Are Adolescent Competitive Swimmers Cleverer?

The impact of competitive swimming and swimming training on cognitive function

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Abbreviations

5-HT	5-hydroxytryptamine
5-HTP	5-hydroxytryptophan
AADC	Aromatic amino acid decarboxylase
ACTH	Adrenocorticotrophic Hormone
ADHD	Attention Deficit Hyperactivity Disorder
AVP	Arginine Vasopressin
BDNF	Brain Derived Neurotrophic Factor
CNS	Central Nervous System
CRH	Corticotrophin Releasing Hormone
FGF	Fibroblast Growth Factor
FSH	Follicle Stimulating Hormone
GABA	Gamma-aminobutyric acid
GnRH	Gonadotrophin Releasing Hormone
HPA	Hypothalamic-Pituitary-Adrenal Axis
HPG	Hypothalamic-Pituitary-Gonadal Axis
HRMAX	Maximum Heart Rate
IGF-1	Insulin-like Growth Factor
L-DOPA	3,4-dihydroxy-L-phenylalanine
LH	Luteinising Hormone
LTP	Long Term Potentiation
MRI	Magnetic Resonance Imaging scanning
mRNA	Messenger Ribonucleic Acid
NE	Noradrenergic System
NMDA	N-methyl-D-aspartate receptor
NGF	Nerve Growth Factor
RAH	Reticular-Activating Hypofrontality Theory
SAS	Sympathoadrenal System
TCATS	Exercise intensity at which significant increases in circulating catecholamines are seen
TrkB	Tropomysin-related kinase B receptor
VO2MAX	Maximum Oxygen Uptake
VEGF	Vascular Endothelial Growth Factor

Foreword

Physical activity is often described as the most cost-effective drug we have. Its benefits are far-reaching, from prevention of disease and improving mental health to impacting the wider determinants of health such as educational attainment, economic productivity and community development.

Swimming, both recreational and competitive, contributes to reducing the risks of a wide range of conditions including lowering the risk of diseases like type 2-diabetes, cardiovascular disease and dementia, and improving the health of people living with many chronic diseases particularly musculoskeletal conditions that can benefit from the support of the water.

Competitive swimming training in a positive, enjoyable environment can help to instil the belief that regular physical activity is good for you and a regular and essential part of our lives. The support and empowerment that comes from competitive swimming is reflected in our Olympic and Paralympic stars such as Ellie Simmonds and Rebecca Adlington. Competitive swimming clubs (like other sports clubs) can offer an environment where young people can learn about the good techniques for success in life such as goal setting, stress management and social interaction.

Although the report focuses on competitive swimming, many of the benefits play out in recreational swimming and it provides an opportunity for all of us to reflect on how team sport and swimming in particular can improve individual's health and the health of the nation.

Duncan Selbie

Chief Executive, Public Health England

Introduction

The genesis of this report lies with a comment made by the headmaster of a high-performing state secondary school who said: *"a school full of competitive swimmers would be fantastic; they are all hard-working and perform highly academically"*. The dissertation tests the working hypothesis derived from this statement that adolescents participating in competitive swimming training have both short and long-term benefits in cognition compared to the wider population. If the hypothesis that adolescent swimmers are both cleverer and work harder is correct, the alternate hypothesis that young people who are more academic, better disciplined, or more determined to succeed are drawn to competitive swimming as a sport will also be considered.

Cognition is defined by Esteban-Cornejo et al (2015) as "the mental function involved in gaining knowledge and comprehension". Cognition is a key factor behind academic performance but not the only factor. The quality and quantity of teaching and the socio-economic background of individuals also impacts on overall academic performance (Keeley and Fox, 2009). In addition to examining the physiological effects of swimming training on cognition in adolescents, there is a second aspect to the headmaster's comment, the "hard working" component which may be related more to psychosocial or psychological factors than cognition. If the headmaster's belief that adolescent swimmers are both 'cleverer' and work harder is correct, an alternate hypothesis that young people who are more academic, better disciplined, or more determined to succeed are drawn to competitive swimming should also be considered - i.e. do certain academic or personality traits attract people to competitive swimming as a sport rather than vice-versa?

Methodology

A comprehensive literature search and an evaluation of the literature on exercise-cognition interaction in adolescent/competitive swimmer populations was undertaken. Where no literature existed for either the swimming or the adolescent population, the impact on cognition of similar types of exercise, or other age-groups has been considered. A detailed analysis of the main areas of relevant physiological, psychological and psychosocial research activity arising from the literature search was used to identify the most likely mechanisms for cognitive benefit to accrue in adolescent swimmers. An assessment of the frequency, type and intensity of swimming training to deliver maximal cognitive benefit for adolescents from swimming training was also undertaken.

Does exercise affect cognition in adolescents?

