Hence, we can be more confident in the baseline values we have gathered and use them as a yardstick against which we can examine deviations in our cohort's performance under other conditions of interest (*e.g.* mean RT and accuracy after moderate intensity exercise and after severe intensity exercise).

One interesting observation regarding the competitiveness element in the RT tests is that not all participants appeared to have responded positively to the challenge of carrying out the reaction task under competitive conditions. Anxiety is not an uncommon psychological response to competition in competitive judoka (Ziv & Lidor, 2013) and it is accepted that high levels of anxiety can lead to a dramatic drop in performance (Hardy, 1996), although not all athletes perceive competition anxiety as detrimental to their performance (Raglin, 1992). Perceived stress however can potentially degrade judgment and decision making skills (Staal, 2004) [see Staal (2004) for an in-depth review on stress, cognition, and human performance].

In Figure 6-8 there is evidence of only one judoka (dotted line) whose performance in the RT test showed a deterioration both in RT and accuracy from Familiarisation to Baseline. This person’s accuracy dropped from second best at Familiarisation to second worst at Baseline. The testing conditions between Familiarisation and Baseline were practically identical with the only difference being that the results in the latter condition counted for a place in the weekly league table. It is reasonable then to conclude that this judoka was overwhelmed by the pressure of competition. Further investigation revealed a history of performance-sapping competition anxiety for this individual that has led to underperformance at important tournaments. We believe that this set of results is further evidence for the ecological validity of our reaction test.

There was another interesting case from a judoka (long dashed line, Figure 6-8) whose mean RT at Familiarisation was a lot lower than anyone else’s whilst the mean accuracy was very close to the overall group average. However, under the competitiveness conditions of Baseline a small improvement in mean RT appears to have been coupled with a remarkable loss in accuracy. This finding suggests that perhaps this judoka was overzealous in maintaining low RTs even at the expense of accuracy. Further investigation revealed that this judoka was error prone at important tournaments and especially in ‘sudden death’ rounds. Judo is a sport where being able to react faster than the opponent can only be an advantage if the correct decision is made. An erroneous rapid response in competitive Judo will at best lead to a missed scoring opportunity and at worst to defeat or injury.

We have highlighted and discussed two cases of judoka whose RT data showed a very different pattern to the rest of the group. These were also two cases whose results were consistent with real life performance issues they were experiencing. However, we have not removed their data from the statistical analyses as at this stage we are only speculating what might have happened to the two participants. Ultimately, we want to reveal our cohort's true parameters of their baseline mean values in RT and accuracy. Therefore, we have to assume that the above examples of performances in the haptic task are within the variability that investigators may encounter in a typical group of elite judokas.

To the best of our knowledge this study is the first in mental chronometry research were competition between study participants was introduced as a way to sustain attention and enhance the quality of RT data collected. Competition in RT tasks is by no means a new concept. The Competitive Reaction Time Task (CRTT) has been utilised under various versions in Psychology research since the 1960s as a laboratory based tool to measure aggressive behaviours (Elson *et al.*, 2014). In brief, in the original CRTT the participants were told that they would compete against another person in a reaction game. The winner would be able to punish the loser with an electric shock of varying intensities. The researchers would use the intensity level of the shock chosen as the measure for a participant's aggressiveness. In reality though, there was never an actual opponent. Of course, in our study the use of electric shocks was not an option we would ever consider – instead, participants were competing purely for 'bragging rights'.

A crucial factor to sustaining attention on a task is motivation. Different people can be motivated by different reasons to carry out a task (Vansteenkiste *et al.* 2009). There may be intrinsic factors that drive motivation *e.g.* a genuine interest to learn about something or taking pride in the knowledge of having accomplished something worthwhile. But there may also be extrinsic factors that can push motivation *e.g.* prizes or praise from peers. Since our cohort of elite judoka was made up of people who were devoted to near daily Judo practice over a period of more than 10 years, it is reasonable to assume that these people are already well self-motivated individuals with a strong drive to achieve success in their sporting careers. It is possible that in an Olympic sport like Judo, where high monetary rewards are rare, the main factor that fuels their impetus to be successful is enjoyment of Judo competition. Indeed, enjoyment of the sport has been shown to have the strongest effect amongst junior tennis players' commitment to their training practice and competition (Weiss *et al.*, 2001). Fun is a motivating force, and one that was realistic for us to utilise to motivate our cohort to sustain their concentration. Our haptic reaction test, although interesting (novelty factor) and not monotonous (inherent variability of choice reactions and short timescale) is unlikely to be perceived as a fun task in itself. In an attempt to improve motivation we therefore added a competitive element to the testing process.

Sustaining attention during a cognitive task can be mentally strenuous and stressful (Warm *et al.*, 2008). Without the required focus on the task the mind can drift off during a test either due to boredom or fatigue. Studies in human RTs have shown repeatedly that the coefficient of variation of response times increases secondary to mind wandering (Hawkins *et al.*, 2019). We have used competitiveness as a way to limit mind wandering during the haptic reaction task in hope to reduce the extent of variability in the results.

Using a league table to maintain motivation in a long series of reaction tests is a rather unusual approach in mental chronometry research. Nonetheless, it was evident to those present during the sessions that all but one of the judoka who took part enjoyed competing against their peers and they were genuinely trying to outperform them every time. We do not believe that such level of engagement in all the tests performed could have been possible without having turned the data collection into an enjoyable experience with a fun competition. In a future study it would be interesting to investigate to what extent competition among participants can reduce variability in a reaction task over repeated tests.

One potential criticism of our method is that we carried out all the tests at the Judo performance centre during and around real training sessions where each judoka was subjected to many potential distractions. We could have performed all of the reaction tests in a laboratory and away from distractions. This approach may have resulted in less variability in the data. However, real life Judo is performed in an environment with many potential distractions. Typically, during a bout, a judoka must filter or prioritise informational cues that may come from many diverse sources: the opponent makes a move, the referee intervenes, the coach shouts instructions, the crowd cheers, the stadium speakers play loud announcements or music. We therefore believe that our data collection during practice sessions had greater ecological validity for judoka than a similar test carried out in a quiet room.

6.11 Conclusion

Data collected from reaction tests can include values that are likely influenced by factors not related to the testing itself *i.e.* distraction. We set out to explore the typical mean RT and accuracy of elite judoka in a haptic choice reaction test facing the challenge of securing results that represented an accurate picture of what these judoka were capable of.

In our method we have used competition during a haptic reaction task to motivate judoka to limit mind wandering and stay focused during each reaction test. We opted for a test with the appropriate sensory modality, and we collected reaction data in the judoka’s training environment where many real life sources of distraction exist. Having added a competition during these tests we have likely added to the ecological validity of our method. As a result, we can be more confident that the range of mean RT and accuracy we have reported here from a cohort of elite judoka is closer to the true parameter values.

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Chapter 7: Effect of Exercise on Haptic Choice Reaction Time in Elite Judoka

7.1 Introduction

In Chapter 6 we showed how competitiveness was used to enhance the quality of the data gathered but also how it contributed to the ecological validity of our test method. In this chapter we demonstrate the impact different levels of exercise intensity had on our cohort’s performance in the haptic reaction test.

Technically a Judo bout is four minutes long, but it can be a lot shorter as an ippon (Judo’s equivalent to a knock out) can be scored at any point before the end of the allotted time. On the other hand, a bout can last longer if the two opponents’ score is tied by the end of the four minutes. In the latter case the fight goes immediately to extra time (there is no break between the rounds) and the first judoka who gets any score wins, hence the extra time is also known as ‘sudden death’ round. Crucially, there is no time limit to how long the decisive round can keep going on. Only a minority of Judo matches at any major tournament go on to be decided on the ‘sudden death’ round, but these bouts can be prolonged by several seconds or many more minutes. The practical significance of the potentially wide variability in match duration is that an elite judoka with superior tactical and technical skills may go through fights in a tournament without having needed to overly exert themselves – but equally, they need to be prepared to cope with the physical and mental demands of an extended high intensity fight. In either case the ability to make fast and correct decisions under any degree of physical stress and emotional pressure remains essential in competitive Judo.

It has been shown that moderate intensity aerobic exercise improves cognitive function (Rattray & Smee, 2013) whilst hard intensity exercise decreases cognitive performance (Draper *et al.*, 2010). It can be argued that elite judoka have years of training experience and are accustomed to physically demanding conditions where intense physical exertion is coupled with the requirement to make tactical choices and execute highly technical skills. It is reasonable to wonder whether elite judoka’s cognitive performance may deteriorate under conditions of highly intense physical exertion. It is prudent then to investigate the effect of extreme physiological arousal, as typically experienced by elite level Judokas, on cognitive performance.

Judo is mostly a kinaesthetic sport therefore we have developed a haptic choice reaction test using a purpose built device (for details see Chapter 3) that can provide information on judoka’s reaction time (RT) and accuracy under different exercise intensity conditions.

7.2 Arousal Model

It has been argued that a sub-maximal level of physical exertion can enhance cognitive performance but as the exercise intensity increases over time then the beneficial effect of exercise on cognitive performance is lost. Thus, an inverted 'U' relationship exists between cognitive performance and physical exertion (Davey, 1973). The implicit assumption from the previous point is that physiological responses from exercise correspond to certain states of arousal.