Chronic (long-term) effects on cognition – Etnier et al, (2016) state that the belief that regular exercise benefits long-term cognitive performance goes back to Roman times. The Roman quotation '*mens sana in corpora sano*' or *'a healthy mind in a healthy body'* (Juvenal, circa 100 AD) can be interpreted as 'to have good mental health, one needs to have good physical health'. The first scientific study exploring the relationship between chronic exercise and cognition was published in the mid-1950s (Weber, 1953). Etnier et al (1997) published a meta-analysis demonstrating that the type and focus of the research in this area has changed over time with early work typically being correlational studies - comparing athletes and non-athletes and their respective performance in academic tests, with later work focussing more on changes in physiological parameters that may affect cognition. In 2010, the Centers for Disease Control in the US published a meta-analysis of 50 separate studies from over 400 publications looking at the association between school-based physical activity and academic achievement, cognitive skills and attitudes, and academic behaviour (CDC, 2010). Of the 251 associations described in the 50 studies, only 4 showed a negative impact. Their overall results showed a 1.5% negative correlation, 48% neutral (i.e. no discernible linkage), and 50.5% had a positive linkage. This meta-analysis is difficult to relate to our adolescent swimmer cohort, however, as there was a huge variation in the amount, frequency and type of exercise undertaken by the participants of the various studies. Esteban-Cornejo et al (2015) conducted a systemic review of 20 publications between 2000 and 2013 exploring the link between cognition and physical activity, specifically in adolescents, and found that over 75% of studies demonstrated a strong relationship between long-term physical activity and cognition in adolescents, and that this relationship was especially strong when "vigorous physical activity" such as swimming training was being undertaken.

Only one study (Lee et al, 2014) was identified that specifically included adolescent swimmers. In this study, when compared to an age-matched control group, adolescent swimmers and some other athletes performed "significantly better" on a range of tests of cognitive function. Gomez-Tolle, (2012) believes that adolescents may prove to have the greatest cognitive benefit from exercise of all age groups as a result of their "unique stage of brain pruning and consolidating". Recent evidence suggests that exercise-induced effects on the brain are seen most clearly in executive functions. Executive functions are defined by Diamond, (2013) as comprising response inhibition (i.e. self-control), selective attention/staying focussed, working memory, responding to unanticipated events, thinking before acting, and cognitive flexibility (i.e. the ability to think laterally, quickly and flexibly). Voss et al, (2013) state that chronic exercise enhances "spatial learning, pattern separation, executive function, working memory and processing speed". Tomporowski et al, (2008) undertook a comprehensive review of the literature on the impact of exercise on cognition, intelligence and academic achievement in children (including adolescents). They state that the development of executive functions in the brain are the most important aspects of exercise-induced cognitive benefit in children as executive functions influence the ability to know when and how to apply knowledge. St Clair-Thompson and Gathercole, (2006) also describe the importance of executive function in learning. They describe that enhanced ability to plan, to inhibit impulsive behaviours, to update working memory, and to quickly move from one task to another results in a better ability to focus in academic situations and therefore an increased likelihood of excelling academically.

In the last few years, research into exercise and cognition has diversified and become more granular. According to McMorris, (2016) this is as a result of there now being an overwhelming consensus that regular aerobic exercise has a positive impact on cognitive function and therefore a shift in the focus of research into how/why this occurs, rather than if it occurs. Hamilton and Rhodes, (2016) confirm that there is now conclusive evidence that exercise such as swimming training provides performance enhancement across multiple cognitive domains and in many different learning and memory tasks.

Acute effects on cognition – As well as regular exercise producing long-term cognitive benefit, acute spells of exercise (e.g. an early morning swimming training session) have been shown to produce significant short-term (< 3 hours) benefits in attention, accuracy of tasks, speed of completion of tasks, and academic achievement tests (Hillman et al, 2009). Cooper et al, (2015) concur and found positive short-term effects on cognition in adolescents resulting from acute exercise, lasting for at least one hour after the exercise stopped. The first suggestion that exercise has a short-term as well as long-term positive effect on cognition was from Davey, (1973), who described exercise as a "stressor" producing "arousal". He linked this to Yerkel and Dodson's, (1908), arousal-performance theory. This theory suggests that when arousal is low, cognitive performance will be low; when arousal is optimal, so is cognitive performance; and when arousal is too high, cognitive performance returns to a poor level. When arousal is plotted graphically against performance therefore, an inverted 'U' shaped curve is produced resulting in this theory becoming known as the inverted U theory. Despite this being the predominant theory behind the acute cognitive impact of exercise for over 80 years, this theory has now lost much support.

McMorris, (2016) states that there is now little support for the inverted 'U' effect on cognition, but the short-term effect of moderate intensity exercise is now believed to be predominantly on the speed of undertaking cognitive tasks. The impact of intense exercise on cognition is less clear-cut with opposing perspectives in the literature, although there is consensus that the speed of undertaking autonomous tasks is still facilitated (McMorris, 2016).

Anatomy and physiology of the brain

Before considering how exercise such as swimming training impacts on cognition in adolescents, it is important to understand how the human brain functions and how we learn. Learning takes place in the human brain via the creation of new pathways between neurons through the firing of synapses - the junction between neurons. This process involves dendrites, neurons, axons, and a wide array of chemical reactions and electrical signals (Vaynman et al, 2003).

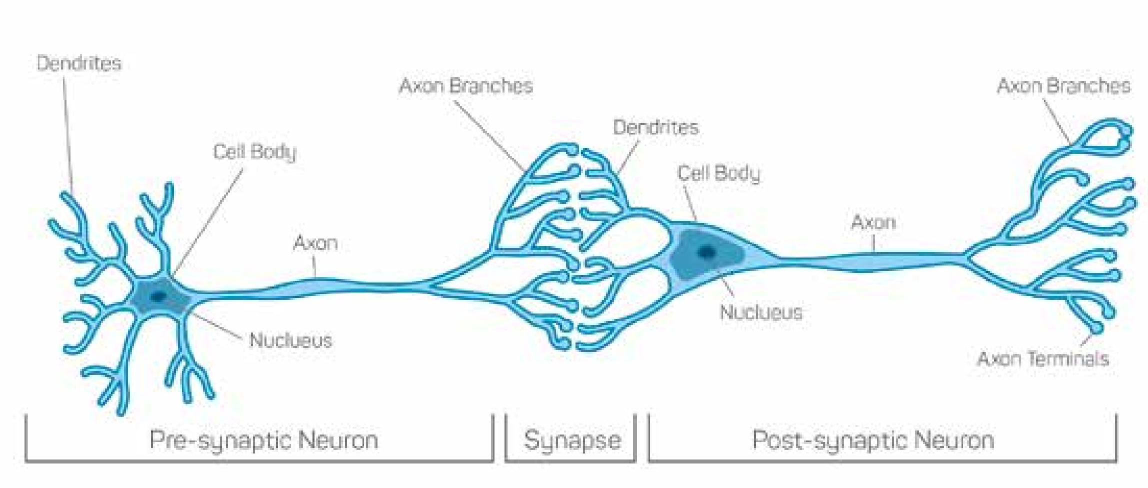

Figure 1: Neurons, axons, dendrites and synapses

The brain comprises one hundred billion neurons of various types that communicate with each other via hundreds of different neurotransmitters (Ratey and Hagerman, 2013). Each neuron receives input from many different signals before responding with its own signal.

This electrical signal passes along an axon of the neuron to the synapse where a chemical neurotransmitter transmits the signal across the synapse from an axon of one neuron to a dendrite of the receiving neuron. The neurotransmitter binds to the dendrite and opens ion channels in the cell membrane, turning the chemical signal back to an electrical one.

If the electrical signal at the receiving neuron passes a threshold, an electric signal is then passed down its axon and the whole process then repeats (see Figure 2 – below).

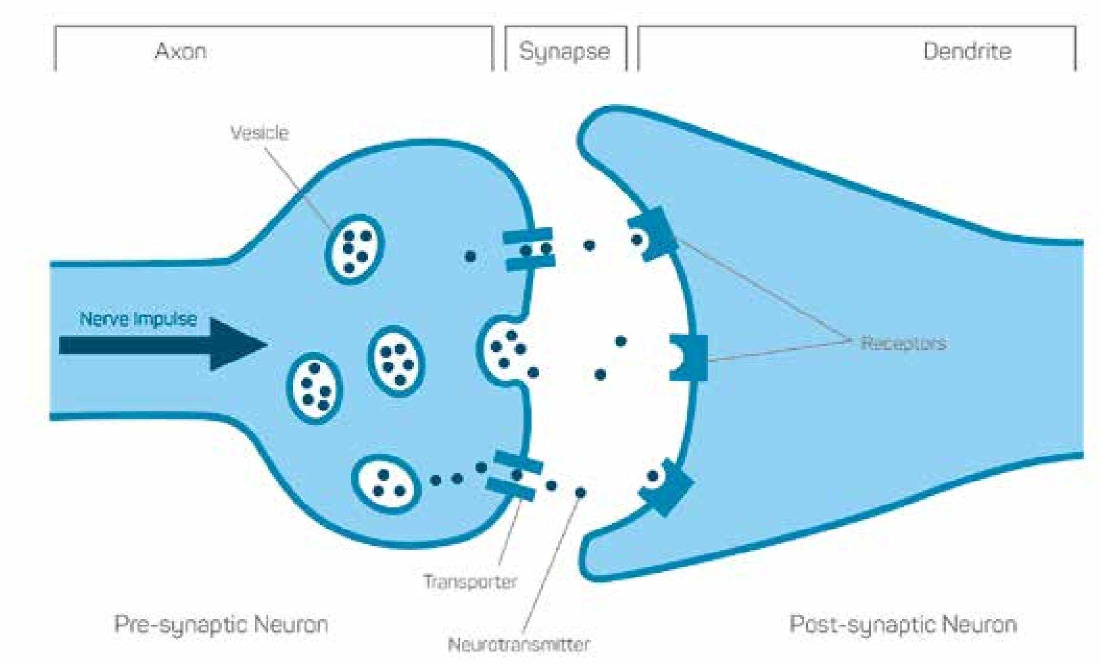

Figure 2: Neurotransmission from neuron to neuron across a synapse (from axon to dendrite)

Neurotransmission

About 80% of neurotransmission across synapses is controlled by two chemicals: glutamate which initiates the signalling cascade, and gamma-aminobutyric acid (GABA) which reduces signalling activity. When glutamate delivers a signal for the first time between the axon of one neuron and the dendrite of another, a new connection is established. The more often this connection is subsequently used, the stronger the linkage between the two neurons becomes - a process known as binding. This is a critical part of the process of learning. Glutamate and GABA are described by Ratey and Hagerman, (2013) as the "workhorse neurotransmitters".