The inverted-U hypothesis was first put forward in 1908 by Yerkes & Dodson following experiments where they used mild electric shocks on mice and found that the mice could learn a discrimination task faster. In contrast, when the electric shocks got stronger the mice performance on the same task worsened. The 'Yerkes-Dodson law' was once the leading paradigm of the arousal-performance relationship in Psychology. However, these experiments on mice examined the relationship between task acquisition and stimulus intensity rather than arousal (Raglin, 1992). Beyond Yerkes & Dodson's theory, later researchers found that when physical arousal increases cognitive performance can improve up to a point beyond which it starts to decline as physical arousal continues to increase (Tomporowski & Ellis, 1986). In essence, there is an inverted-U hypothesis to support the idea that cognitive performance is optimal with moderate intensity exercise, and sub optimal with exercise of low or high intensities.

Optimal physiological arousal is critical for attention and it has been suggested that in the central nervous system a major contributor to arousal is the locus coeruleus (LC) noradrenergic system (Aston-Jones & Cohen, 2005). The LC is located in the pons of the brainstem and it is where most of the brain synthesis of noradrenaline takes place, hence the LC plays a role in the stress response. Together, the LC and the areas of the body that receive and respond to the noradrenaline produced are known as the LC noradrenergic system. Brain studies in primates by Aston-Jones & Cohen (2005) revealed performance patterns consistent with an inverted-U relationship between arousal and performance. Aston-Jones & Cohen created a visual cue task for a group of monkeys that were required to release a lever only when a specific cue was presented to them and to ignore any alternative visual cues displayed. When the monkeys responded correctly, they were rewarded with a small quantity of fruit juice but were penalised with a brief time out when they made a mistake. The accuracy with which the monkeys performed this task was over 90% and the researchers showed that the monkeys' performance parameters were poor when the LC tonic discharge (LC baseline activity) was low *i.e.* drowsy and non-alert monkeys, whilst their performance was best during moderate LC tonic activity following goal-relevant stimuli, and finally, the monkeys' performance variables were poor again at elevated levels of tonic LC activity.

Despite specific mechanisms that potentially influence the quality of performance in cognitive tasks it is noteworthy that, across studies carried out since the early 20th century, researchers have found exercise to be either beneficial or detrimental to cognitive performance (Wohlwend *et al.*, 2017) and this contradiction is likely due to the inconsistency in the testing methods used, the conditions during tests, the fitness levels of the cohorts studied, the exercise mode, the exercise intensity levels chosen, and the duration of exercise (Brisswalter *et al.*, 2002). However, some clarity from the studies published in recent decades was achieved through a meta-analysis (Lambourne & Tomporowski, 2010) where it was shown that the effect size of exercise on cognitive performance was influenced by the duration, mode, and type of exercise. More specifically:

- Effect size was dependent on the duration of the continuous exercise carried out prior to when the cognitive tasks were performed, with negative effect sizes in the first 20 minutes and positive effects after the first 20 minutes of exercise.
- Effect size was larger and negative in testing protocols that used running compared to studies that used cycling where the effect size was smaller and positive.
- Effect size was positive during steady-state exercise but negative in studies where the exercise protocol was designed to evaluate the effects of the inverted-U hypothesis.

As highlighted earlier, Judo bouts can be highly challenging both in terms of physical and cognitive demands. Crucially, the intensity and duration of a single bout experienced by a competitive judoka at any tournament can vary considerably. Collectively, the above information confirms the need to investigate the impact of different exercise intensities on elite judoka’s cognitive performance.

7.3 Methods

Judokas must make consistently quick and correct choices during randori (Judo sparring) so it seems proper that we investigate the change in the mean RT, accuracy, and their consistency in a haptic reaction task at various levels of exercise intensity. But in this comparison, we are not simply interested in knowing whether a difference exists in the mean parameter values between Baseline and either of the two other conditions *i.e.* ‘Moderate Intensity’ and ‘Severe Intensity’. We also want to know the magnitude of the difference and our uncertainty about this magnitude estimate. This approach can allow us to determine how much the distinct levels of exercise intensity affect the cognitive performance parameters we have tested with our reaction device and how much confidence we should have in our findings.

From the data presented in Chapter 5 we determined the range within which lies the Baseline mean RT and the mean accuracy for the cohort of elite judoka in a haptic reaction task. We now want to use the Baseline parameters as the yardstick against which we can compare the same parameter values under two different conditions: 1) after the end of a generic and judo specific warm up, which we called ‘Moderate Intensity’, and 2) immediately after the completion of an all-out effort in one of the judoka’s routine physiological tests, which we called ‘Severe Intensity’.

7.3.1 Participants

The study was approved by the School of Sports Research Ethics Committee of the University of Stirling. Ten healthy, elite level judoka (Four females aged 21.3 ± 2.2 years; weighing 62.3 ± 8.5 Kg; and six males aged 21.2 ± 1.6 years; weighing 72.2 ± 8.3 Kg) who compete at World ranking tournaments volunteered for this study and gave written consent after the purpose and details of the study were explained to them (for details see Chapter 2). All participants knew that they could withdraw from the study at any point if they wished to do so without having to provide any explanation.

Every participant was given multiple opportunities to familiarise with the haptic reaction device to control for any learning effect. Subsequently, a baseline standard was established for the group haptic choice RT and accuracy (for details see Chapter 6).

7.3.2 Study Design

The data collection to investigate the cognitive performance of elite judoka under different levels of exercise intensity took place over a period close to six months and outside the competition season. Not including major tournaments within the study time period meant that we were able to avoid any impact on cognitive performance from dehydration or other weight management techniques typically used by judoka and other athletes trying to make weight for competition (Artioli *et al.*, 2010). Each test was carried out on repeated occasions during regular training hours at the High Performance centre of Judo Scotland. We selected three distinct conditions for data collection:

- For the ‘Baseline’ measurements the data were collected over a period of about two months and prior to the start of the judoka’s warm up at sessions where they had randori practice.
- For the ‘Moderate Exercise’ measurements the data were collected over a period of just over one month, approximately 40-50 minutes from the start of the judoka’s randori session. During this time period the judoka would complete a general warm up routine followed by some more Judo specific warm up drills that were in turn followed by several short rounds of randori. At the end of the specific warm up the judoka were given 10 minutes to prepare for the main randori practice and during that time the judoka in our cohort would carry out the haptic reaction test. It took under two minutes for a haptic choice reaction test to be completed and because we had four devices available we were able to collect data from all 10 participants within six minutes. We were confident that our data collection process was not perceived as being intrusive or disruptive by either the coaches or any of the judokas, but we were still mindful not to repeat the tests more times than necessary. Even though the structure of each training session and the drills carried out were not prescribed they followed the same overall process and exercises, which made the sessions, and the data collected, comparable to each other.

- For the ‘Severe Intensity’ measurements the data were collected on four dates when the judoka had their fitness tests. There was never any randori practice, or any other type of training on test days as judoka were encouraged to be rested and available for the ‘all out’ efforts expected of them during the fitness tests. The main test was performed on a rowing ergometer where judoka were asked to maintain the highest power output they could manage for a fixed distance of two kilometres. Not too long into the test it was obvious that the judoka were doing their best to maintain their very high power outputs and by the end they were visibly exhausted. Each haptic choice reaction test took place immediately after the completion of their effort on the ergometer. In this ‘Severe Intensity’ condition the sessions followed a very strict and consistent protocol of what was carried out on the rowing ergometer, which gave us confidence that the measurements we collected from all sessions were comparable and from truly ‘all out’ efforts.

The haptic choice reaction test itself involved 20 reaction episodes with the haptic device (for a description of the test see section 5.2.2 in Chapter 5).

7.4 Statistical Analyses

In this chapter we have used Bayesian inference for the statistical analyses. More specifically, we have used Bayesian techniques such as the Highest Density Interval (HDI) and the Region Of Practical Equivalence (ROPE) to compare paired means from a level of exercise intensity (*i.e.* Moderate or Severe) against Baseline values (see section 2.3 in Chapter 2 for the principles and rationale behind Bayesian Statistics and Bayesian analysis tools such as Bayes Factors, HDI + ROPE, Markov Chain Monte Carlo, and Credible Intervals). Cohen's effect size (d) was used with its conventional interpretation (Cohen, 1988):

- Small effect = 0.2
- Medium Effect = 0.5
- Large Effect = 0.8

Data filtering was carried out as described in section 5.2.4. All data processing (data wrangling) was carried out in R, version 3.6.1 (R Core Team, 2019) using the *tidyverse* package, version 1.2.1 (Wickham, 2017). For the statistical analyses we have used the *BayesFactor* package, version 0.9.12-4.2 (Morey & Rouder, 2018) and the *BEST* package, version 0.5.1 (Kruschke & Meredith, 2018) and its *BESTmcmc* function to compare the means of two groups by generating posterior distributions with Markov Chain Monte Carlo (MCMC) sampling from the two groups' RT values (for details see Chapter 7 of Kruschke, 2011). The HDI limits were computed from the MCMC chain using the method explained in section 23.3 of Kruschke (2011) and with an effective sample size that exceeded 10,000; the higher the number the higher the resolution of the posterior distribution (Kruschke, 2013). Plots were generated using the BEST library and the *ggplot2* package, version 3.2.1 (Wickham, 2016).

7.5 Results

The mean RT (SEM) at Baseline, Moderate Intensity, and Severe Intensity conditions were 359 (18) msec, 319 (13) msec, and 357 (10) msec respectively (Table 7-1).