Three other regulatory neurotransmitters - serotonin, noradrenaline (norepinephrine) and dopamine - are also of critical importance to the functions of the brain although they are only produced by about 1% of neurons. The regulatory neurotransmitters have a variety of roles including stimulating glutamate production and changing the sensitivity of neurons, thus increasing or reducing brain activity. The prime role of these regulatory neurotransmitters is to modify the flow of information around the brain and fine-tune the overall neurochemical balance in the brain. Serotonin's key role is to keep brain activity under control. It influences factors such as mood, impulsivity, anger, and aggressiveness; Noradrenaline influences attention, perception, motivation and arousal; and Dopamine is the neurotransmitter that influences learning, satisfaction, attention and movement but takes on contradictory functions dependant on which part of the brain it is acting on (Ratey and Hagerman, 2013). As will be discussed later, one of the effects that exercise has on the brain is to elevate and balance levels of these neurotransmitters and other neurochemicals.

Learning occurs through the process of Long Term Potentiation (LTP) which is the strengthening of linkages between neurons with, over time, the production of new neurons (neurogenesis) and branches of neuronal axons and dendrites (neuroplasticity). For example, if an individual learns a new word in a foreign language, the first time the word is heard, neurons create a new circuit as a result of a glutamate signal passing across the synapse. If the word is never used again, over time this linkage diminishes. If, however the word continues to be used, the synapse keeps firing. This repeated activation causes the synapse(s) involved to swell and make a much stronger connection. Continued usage of a new pathway also causes the neuron to create new axons and dendrites, a process known as neuroplasticity (Kandel and Pittenger, 1999).

Whilst neurotransmitters are responsible for signalling or message transmission around the brain, proteins known as 'factors' are responsible for building and maintaining the brain circuitry itself. The most prominent of these factors is BDNF (Brain-Derived Neurotrophic Factor). BDNF has several roles: it stimulates the production of new branches, axons and dendrites in the neurons producing the structural growth for LTP and learning; it binds to synapse-receptor sites increasing the signal strength; it activates genes to produce more BDNF and serotonin; and it improves the function, growth, strength and life-span of neurons (Ratey and Hagerman, 2013). These authors refer to BDNF as "a crucial biological link between thought, emotions and movement" and acting like "fertiliser for the brain".

Anatomy of the brain

Anatomically, the brain is comprised of separate regions with each of these regions having distinct roles. The dominant part of the brain is the cerebrum, the large structure that forms more than three-quarters of the total volume of the brain. The cerebrum has two hemispheres – left and right - which are connected by the corpus callosum, a bridge of nerve fibres. The cerebral cortex is the outer layer of the cerebrum and comprises four lobes – the frontal lobe, the parietal lobe, the temporal lobe and the occipital lobe (Carter et al, 2014).

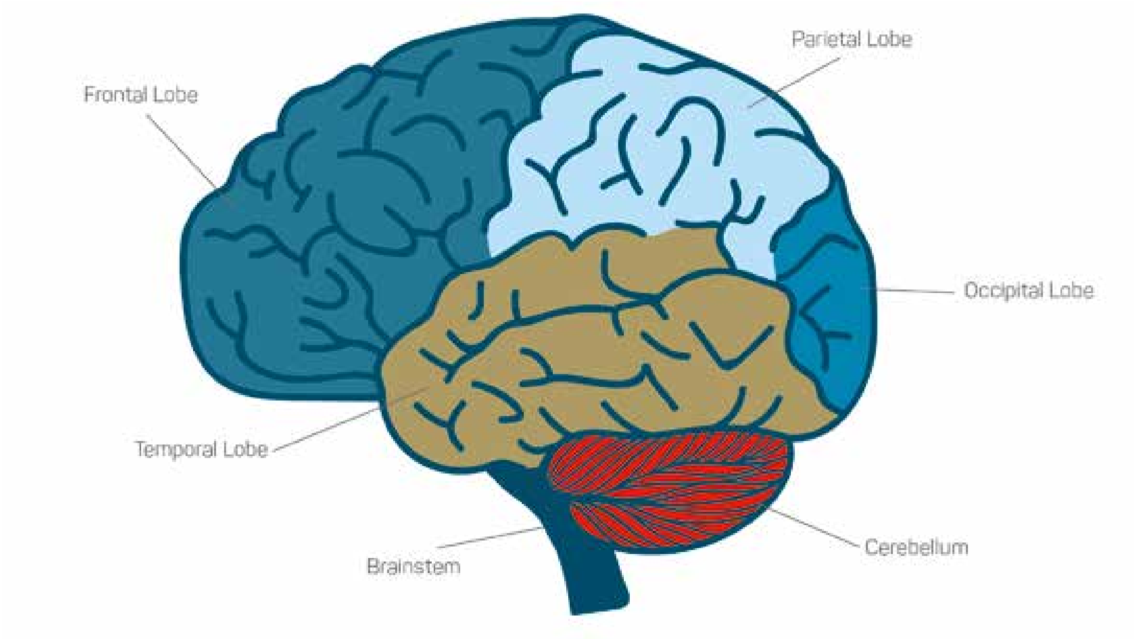

Figure 3: The Lobes of the Cerebrum, the Brain Stem and the Cerebellum.

The cerebral cortex is the area of the brain responsible for complex thought. The occipital lobe is responsible for processing vision, with the temporal lobe processing language and sound. The temporal lobe also includes the hippocampus (memory and learning) and the amygdala (emotion). The parietal lobe has an integrative function for the different senses and also handles navigation and spatial orientation.

The brainstem consists of the medulla oblongata, the pons, and the midbrain. It connects the brain to the spinal cord and passes information between the brain and the rest of the body as well as managing critical functions such as breathing, consciousness and the heart. The thalamus and hypothalamus sit between the cerebrum and the brainstem. The thalamus is responsible for relaying motor and sensory signals to the cerebral cortex as well as regulating consciousness, sleep and alertness. The hypothalamus is the connection between the endocrine system and the nervous system via the pituitary gland. The cerebellum lies underneath the cerebrum and plays a key role in co-ordination and balance as well as motor control and some cognitive functions (Carter et al, 2014).

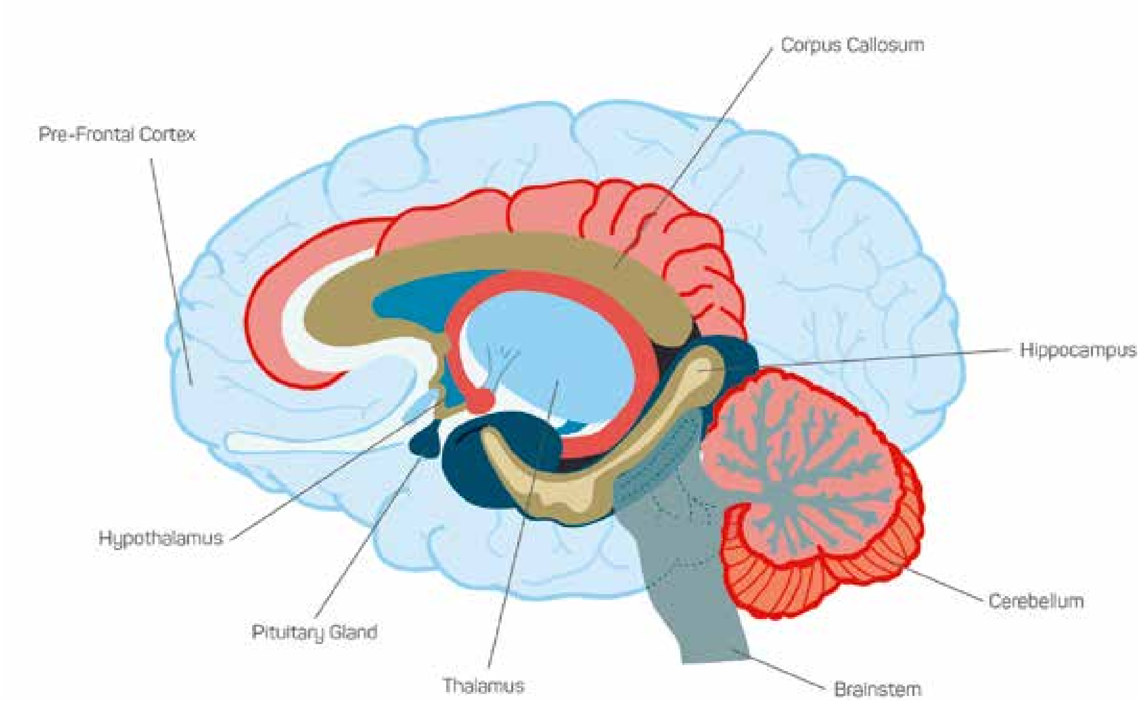

Figure 4: Cross-section through the human brain

Of particular relevance to the exercise-cognition interaction in adolescent swimmers are the cerebellum, the hippocampus, the pre-frontal cortex, and the more primitive areas of the brain - the basal ganglia and the brain stem. No one part of the brain is exclusively responsible for cognition and learning.

The cerebellum is responsible for co-ordinating movement as well as thinking, attention, emotions, and social skills (Carter et al, 2014). The pre-frontal cortex organises physical and mental activity by receiving a wide range of inputs and then issuing instructions to other parts of the brain. It is also the centre for the executive functions of the brain which, as already described, include working memory, inhibiting or initiating action, making judgements, planning ahead, and predicting what may happen next. The hippocampus is believed to be the most important part of the brain when it comes to learning, although it is subservient to the pre-frontal cortex, from where it receives information and checks to see if similar existing memories exist or if new associations between neurons need to be made. If the experience is new, the hippocampus maps out the new neuronal linkages that have been made and reports this back to the pre-frontal cortex (Ratey and Hagerman, 2013). These authors describe the hippocampus as acting as the "cartographer of the brain". Returning to our earlier example of learning a new word in a foreign language, functional MRI scanning shows that when the new word is first heard or being learnt, the hippocampus and pre-frontal cortex are very active, along with other specific areas of the brain such as the auditory cortex. Once the new neuronal circuit has been established by glutamate signalling across the synapse, the pre-frontal cortex is no longer activated and reduced activity is also seen in the hippocampus. Over-time, as using the word becomes normal or second-nature, the thinking patterns or maps move from the hippocampus to be stored in the cerebellum, brain stem or basal ganglia.