Test Condition	Mean RT (SEM)	Accuracy (SEM)
Baseline	359 (18) msec	78.4 (3.7)%
Moderate Intensity	319 (13) msec	75.5 (4.1)%
Severe Intensity	357 (10) msec	65 (5.4)%

RT= Reaction Time, SEM= Standard Error of the Mean

Table 7-1. Mean RT and accuracy at different intensity levels.
Descriptive statistics of the group's mean reaction time and accuracy rate under Baseline, Moderate Intensity, and Severe Intensity Conditions.

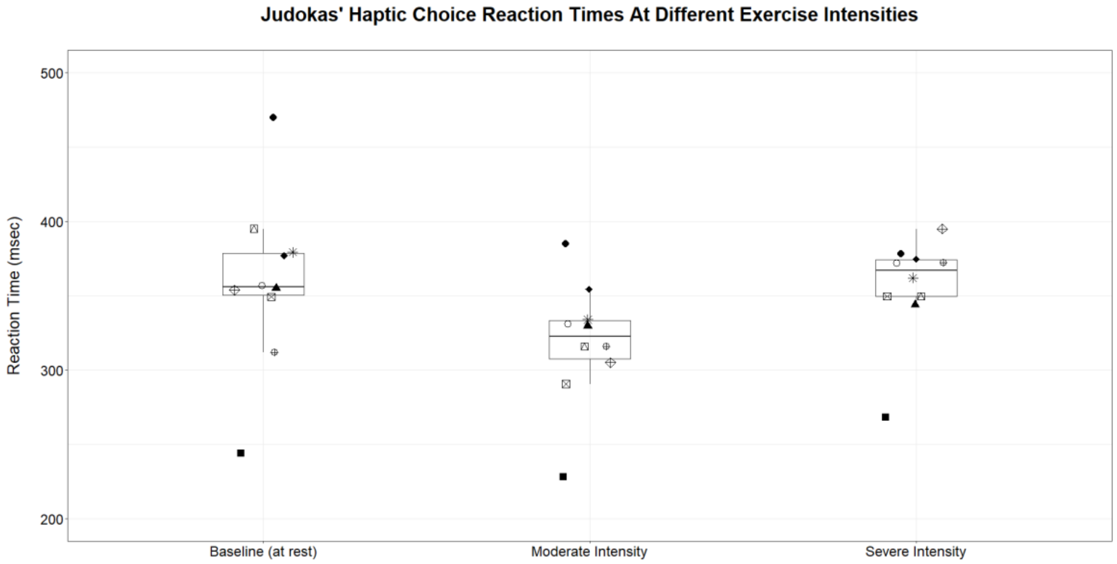

Figure 7-1. Mean RT at different intensity levels.

Individual judoka's mean reaction times (points) and the group's robust descriptive statistics (boxplots) for each of the three exercise intensities: Baseline (at rest), Moderate Intensity, and Severe Intensity.

Figure 7-1 shows each participant's mean RT in the haptic choice reaction test, as well as the group's robust statistics for each of the three exercise intensities: Baseline (tests at rest: before exercise started), Moderate Intensity (tests 40-50 minutes into randori training), and Severe Intensity (tests immediately after 'all out' work). There is a well-defined improvement in the RT mean values from Baseline to Moderate Intensity whereas there does not appear to be as much of a difference in the RT mean values from Baseline to Severe Intensity.

We have also plotted the judoka's RTs against accuracy under each condition in order to display any shifts in accuracy at different exercise intensities (Figure 7-2). We can see three panels in Figure 7-2 with each having the RT on the y axis and accuracy percentage on the x axis: the left panel shows Baseline data, the middle panel shows Moderate Intensity data, and the right panel shows Severe Intensity data. Also, on each panel we have superimposed a red vertical line at a fixed point on the x axis to denote the group's accuracy rate at Baseline and to help us visualise how the heat spots shift in relation to the red line (Baseline accuracy) under each condition.

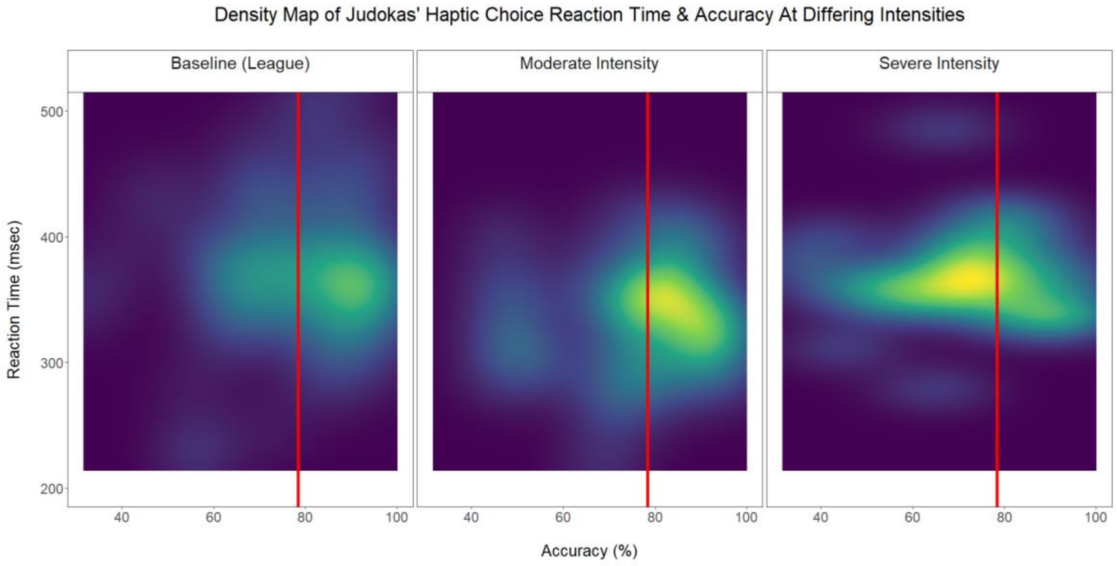

Figure 7-2. Heat map of RT over accuracy at different intensity levels.

A density map with judoka's individual responses that allows us to view the concentration (heat spots) of data. The red vertical line signifies the group's accuracy rate at Baseline. Note the shift of the heat spot in the far right panel, under Severe Intensity, to the left side of the red line, which indicates a remarkable drop in the group's accuracy rate compared to what they were able to achieve at rest.

In the middle panel (Moderate Intensity) of Figure 7-2 the heat spot is lower on the y axis when compared to the first (left) panel, which indicates an improvement in RT from Baseline – and it is consistent with Figure 7-1 where we first showed the improvement in mean RT values from Baseline to Moderate Intensity. But the heat spot on the same panel appears to have stayed at a similar position on the x axis, which indicates that there has been no remarkable difference in the accuracy rate between the two conditions. In the third (right) panel the heat spot does not appear to have shifted on the y axis when compared to the position of the heat spot on the first panel, which indicates no difference in RT between Baseline and Severe Intensity. However, there is a noticeable shift of the heat spot on the x axis to the left side of the red line, which indicates a remarkable drop in the group's accuracy rate at Severe Intensity compared to what they were able to achieve at rest.

We can see that, overall, an improvement in response time was noted in the second condition, when judoka had spent some time exercising but that improvement was diminished at the extreme condition, which also resulted in a remarkable loss of accuracy.

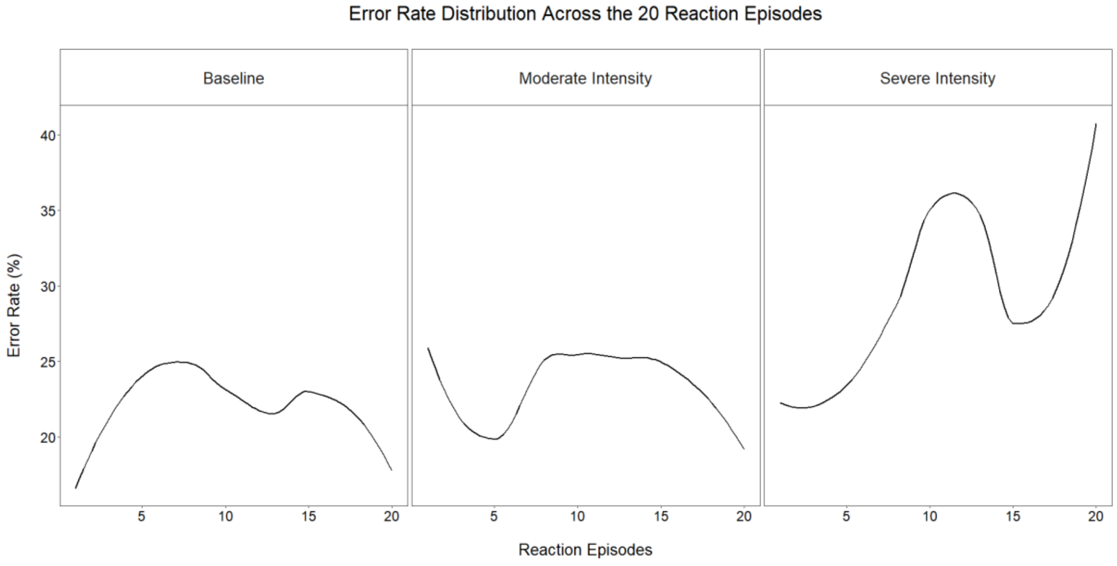

Figure 7-3. Error rate pattern across all 20 episodes per exercise intensity.