This delegation process frees up the pre-frontal cortex and hippocampus to continue learning and adapting. This process is critical to avoid brain overload and exhaustion (Carter et al, 2014).

Adolescence and the brain

The Oxford English Dictionary defines adolescence as "the period following the onset of puberty during which a child develops into an adult" (Simpson and Weiner, 1989). Typically, adolescence includes young people from about 11 to 18 years of age, although puberty can start significantly earlier than this. Adolescence is a time of huge change for children in which they experience puberty, shift their primary focus from parental to peer relationships, learn to think abstractly, and discover their sexuality (Lowus-Deitch, 2015). The pace of physical development or progression through puberty is very variable between individuals (Tanner, 1969). The sequence, timing and pace of physical changes during puberty have been categorised, and criteria for evaluation or self-evaluation known as the Tanner scale developed (Tanner, 1969). The Tanner scale assesses the extent of development of external genitalia (boys), breasts (girls), and public hair (boys and girls) and classifies individuals on a scale from 1 to 5. These physical changes and the Tanner scale are considered to be a useful proxy to assess cognitive and psychosocial maturation (Child Growth Foundation, 2016).

Adolescence is a time when, even without stimulation from exercise, the human brain is in a unique phase of complex development through learning as well as physiological and psychological changes (Sisk and Zehr, 2005). Blakemore and Choudhury, (2006) describe adolescence as being the most critical period of development for higher levels of executive functioning, thought processing and increased memory capabilities. Huttenlocher et al, (1983) were amongst the first authors to demonstrate that the frontal cortex undergoes significant changes during puberty.

Giedd, (2004) demonstrated via MRI scanning that early puberty (Tanner stages 1 and 2) sees the formation of new synapses (synaptogenesis), unused synapse removal (pruning), and the creation of new dendrites (dendrogenesis) and maturation of nerve fibres (myelogenesis). Myelogenesis improves the speed of signal transmission around the brain. Giedd, (2004) describes a second stage of neuronal proliferation/pruning that coincides with final stages of puberty (Tanner stages 4 and 5), reinforcing the view that different parts of the brain mature at different rates through adolescence. Recent research shows that brain maturation is not fully complete until an individual reaches their early 20s, many years after an individual's physical maturation process has finished. Those areas involved with processing sensory information and controlling movement reach maturity first, in early adolescence whilst those areas of the brain responsible for controlling impulses and forward planning are the last to mature (NIMH, 2016). This differential brain development combined with hormonal changes is believed to explain the 'risk-taking' and other challenging behaviour sometimes seen in mid-to-late adolescence (NIMH, 2016).

Theories for the pro-cognitive benefits of swimming training during adolescence

As previously described, exercise has both a chronic (long-term) and acute (lasting only a few hours) effect on the brain (Hamilton and Rhodes, 2016). Immediately after exercising an individual's blood pressure will be raised, their heart rate will be elevated and blood adrenaline levels will be high. It takes some time for these parameters and other biochemical changes brought on by exercise to return to normal. The acute impact of exercise on cognition occurs as a result of short-term effects of these exercise-induced physiological changes on the brain.

The long-term or chronic effects of exercise on cognition are more complex, less well understood, and probably more relevant to adolescent swimmers. Hamilton and Rhodes, (2016) describe that repeated exercise over weeks, months and years leads to substantial cumulative changes in the physiology and morphology of the brain which then takes a significant period of time to reduce after exercise is stopped. Chronic exercise has been demonstrated to enhance cognitive performance in many different areas including executive functioning, pattern recognition, speed of processing and working memory (Voss et al, 2013) through "increasing the total number of granule neurons of the dentate gyrus of the hippocampus" and through neuroplasticity (van Praag et al, 2016). Recent research into how regular intense exercise such as swimming produces both acute and chronic cognitive benefit on adolescents can be grouped into six main hypotheses. These are described below in increasing order of their likelihood of them having an impact on the cognition of adolescent swimmers.

1. Cerebrovascular Reserve theory

This hypothesis is based on the ability of cerebral blood flow to increase from the cerebral reserve in response to chemical stimuli from increased metabolic demand (Davenport et al, 2012). As we age, dysfunctions in cerebral blood flow and vasculature are observed including increased blood pressure, increased oxidative stress, and vascular stiffening (Grace et al, 2015) which impacts on the ability of the cerebrovascular reserve to deliver an enhanced local blood flow at times of demand. Regular exercise helps protect against these age related vascular changes, preserving the ability of the cerebral vasculature to react to demand. The cerebrovascular reserve theory can be discounted as providing any cognitive benefit to adolescent swimmers as it is associated with protection of cognitive function from age related decline rather than the enhancement of cognition in the young (Hillman et al, 2008).

2. Cardiovascular Fitness theory

This hypothesis is based on the premise that good cardiovascular/aerobic fitness produces improved oxygen transport to the brain. This improved oxygen transport to the brain subsequently supports enhanced metabolism in the brain and improved neurotransmitter function, which subsequently produces cognitive benefit (Dustman et al., 1990). This hypothesis has lost much support over the last decade. Etnier et al, (2006) published a meta-analysis of the relationship between levels of fitness and levels of cognition and found no evidence of any correlation between the two. Voss (2016) states that support for the concept of cardiorespiratory fitness being responsible for cognitive enhancement is mixed with further research being needed to ascertain whether or not fitness in itself has a direct impact on the brain.

Ando, (2016) disagrees however and states that alterations in cerebral blood flow/oxygenation are "not directly associated with changes in cognitive function during exercise".

3. Early years swimming lessons

Jorgensen, (2013a) published results of a study into the linguistic, social, cognitive, and physical benefits of swimming lessons for Australian children aged three to five years. Circa 7,000 parental survey responses detailing achievement of young swimmer's developmental milestones were analysed. A subset of 177 swimmers were also subjected to independently performed tests to assess for any bias in the survey responses. A "considerable difference" was found between children participating in regular swimming lessons and the population in achievement of a range of developmental milestones. Young swimmers achieved milestones much earlier than the wider population, regardless of their socio-economic background or gender. The milestones included not just physical development, as previously reported by Sigmundsson and Hodges, (2010), but also cognitive and language skills milestones. Swimmers were found to be between six and twelve months ahead of the norm in physical skills, cognitive skills, mathematics, language development, counting and the ability to follow instructions (p>0.001). The results of the independently-tested children confirmed the results of the parent reporting through the survey, but not as strongly. The areas in which young swimmers were found to have enhanced development were considered by the authors to be the key skills utilised in "formal education contexts" which they believe may give swimmers a "considerable advantage" as they start their academic studies.

Jorgensen (2013a) concludes that "swim lessons offer considerable potential to add capital to young people" through exposing young children to "new experiences that extend their repertoire of skills, knowledge and dispositions". Swimming children performed less well than the non-swimming population in only one area - object manipulation, specifically ball- handling skills. Jorgensen, (2013b) explored in more detail the advantage in numeracy/mathematics that the young swimmers have over their peers, suggesting that this may be due to mathematical concepts being used in swimming lessons such as counting to 3 (or 10 depending on age/ability), linkages between counts and actions, general mathematical language, and timing. Whilst this research relates to swimming lessons rather than training, and to a younger population than we are interested in, the Nuffield Foundation, (2015) describes "growing evidence that the development of both cognitive and non-cognitive skills in the early years are important in……[achieving] later outcomes for children". Therefore, there may be some residual benefit for adolescent swimmers due to the early years' cognitive benefit gained from swimming lessons. Pesce and Ben Soussan, (2016) demonstrated that exercising and cognitive tasks combined, as happens in swimming lessons and later in swimming training, produce an enhanced beneficial effect in cognitive functioning and learning for young people. On the basis of their results, Jorgensen (2013a) recommends that swimming lessons should be considered for children who are finding entry to schooling challenging as this may enhance their skills for transition to school.

4. Motor Fitness theory

The motor fitness hypothesis proposes that some of the cognitive benefits of physical exercise are "derived from the increased experience-dependant plasticity of the motor system" (Voss, 2016). This brain plasticity results from the high degree of motor co-ordination and postural control required to participate at a competitive level in sports such as swimming. Voelcker-Rehlage et al, (2013), state that achieving enhanced motor co-ordination requires significant higher-level neuro-processing, the achievement of which stimulates neuroplasticity through synaptogenesis and angiogenesis in the hippocampus, thus producing a wider cognitive benefit. Historically, movement and cognition were thought to be controlled by entirely separate cortical regions of the brain (Hackney et al, 2016). Domellof et al, (2011) were the first authors to suggest that the neural systems serving motor and cognitive functions overlapped. Oddie and Bland, (1998) demonstrated a close correlation between neuronal activity in the hippocampus and the intensity of muscular contractions. They demonstrated that the pattern of neuronal activity linked to exercise is different to that which occurs when a new task is being learned, suggesting that that there may be two separate functions for the hippocampus: one connected with memory and learning, and the other with "generating or sensing intense movements". According to Hamilton and Rhodes, (2016) the numbers of cells in the hippocampus involved in memory and learning is small and sparsely distributed compared to the number of cells in the hippocampus that are activated when exercising. These authors hypothesise that exercise-induced hippocampal neurogenesis may therefore primarily enable the brain to support the intensity of exercise with secondary benefits manifesting in cognitive ability.

Hamilton and Rhodes, (2016) describe it as "strange and intriguing that exercise which…. does not involve huge amounts of learning and memory acutely activates the hippocampus and results in such profound neuroanatomical, biochemical and physiological changes". Researchers in Parkinson's Disease have identified that increased bradykinesia (a reliable clinical measure of the nigrostriatal lesion in Parkinson's Disease) is associated with cognitive impairment and reduced executive function (Poletti et al, 2012). Although this research does not demonstrate that motor fitness benefits cognition, it does show a close linkage between these two functions by demonstrating that motor function impairment may also result in cognitive impairment, thus supporting the premise of this theory.