A LOESS smooth curve (local polynomial regression) revealed the pattern of mean accuracy across the 20 reaction episodes under each condition. Note the much wider proportion of erroneous responses at Severe Intensity (right panel).

A LOESS curve (see section 5.2.3 in Chapter 5) was used to visualise the distribution of the group's mean error rates at each one of the 20 reaction episodes of the haptic choice responses at every exercise intensity level (Figure 7-3). In both Baseline and Moderate Intensity conditions the mean error rate fluctuated within a similar range. However, in the Severe Intensity condition the mean error rate trajectory fluctuated at much higher values and within a much wider range compared to the other two conditions.

7.5.1 Baseline Vs Moderate Intensity (Reaction Time)

We used the *BEST* package in R to estimate the posterior probability density for the difference of the means. We set the effective sample size at 15000 (to increase the resolution of the posterior probability). With no previous studies to draw knowledge from we used the standard deviation of all raw data at Baseline (101 msec) multiplied by a small effect size d (0.2) to compute the ROPE (for details see section 2.3.5 in Chapter 2). Therefore, ROPE = σ x d = 101 msec x (± 0.2) = ± 20 msec.

The estimation of the difference between the mean RT in Baseline and the mean RT in Moderate intensity shows that 95% of the most credible values (*i.e.* HDI) is between 35 and 46 msec (Figure 7-4). The HDI does not include zero and it also falls completely outside the ROPE. Thus, as per the HDI + ROPE rule we declare that the null value, no difference in the mean values, is rejected for practical purposes. Also, because the mean difference is positive, we can deduce that the Moderate Intensity mean RT is shorter than the Baseline RT.

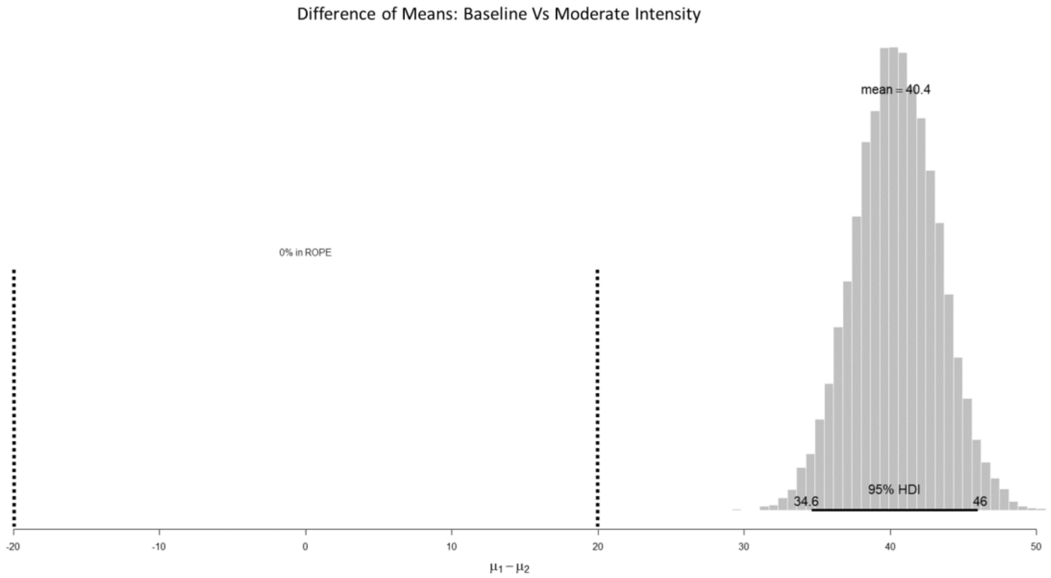

Figure 7-4. HDI of mean RT difference; Baseline Vs Moderate.

The mean reaction time difference between Baseline and Moderate Intensity. The histogram shows the posterior distribution for the mean difference between Baseline and Moderate Intensity conditions. The 95% HDI for the mean difference is represented by the black horizontal line and it is 100% outside the ROPE limits. The ROPE limits of ± 20 msec are denoted by the vertical dotted lines.

The HDI for Cohen’s effect size d on RT from Baseline to Moderate Intensity exercise was entirely outwith the ROPE limits (Figure 7-5). The HDI range of 0.69 to 0.94 indicates a moderate to strong positive effect of Moderate Intensity exercise on RT

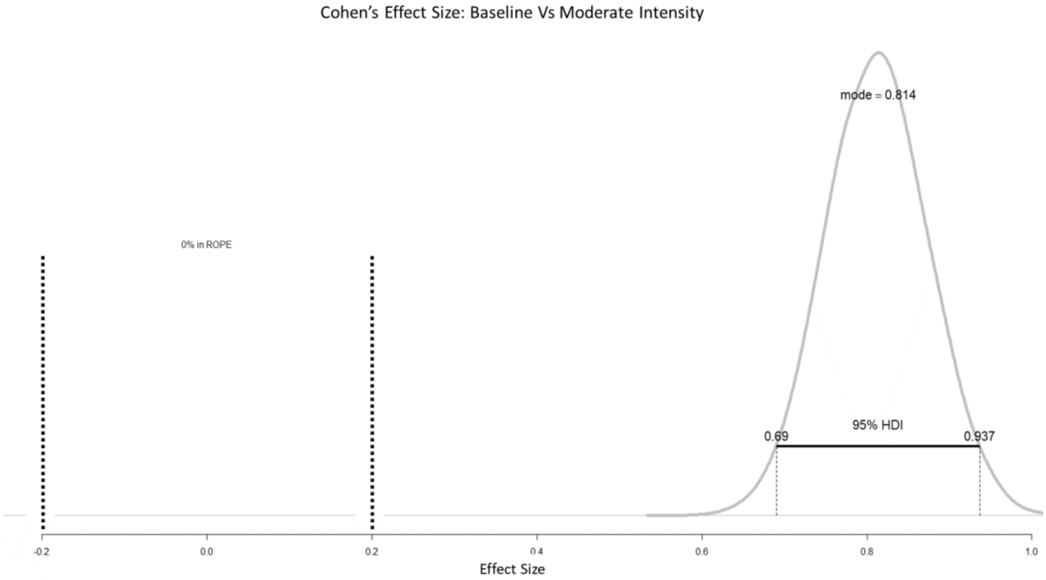

Figure 7-5. HDI of d on mean RT difference; Baseline Vs Moderate.

The Cohen’s effect size (d) on mean difference in reaction time between Baseline and Moderate Intensity conditions. The density curve shows the posterior distribution for the effect size. The 95% HDI for the Cohen’s d is represented by the black horizontal line and it is 100% outside the ROPE limits. The ROPE limits of ± 0.2 are denoted by the black vertical dotted lines.

7.5.2 Baseline Vs Severe Intensity (Reaction Time)

The estimation of the difference between the mean RT at Baseline and the mean RT at Severe Intensity shows that the 95% HDI is between 3 and 16 msec (Figure 7-6). The HDI does not include zero but it falls completely inside the ROPE. Thus, as per the HDI + ROPE rule, we accept that there is no difference in RT between the Baseline and Severe Intensity conditions.

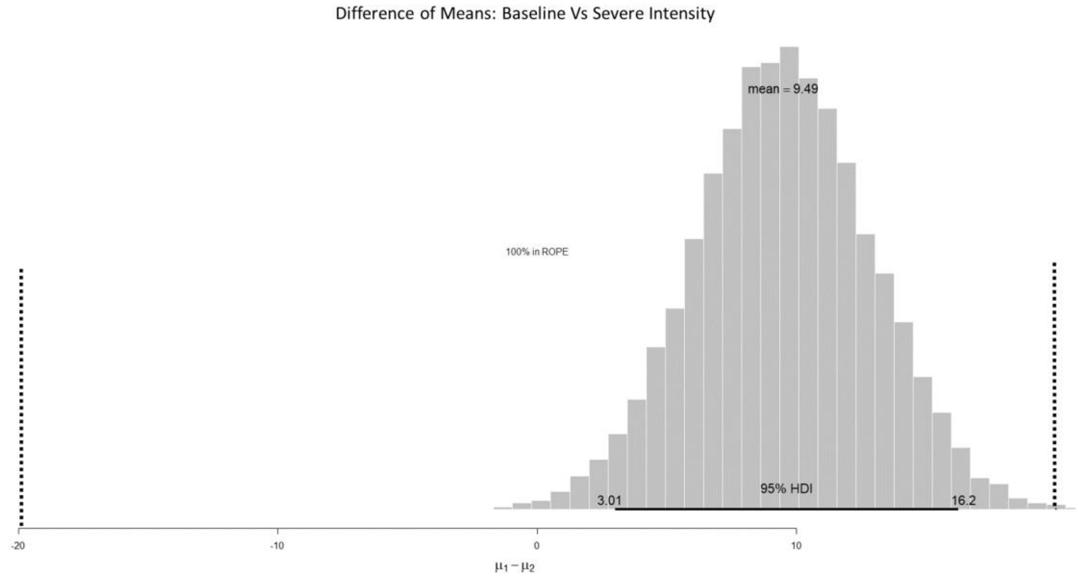

Figure 7-6. HDI of mean RT difference; Baseline Vs Severe.

The mean RT difference between Baseline and Severe Intensity. The histogram shows the posterior distribution for the mean RT difference between Baseline and Severe Intensity conditions. The 95% HDI for the mean difference represented by the black horizontal line and it is 100% inside the ROPE limits. The ROPE limits of ± 20 msec are denoted by the vertical dotted lines.

The 95% HDI for Cohen’s effect size on RT from Baseline to Severe Intensity exercise is between 0.05 and 0.3. With 57% of the HDI inside the ROPE we remain undecided on the magnitude of the effect Severe Intensity exercise has on mean RT (Figure 7-7).

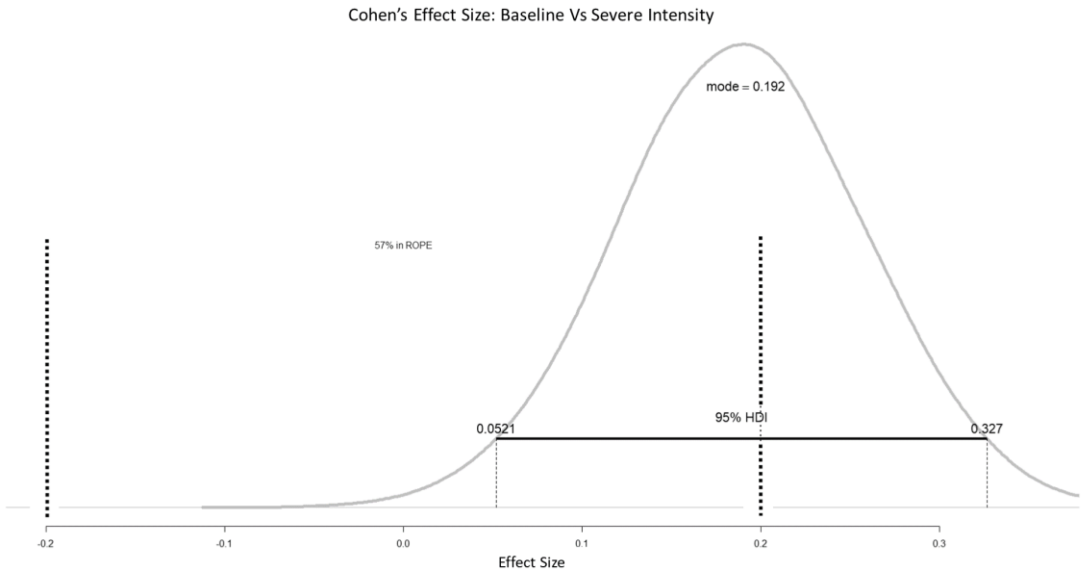

Figure 7-7. HDI of d on mean RT difference; Baseline Vs Severe.

The Cohen’s effect size (d) on mean difference in reaction time between Baseline and Severe Intensity conditions. The density curve shows the posterior distribution for the effect size. The 95% HDI for the Cohen’s d is represented by the black horizontal line. The ROPE limits of ± 0.2 are denoted by the black vertical dotted lines.

7.5.3 Baseline Vs Moderate Intensity (Accuracy Rate)

We have used Bayes Factors (BF) to compare paired means of accuracy rate between Baseline and Moderate Intensity. We have assigned an equal ratio of prior probabilities on the two hypotheses *i.e.* there is a 50% chance that no difference exists between the two conditions and 50% chance that a difference does exist, and the Bayes Factor is the posterior odds.

Hypothesis (H)	**Prior (H)**	**Posterior Probability (H|data)**	**$BF_{H0/H1}$**	**95% Credible Interval on μ_{diff}**
$\mu_{diff} = 0$ (H0)	0.5	0.76	3.15	-4.3 – 9.3
$\mu_{diff} \neq 0$ (H1)	0.5	0.24		

Table 7-2. BF analysis of accuracy; Baseline Vs Moderate.

Bayes factor analysis for the hypothesis that the mean accuracy over Baseline versus Moderate Intensity is different from zero.

The $BF_{H0/H1}$ was 3.15 (Table 7-2) providing support for the hypothesis of no difference in mean accuracy rate between the Baseline mean accuracy and the Moderate Intensity mean accuracy. There is 95% probability that the true mean difference in accuracy between the two conditions is within -4%, 9% and as this includes zero then it is likely that the mean difference is not different from zero (Figure 7-8). The 95% CI suggests a small bias in favour of a higher mean accuracy rate at Baseline. The effect size d was calculated to be 0.20 and is consistent with the evidence so far that shows a weak effect of Moderate Intensity on mean accuracy.

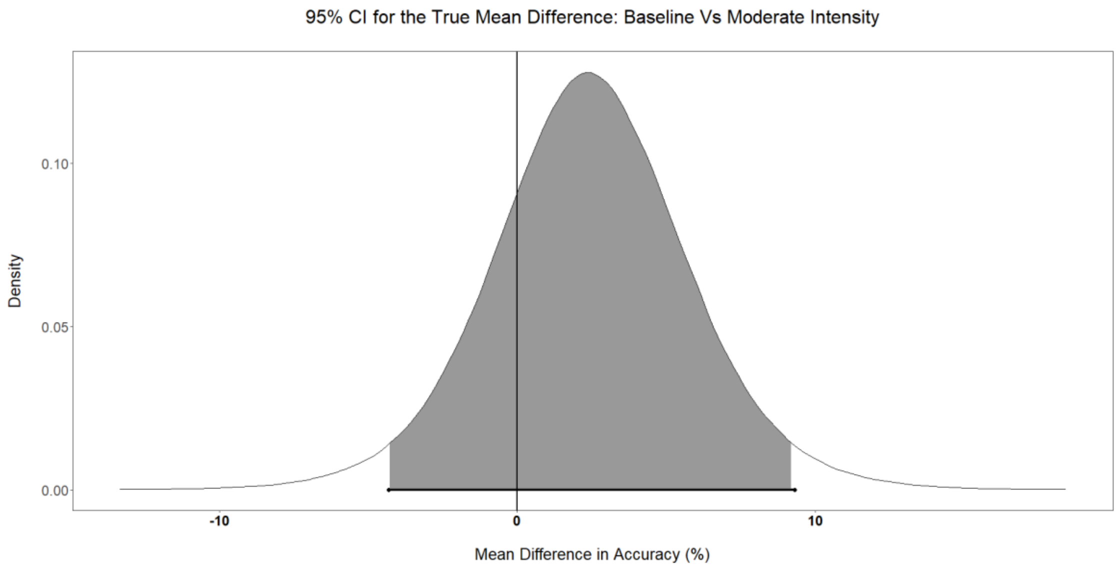

Figure 7-8. Mean accuracy difference 95% CI; Baseline Vs Moderate.

The 95% Credible Interval (CI) for the mean difference in accuracy between Baseline and Moderate Intensity conditions. The 95% CI is indicated by the shaded region.

7.5.4 Baseline Vs Severe Intensity (Accuracy Rate)

Hypothesis (H)	Prior (H)	Posterior Probability (H|data)	$BF_{H1/H0}$	95% Credible Interval on μ_{diff}
$\mu_{diff} = 0$ (H0)	0.5	0.13	6.94	3.36 – 20.87
$\mu_{diff} \neq 0$ (H1)	0.5	0.87		

Table 7-3. BF analysis of accuracy; Baseline Vs Severe.

Bayes factor analysis for the hypothesis that the mean accuracy over Baseline versus Severe Intensity is different from zero.

From the BF analysis in Table 7-3 we can see that the $BF_{H1/H0}$ result indicates that the alternative hypothesis ($\mu_{diff} \neq 0$) is almost 7 times more likely than the null hypothesis ($\mu_{diff} = 0$) for the difference between the Baseline mean accuracy and the Severe Intensity mean accuracy. There is 95% probability that the true mean difference in accuracy between the two conditions lies within 3% and 21%, which supports a higher mean accuracy at Baseline than at Severe Intensity (Figure 7-9). The effect size d was calculated to be 0.83, which suggests a strong effect of Severe Intensity exercise on mean accuracy.

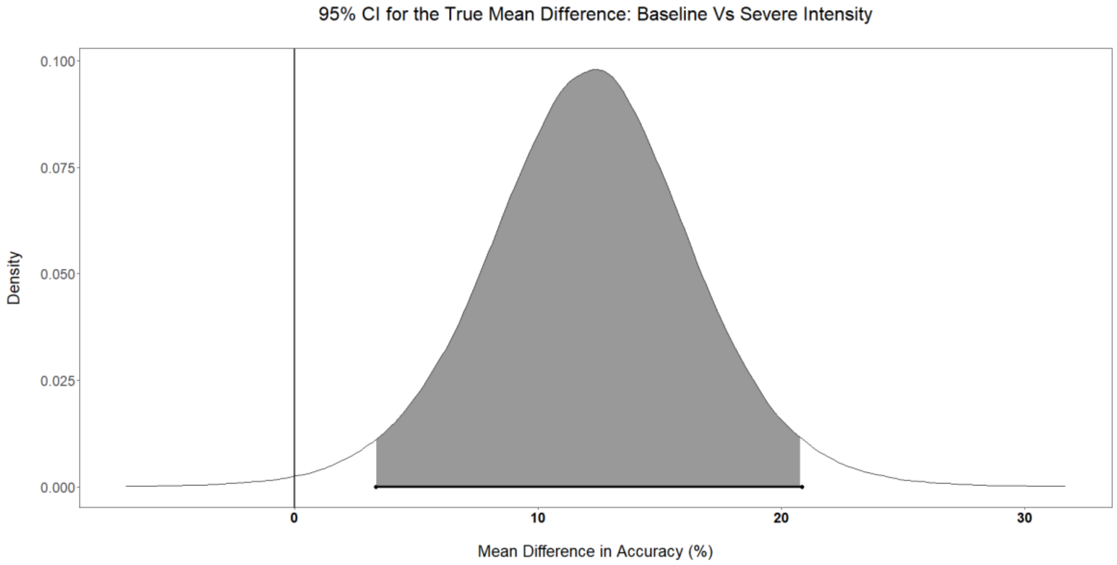

Figure 7-9. Mean accuracy difference 95% CI; Baseline Vs Severe.

The 95% Credible Interval (CI) for the mean difference in accuracy between Baseline and Severe Intensity conditions. The 95% CI is indicated by the shaded region.

7.6 Discussion

We have estimated the mean RT and mean accuracy in a haptic choice reaction test in a group of elite judoka under different exercise intensities. To the best of our knowledge this study is the first to show how haptic choice RT and accuracy can vary in a group of elite judoka's under various levels of physical exertion *i.e.* rest vs post warm up vs post maximum sustained effort. Collectively, this study has revealed a substantive effect of Moderate Intensity exercise on mean RT but with no evidence of change in mean accuracy. Specifically, the mean RT appears to reduce after generic and Judo specific warm up without any measurable change in mean accuracy rate. The comparison between Baseline and Severe Intensity yielded the opposite result showing no difference in the mean RT but strong evidence for a drop in mean accuracy rate. Our results agree with earlier studies where it was demonstrated that moderate intensity exercise can improve performance in a cognitive task (Rattray & Smee, 2013) but accuracy decreases during severe exercise (Wohlwend *et al.*, 2017).

According to a review by Lambourne & Tomporowski (2010) the effect of exercise-induced arousal on cognitive tasks that involve rapid decisions is positive after the first 20 minutes of exercise. But exercise longer than one hour is likely associated with symptoms of fatigue (Brisswalter *et al.*, 2002). Our result on the mean RT at Moderate Intensity is consistent with the findings of Lambourne & Tomporowksi (2010) as we demonstrated a clear improvement in the mean RT in all judoka after 40-50 minutes of warm up and Judo specific exercises. The same authors reported that “regardless of the type of physical activity performed, participants' cognitive performance improved when tested after exercise”. Our findings could not support such comment for RT. In the case of the Severe Intensity condition there was no practically significant improvement in mean RT compared to Baseline.

The mean difference between Baseline and Moderate Intensity was around 40 msec, which equates to around 11% improvement on mean RT from Baseline to Moderate Intensity. This finding strengthens the importance of proper ‘warm up’ routines prior a main performance as a way to prime cognitive performance and facilitate faster and accurate responses. Studies have already shown the positive effects of appropriate warm up routines on various sporting actions such as judo throws (Lum, 2019), jumping (Pagaduan *et al.*, 2012), golf drive (Langdown *et al.*, 2019), running (Zourdos *et al.*, 2017), or even as a strategy for injury prevention (Mayo *et al.*, 2014). Warm up routines are perhaps effective because they lead to an increase in body temperature, increase in muscle metabolism, increase in muscle contractile activity, VO_2 kinetics, and psychological arousal (McGowan *et al.*, 2015). We add to this body of work by showing that a judo specific warm up routine as typically performed in Judo training prior to randori practice can improve cognitive performance parameters in a group of elite judokas. This finding is in agreement with an earlier study where the authors concluded: “Where activities require a performer to respond quickly to a stimulus amongst alternatives, our results suggest that exercise at moderate to heavy intensity prior to task engagement is facilitative” (Draper *et al.*, 2010). We believe that such finding is of practical significance for the Judo community considering that it is not uncommon to find judoka at competitions who do not spend enough time, if any at all, on their warm up prior bouts. In fact, the coaches we talked to from the Scottish Judo programme reported cases of judoka who tend to avoid warm up at tournaments because, in their own words: “…they try to conserve energy”.

We found no significant difference in mean RT between Baseline and Severe Intensity. But then, if we accept that the mean RT can improve by almost 11% from Baseline after warm up and that mean RT after sustained extreme effort matches that at Baseline then in reality mean RT has deteriorated by almost 11% as a direct result of the Severe Intensity condition.

There was no practical difference in the mean accuracy between Baseline and Moderate Intensity conditions but the mean accuracy between Baseline and Severe intensity conditions was lower by over 13%. In other words, in a test of 20 reaction episodes a judoka was likely to commit, on average, 2-3 more errors under Severe Intensity conditions compared to Baseline. In a study where a group of experienced male judoka performed Judo bout simulations at three different duration levels (1.5 minutes, 3 minutes, and 5 minutes) and at high enough intensities to force blood lactate concentration above 10 mmol/L (an indicator of exhaustive anaerobic exercise) the authors did not find a significant change in mean RT from rest. But they did find a significant increase in error rate, which was attributed to the high physical intensity involved (Lima *et al.*, 2004). Our findings are consistent with the conclusion of Lima *et al.* (2004).

The practical implication of these findings, in the context of Judo competition, is that we can expect a judoka's mean RT to increase and their accuracy to deteriorate to some extent after a point during an intense bout. We do not have sufficient data to know whether or not the magnitude of the potential deterioration in mean RT and mean accuracy can have tangible impact on the outcome of a bout. We can be more confident though in speculating that a judoka who can minimise unforced errors stands a better chance winning a fight than a judoka who commits more errors when fatigued.

We have already highlighted in Chapter 6 that humans cannot fix their RT or accuracy to a specific level and have to make conscious efforts to sustain their attention over repeated tasks (Smilek *et al.*, 2010). Under Severe Intensity the variability of the response-by-response mean error rate across the 20 reaction episodes increased sharply compared to Baseline and Moderate Intensity (Figure 7-3) exposing a remarkable inability to sustain attention. It has been shown that during exercise of high intensity and long duration attention focus is dominated by the awareness of the extreme physiological discomfort (Hutchinson & Tenenbaum, 2007). It is unknown though if the notable inconsistency in accuracy under Severe Intensity is limited to: 1) the inability to sustain attention secondary to acute fatigue (*i.e.* overwhelming physiological sensations), or 2) the lack of habituation on having to perform a demanding mental task whilst in severe physical discomfort from the 'all out' effort.

At any major tournament it is often impossible for a judoka to avoid extreme physical intensity during a fight if their opponent chooses to increase the pace and intensity of their actions. In Judo it can only take one wrong decision to lose a match, so it is in the best interest of any elite judoka to maintain the necessary focus and prevent loss of accuracy even under conditions of extreme physical intensity. We have shown that in a cohort of elite judoka the likelihood of erroneous choices increases under conditions of extreme physical effort. There are a couple of practical suggestions for Judo coaches based on the data presented here. Firstly, we would encourage judokas, assuming they have a high level of fitness, to keep the intensity of randori at high pace during tournaments as this way they may force their opponent to a higher error rate. Secondly, our haptic test can serve as an important training tool to either help identify judoka with low accuracy under conditions of severe intensity or assess progress in those who work to improve accuracy under extreme pressure. We should make it clear that we do not expect an elite judoka who responds accurately in a haptic test to also be able to make consistently correct decisions in randori too. However, we believe that if someone is capable of processing information rapidly and accurately under pressure (evidence for which can be gathered through the novel haptic task) then it is reasonable to expect that person to be capable of the same trait under Judo competition conditions as well.

One of the suggestions to explain the diversity of results from studies looking at the effect of physical exertion on cognitive performance has been not having controlled for the participants' physical fitness (Brisswalter *et al.*, 2002). For example, it is thought that physically fit individuals can outperform less physically fit individuals in cognitive tasks during exercise (Tomporowski & Ellis, 1986). In our study, we did not carry out a fitness assessment of our volunteers. But whilst we are not able to provide information on each judoka's estimated VO_2max (aerobic capacity), or on their anaerobic capacity, we are confident in our assumption that all of our elite judoka are fit and athletic. The cohort of elite judoka had at least 10 years of regular Judo training and they all had to achieve satisfactory results at National Championships and international competitions to gain, and to maintain, a place in the National High Performance Judo programme where they are expected to maintain a regular attendance to highly demanding training sessions and physical tests both on the judo mats and in the gym. In other words, our judoka's presence in Scotland's Judo High Performance programme suggests that they are fit enough for the demands of elite level Judo and that they should be considered as athletes with a high level of physical fitness.

A potential criticism of this study is that we used a rowing test, and not a Judo specific activity, to simulate the Severe Intensity condition under which we examined cognitive performance. The rowing test has been used by the Judo squad for several years as the coaches and the exercise physiologists in the Judo High Performance Programme believe that the metabolic demands of a prolonged ‘all out’ rowing exercise are comparable to the metabolic demands of an intense judo bout. It was not in the scope of this study to prove or disprove the above assumption. Regardless of the true equivalence in metabolic demands between an ‘all out’ rowing effort and an intense judo match there are some important similarities that cannot be ignored: they both force blood lactate to rise to high levels, they both need a critical level of muscle coordination and movement timing to be maintained throughout, they both use all the major muscle groups, and they both need a high degree of mental resilience to sustain the severe intensity despite the inordinate discomfort experienced as a direct result of such extreme physical effort. It may be argued that rowing is a weight supported activity unlike Judo where competitors fight on their feet, but this statement is not necessarily true. The reader only has to look at any Judo competition to see that most bouts quickly develop into a fight on the ground (ne waza). Ultimately, all judoka were familiar with the rowing test protocol that could push them to their limits in a specific and predictable way, which is unlike a randori match where the intensity is subject to many more variables *e.g.* the difference in the two opponents’ skill levels and size, their fitness and strength levels, and their motivation levels to engage in a bout against a given opponent.

A strength of this study is the ecological validity of the method used. We carried out the tests in an actual Judo training environment, with a cohort of elite judokas, around and during their regular training sessions and tests. None of the participants had to alter their training schedule or Judo drills during training to accommodate the execution of the haptic tests. By allowing judoka to follow their usual training methods and routines, and simply collect data when it was convenient with a method that was not invasive, time consuming, or arduous we were able to collect data on multiple occasions and achieve 100% compliance with our 10 elite judokas. We used a RT device with tactile prompts, which is consistent to the main sensory modality experienced by judokas. Also, we investigated choice RT, rather than simple RT, an important difference for an open sport like Judo where competitors are faced with constant choices on how to create and how to respond to scoring opportunities. In contrast, a simple RT task would have been suitable if we had investigated a closed skill sport with a predetermined action in response to a specified stimulus *e.g.* a sprinter who powers off the starting block at the sound of the starting gun.

It may be argued that the strength of the study was also its limitation. By not having the tests carried out in a laboratory and under strict conditions prior and during the completion of haptic choice reaction tests we have not been able to control for potential confounding factors such as fitness, hydration, diet, and fatigue. However, we remain confident that the results obtained in this study are more likely to reflect the true parameter values that can be expected under real life Judo training than results obtained in the clinical conditions of a laboratory. Furthermore, it is reasonable to assume that we would only have been able to collect a fraction of the data we have managed to collect if the judoka were expected to travel to the Exercise Physiology laboratory at the University of Stirling to complete the haptic reaction tests.

We believe that the results from our study could be relevant to other judoka at High Performance Judo programmes around the World. Our elite judoka participate at competitions and training camps on most continents and their training methods and routines are influenced by, and in line with, training methods elite judoka use in other countries with excellent Judo programmes, most notably Japan, Korea, and France. We hope that more Judo performance programmes will collect data using our method to expand on what has been presented in this and the rest of the chapters.

7.7 Conclusion

The results from this study have provided us with a valuable insight on the effects of varying intensities of exercise on the cognitive performance in a cohort of elite judoka as measured by a novel haptic choice reaction device.

We have shown that the mean RT can improve by a considerable margin in a group of elite judoka after they have completed a typical judo specific warm up session. No significant difference was found between the mean RT at Baseline and at Severe Intensity, which can be seen as a deterioration in response time when compared to the same test results after warm up (Moderate Intensity). We have also shown that immediately after sustained ‘all out’ efforts there is a greater likelihood that a judoka will make erroneous decisions.

The practical implications of our findings highlight the importance for elite judoka to engage in proper warm up routines. And for the coaches to consider coaching interventions that challenge, and tools that evaluate, cognitive performance in elite judoka under conditions of extreme physical intensity, as typically experienced during high pace and high intensity randori. Although the focus of this research has been on elite judokas, the findings presented are potentially applicable to other judoka and to other open skill sports where athletes must make quick and correct decisions under intense physical effort.

7.8 References

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Chapter 8: General Discussion and Conclusion

8.1 General Discussion

Our original intention when we started this research was to investigate the effect acute dehydration can have on cognitive performance in elite judokas. However, initial research findings revealed that there had not been an ecologically valid assessment of reaction time (RT) in elite judoka nor was an ecologically valid assessment tool available. We therefore had to address that knowledge gap. Hence, we embarked on a journey to design a reaction test method that reflects the dominant sensory modality judoka are exposed to when in practice and competition.

We have developed a novel reaction test method that can provide an assessment of a judoka’s ability to process tactile cues quickly and accurately. Our method takes into account factors that can influence reaction time and accuracy to a tactile stimulus such as: complexity of information received (*i.e.* choice reaction test), the sensory route (*i.e.* haptic response), the magnitude of the stimulus intensity (*i.e.* vibration frequency), participants’ motivation to complete a test, and participants’ ability to sustain attention during each test (both of which we have attempted to enhance by asking the participants to compete against each other for the best results in the tests). This low-cost haptic reaction test device allows for the process of data collection to be efficient and minimally disruptive to the judoka’s training. We believe that the simplicity and efficiency of the testing was instrumental for the compliance of our participants during the multiple testing sessions.

One potential criticism against the haptic reaction task we employed for our method is that although the device handles were designed to allow for a Judo specific grip, the task itself was not a simulation of a Judo movement. Had we opted for Judo movements as the reaction task then we would have increased the variables involved and most likely the variability of the results too. In addition, we would not have been able to keep the response tasks consistent across individuals as we would have had to account for many more factors such as: hand laterality, skill level, degree of familiarisation, and even individual preferences for any given Judo specific task. As already described in Chapter 5, the overall response time is the sum of reaction time and movement time. The inclusion of a Judo movement in the reaction task would have prolonged the overall response time and would have added more uncertainty about the true limits of our cohort's typical RT to a haptic stimulus. For example, in a visual simple reaction model the mean RT (380 msec) of the judoka who participated in the study was quite slow for a simple reaction test (Morales *et al.*, 2018). The reaction task of that study required the participants to step forward 20 cm from a standing stance onto a contact platform in response to a light signal. This set up increased considerably the contribution of movement time to the overall response time. In the method we have developed we have tried to assess elite judoka's ability to process information quickly and make correct decisions in response to a tactile prompt. In our method the task requires minimal contribution of movement time in the overall response time. But at the same time our method does allow for flexibility in the response task chosen; it is conceivable that future studies could utilise the device in some way that incorporates Judo specific movements.

Another potential criticism could be against our decision to build a bespoke haptic reaction device when we could have produced an online haptic reaction test instead. It is true that it is possible to develop an application to turn personal computers, laptops, smartphones and tablets into a haptic reaction testing device (assuming integrated haptic technology in the electronic device chosen). An online reaction test application may sound like an appealing proposition as a lot more people could access the test instantly and at no cost whenever they decided to do so. However, allowing the test on multiple devices, especially ones for which we have no knowledge of their technical latency, would have introduced an unacceptable level of uncertainty in our results. There is evidence that the visual reaction tests commonly used by online cognitive assessment tools are very inaccurate (Kim *et al.*, 2020). In fact, the impact on the variability of RTs by the inherent latencies of hardware (computer monitor and mouse) and software (operating system) raises a question about the reliability of any online cognitive assessment tools (Holden *et al.*, 2019). Results from a haptic reaction test application downloaded on mobile phones would have presented the investigators with an insurmountable challenge as the variation in (the mostly unknown) technical latency across the myriad of smartphone options would have been a confounding factor. Therefore, we remain confident in our decision to build a bespoke device for which we have a clear understanding of its latency and evidence of its reliability and validity.

Our data presented in Chapter 5 contribute to the limited evidence available in academic literature regarding the temporal pattern of attention. Moment-to-moment fluctuations in attention are normal and perhaps they account for some proportion of unforced errors or missed scoring opportunities from elite judoka during competition. One question that comes out of this work is whether some intervention could help elite judoka improve their capacity for sustained attention *e.g.* can purposeful focused practice reduce the variability of RT in choice reaction task similar in duration to a Judo bout? Our haptic method has the potential to be a useful tool in the assessment and evaluation of any intervention aimed at improving attention.

Our work has been well received by the Judo coaches in the High Performance programme. When the graphs in Chapter 5 were presented to the Judo coaches they described them as “helpful” because they enabled them: 1) to realise that attention cannot be sustained even in a task just under two minutes long, and 2) to consider applications of our method that may help them identify judoka who struggle to sustain their attention so that they can adjust coaching interventions accordingly *e.g.* shorter randori practice rounds.

In Chapter 6 we highlighted the case of a judoka who did not appear to cope well under the pressure of competition. ‘Chocking under pressure’ is not uncommon in competition (Baumeister, 1984) but we did not expect that through our method we would be able to identify an individual in our cohort who suffered from performance-sapping competition anxiety. Such outcome has added to the evidence of ecological validity of our method and suggests that there may be some scope for its application beyond what we have designed it for. Indeed, the Sports Psychologist who works in this performance programme was open to exploring the possibility of our method having some place in their work with judoka who may present with levels of competition anxiety disruptive to their progress and success. Such discussions are still informal and at an early stage so it is yet unknown how and to what extent can our haptic test be used, and what can be pragmatically achieved. However, we note the interest our findings have generated for other support staff.

Our results presented in Chapter 7 contribute to the evidence in the academic literature showing that moderate exercise can improve RT. There can hardly be any argument against proper warm up (McGowan, Pyne, Thompson, & Rattray, 2015) but we have demonstrated that a Judo specific warm up routine can improve cognitive performance parameters in a group of elite judoka when compared to baseline. This finding agrees with earlier studies where it was shown that exercise can facilitate faster responses (Draper *et al.*, 2010). It was very rewarding to see that our data from the Moderate Intensity condition: 1) were used by the Judo coaches and other support staff to highlight to judoka the importance of a thorough warm up prior to a bout, 2) encouraged further investigation of best warm up protocols that was led by the Exercise Physiologist, and 3) encouraged the coaches to ask the judoka to develop and implement an appropriate warm up routine for competition that included reaction drills, as it was recognised that some way of challenging cognitive performance should be an integral part of the competition day warm up.

Another contribution to the body of academic research from Chapter 7 is the evidence showing the negative impact extreme physiological efforts can have on response accuracy. We have shown the detrimental effect extreme physical effort had on our cohort’s accuracy in agreement with the results reported by Lima *et al.* (2004) from a different cohort of judokas. Experienced athletes are likely to demonstrate faster responses compared to less experienced athletes (Lee *et al.*, 1999) due to neurological adaptations from repeated practice and learning thus reducing cognitive burden and allowing for better attention (Bengtsson *et al.*, 2005; Reis *et al.*, 2009). It could be argued that one reason for the deterioration of accuracy under extreme efforts is the lack of purposeful cognitive practice under such conditions. In fact, the coaches and all other support staff acknowledged that historically all maximal physiological tests were carried out without consideration of cognitive load *i.e.* judoka were not required to process information and make decision during an ‘all out’ effort. Following our findings, the coaches and the support staff have expressed their interest to include haptic choice RT tests alongside the already established maximal conditioning tests as a way to evaluate judoka’s ability to process tactile information accurately under conditions of extreme physical effort.

A lot of emphasis has been placed in this study on estimating the baseline mean RT and mean accuracy from a cohort of elite judokas. We do not imply that judoka who are shown from our method to be capable of consistently processing tactile information quickly and accurately can also be guaranteed success in Judo competition. Even though we found that the judoka who combined high accuracy and fast reactions (see Figure 5-6) were also some of the most successful competitors in the group, we make no claim of any correlation between the results in the haptic test and performance in Judo competition, or the quality of execution of Judo skills. The correct, efficient, effective, and quick execution of Judo movements is subject to several factors out with the scope of this study and beyond cognitive performance *e.g.* neuromuscular coordination, muscle fibre physiology, somatotype, training history, and many others. Moreover, during a Judo match, judoka have to perform highly advanced motor skills and at the same time focus their attention on a multitude of areas such as: 1) awareness and evaluation of the situation, 2) Judo technique, 3) strategy and tactics, 4) psychological state, and 5) peripheral attention (Bahmani *et al.*, 2019). What is more, the processing of information and the quality of skill execution can be enhanced or hindered by performance anxiety (Raglin, 1992).

We understand that attention is complex and dynamic and its importance in our method is recognised by having a condition (*i.e.* competition) specifically to motivate judoka to sustain their attention. It is not unreasonable to expect a judoka who does not exhibit the cognitive capacity to process information quickly and accurately in our haptic test to be less likely to possess the cognitive capacity to process the much more complex information load of a competitive Judo match. Following the results we presented in Chapter 5 (Figure 5-6) it may be appealing to think that performance in the haptic test may be correlated with Judo-competition-specific qualities, but of course such hypothesis should be put to the test in future studies.

Our Judo specific studies were carried out with 10 elite judokas. We understand that more data will need to be collected from more judoka so that we can confirm or adjust the results reported in chapters 5-7. As more data accumulate, we will eventually be in position to determine more accurately the typical values for mean RT and mean accuracy amongst elite judoka at rest and under different conditions (*e.g.* after warm up, under extreme physical effort, and following intentional dehydration to ‘make weight’ for competition). Potentially, over time not only can we increase our confidence for the true mean RT and mean accuracy rate in elite judoka but also determine how such parameter values may vary at different standards of competition (*e.g.* club level vs World class) and at different stages of development (*e.g.* cadet level vs youth level vs adults), and more importantly, whether changes in cognitive performance parameters correlate with performance in Judo competition.

We have contributed to the body of academic research with our novel haptic choice reaction method, which we believe has higher ecological validity as a reaction test for judoka compared to using a visual or acoustic choice reaction test instead. Our findings have influenced Judo coaches’ interventions as well as the work of other practitioners in the support team. As a result, through our work we have been able to effect coaching interventions, testing protocols, and warm up routines in a High Performance Judo programme.

Although many interesting findings with practical applications have come out of our study there are several limitations that we should address:

- We have used a small cohort of 10 judoka and caution should be exercised on the interpretation of the results and on any inferences we may consider making over the wider population of elite judokas. However, we cannot ignore that this cohort is made up of highly specialised individuals who are outstanding in their sport and as such are best equipped to help us understand how some cognitive performance parameters may fluctuate in this group under different conditions.
- RT tests were not carried out within the controlled conditions of an exercise laboratory. All the RT data we gathered from the judoka were at their training venue (dojo) and around sessions that were part of their normal training schedule. Hence, during every test session each volunteer was subject to all sorts of potential distractions. However, we would argue

that such conditions added to the ecological validity of the testing method as any distractions were identical to the ones the judoka experience already in training.

- The haptic signal intensity is a factor in how fast a person can react to that signal. Although from our pilot studies we were satisfied that the haptic signal in our reaction device was strong enough, the frequency produced from the vibration motors was less than the maximum frequency perceivable to humans. It is conceivable that future studies may show further improvement in mean RT and mean accuracy by the same or similar cohort if we were to replace the motors in our device with ones of higher frequency. Arguably though, by not having used the maximum frequency we have created a testing method that gives an advantage to judoka or other athletes in sports with strong tactile feedback who are likely better conditioned to detect weaker haptic signals.
- It is possible that we were biased to the device's performance as we were also the ones behind the inception of the device and its production – we cannot deny our invested interest to see the device work. Nonetheless, the statistical approach we chose with Bayesian techniques to derive a posterior distribution for the parameters of interest is likely to have mitigated the risk of observer bias.
- We have developed a completely new test method to collect RT data. Since there are no previous studies where an approach like ours was followed, we have no way of 'sense checking' the data from our novel method against similar data.

8.1.1 Future Research

Research on coaching interventions and nutritional strategies to augment elite judoka's cognitive performance or to minimise its deterioration under conditions of extreme physical effort has been limited. Similarly, although the negative impact of acute dehydration methods on RT has been recognised, it remains unknown how well elite judoka can recover by the morning of their competition day following a period of acute weight management to 'make weight' for the weigh-in the day prior. Therefore, future studies should utilise the haptic choice reaction test we have developed to answer some important questions:

- Judokas may use extreme dehydration methods to reduce their body mass to within the allowed weight range for the weight division they want to compete in. If judoka can achieve acute weight loss safely, can they match their own baseline cognitive performance standards immediately after they have weighed in successfully?
- In all major tournaments judoka are expected to weigh-in the day before the competition, which likely encourages more extreme weight making efforts as more time to recover is available. If judoka have shown evidence of cognitive performance decrement after weigh-in, can they recover fully by the following day of competition or are they more prone to erroneous decisions?
- We have shown that directly following an extreme physical effort elite judoka's error rate increases remarkably. Can a period of extreme conditioning combined with decision making tests lead to an improvement in cognitive performance under highly intense physical efforts as seen in closely contested matches?
- Are there nutritional interventions that could minimise the deterioration typically seen under conditions of extreme physical effort *e.g.* caffeine supplementation?
- Some high performance Judo programmes use metrics to predict the fatigue levels of their athletes. Is there a correlation between cognitive performance parameters and metrics that indicate physiological fatigue?
- Can our test be used as part of a toolkit practitioners use when they try to assess 'return to play' in athletes who are recovering from concussion?

8.2 General Conclusion

We set out to determine the typical range of haptic choice reaction parameters in a group of elite judoka as a measure of cognitive performance and to determine how they can be influenced by different levels of physical effort. In trying to fulfil the above we have created an affordable, reliable, easy to use, and portable haptic reaction testing device with evidence of ecological validity. Furthermore, our novel test method allows for the collection or RT data from elite judoka at their training or competition environment without disrupting the training session or warm up routines.

We have been able to contribute new knowledge by having determined the typical baseline RT and accuracy range in a group of elite judoka in a haptic reaction task. We were also able to demonstrate how different levels of exercise intensity can influence cognitive performance. With our results we have demonstrated for the first time that elite judoka's attention fluctuates even during a period as short as two minutes. With our method the coaches and support staff have a tool they can use to identify judoka's ability to achieve sustained focus over a set number of reaction episodes, or over a fixed time period, under different states of physical exertion.

With a baseline of relevant parameter values determined and a method with ecological validity available, further research is now possible to help coaches and support staff reveal elite judoka's limiting factors to sustained attention or factors that may have a negative impact on cognitive performance (*e.g.* typical weight making strategies).

We have been fortunate to witness the coaches in the High Performance programme show a great deal of interest in our data. We have contributed to the body of academic research with results from a novel and ecologically valid method. Our findings have already been disseminated to Judo coaches who have not hesitated to inform their coaching decisions based on the data reported in this thesis. It was our ambition to see our academic work influence front line practice and we have already been able to effect coaching interventions, testing protocols, and warm up routines in a High Performance Judo programme.

8.3 References

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