5. Psychological aspects

Many authors consider sport and exercise to have a major positive impact on the psychological and psychosocial development and mental health of children and young people, especially adolescents. Five factors known to impact on psychological and psychosocial development are particularly relevant to adolescent swimmers: self-affirmation through success and team/peer relationships; compliance with rules and discipline and Freudian theory; stress management; Piaget's Development Theory; and sleep patterns.

i. Self-affirmation, success and relationships

Robbins, (1983) describes self-image as having four dimensions – self-consciousness (the accuracy of an individual's perception of themselves), perceived self (does an individual's perceptions of themselves match others' perceptions of them), stability (how important or valuable does an individual believe their contributions in a given situation to be), and self-esteem (the general feeling that individuals have about themselves).

Adolescents are able to boost all four of these dimensions through regular participation in sport such as swimming (Loewus-Deitch, 2015). Daley and Leahy, (2003) describe adolescent sport participation as a "self-affirming behaviour" with personal achievement, mastery of skills, and performance, all allowing the adolescent to gain self-assurance. Weiss and Duncan, (1992) describe a correlation between competence in sport and peer acceptance with Feldman and Matjasko, (2005) confirming that athletes have much larger friendship groups than non-athletes. Roseth et at, (2008) demonstrated a close correlation between strong peer relationships and academic achievement, with McCabe et al, (1991) stating that participation in sport allows adolescents to engage intimately with a peer group in a team context with these enhanced interpersonal experiences giving adolescent athletes a "huge" psychological advantage compared to those who don't participate in sport. Being a member of a sports team or squad is believed by McCabe et al, (1991) to reduce the likelihood of adolescents to simply focus on their own individual perspectives, thoughts and feelings and increase their likelihood to rely more on others' views, perspectives and opinions. Feldman and Matjasko, (2005) state that involvement in sports such as competitive swimming allows adolescents an enhanced opportunity to adopt values and norms, to explore personal preferences, to interact on a regular basis with peers, to identify with role models, and to expand their social group to include people that they may not otherwise interact with (e.g. older adolescents) which can speed up their process of psychological maturation. According to Olhoff, (1996), this early "social competence" seen in adolescent sports-participants is a better predictor of success and health in later life than either IQ or academic qualifications.

ii. Freudian theory, Rules and Discipline

Freud's psychosexual development theory describes three personality concepts (id, ego, and superego) around which are based stages of psychosexual development (Heffner, 2000). Freud describes children as being born with only an id – an instinct based purely on achieving pleasure and avoiding pain. The ego develops in the first 3-4 years of life when understanding others' needs and desires starts to influence behaviour, i.e. it's not all about self. The superego develops by about age 6. Superego is concerned with morals and restraint, with ethics developing later – or about what is right and what is wrong. The ego has a balancing role between the id and the superego (Heffner, 2000). Competing and training in swimming is described by Turp, (2007) as having a key role in reinforcing and developing the role and awareness by an individual of their ego. Competitive swimming training and competition are recognised as being highly structured environments with high levels of both self- and imposed discipline and well-defined rules. Turp, (2007) explored the impact of this type of environment on the psychological development of adolescents, concluding that through participating in competitive sport and regular training, adolescents are directly faced with the "reality principle" on a regular basis, and therefore become much more aware of their ego. This increased awareness of ego leads to a suppression of perceptions of invincibility and omnipotence in adolescent swimmers, and a greater awareness of actual physical limitations compared to those who do not regularly participate in competitive sport. This results in a reduction in risk-taking behaviour in adolescent swimmers which may manifest as them being better disciplined and better behaved in the school setting (Turp, 2007).

Weatherill and Fromme, (2007) found, however, that some late-adolescent contact sports competitors in the USA demonstrated a reversal of the early and mid-adolescence reduction in risk-taking behaviours with unsafe sex, multiple sexual partners and substance misuse becoming more common than in the age and gender matched general population. Weatherill and Fromme, (2007), suggest that this may be due to an over-done reduction in an individual's perceptions of perceived risk resulting from years of receiving 'preferred status' from their peers and teachers, including less punishment for misdemeanours and special tutoring opportunities. These findings have not been widely repeated outside the USA, or outside contact sports, so this may be a US High School culture-specific, or sport- specific phenomenon.

iii. Stress

If, as described above, adolescent competitive swimmers have stronger and larger friendship groups and a greater level of self-awareness, confidence, self-esteem and self-assurance than their peers, it is likely that their psychological stress levels are also lower than their peers. Although outside the scope of this report, much has also been published about endorphin release as a result of exercise and its effect on reducing stress levels (Yeung, 1996). Sapolsky, (2003) describes that stress negatively affects thought-processing and has a negative effect on both the volume and plasticity of the hippocampus. Therefore, stress-reduction caused by regular exercise in our adolescent swimmers may guard against any detrimental impact of stress on cognition. Participation in a competitive sport can of course increase stress levels (e.g. on the day of a big race), but this form of stress is typically short-lived (i.e. until the start of the race) and is not "enduring stress", described by Sapolsky as causing negative effects on cognition.

iv. Piaget's Development Theory

In the mid-1930's, Piaget proposed a theoretical model for cognitive development from childhood through adolescence to adulthood (Piaget, 1936). This theory is based on the premise that humans, as they gain experience of the world around them, uncover and store patterns which allows for better future acquisition and use of knowledge (Huitt and Hummel, 2003). Piaget's theory comprises four distinct stages of development, but it is only the last of these four stages, the "Formal Operational" stage, which is relevant to adolescent swimmers. This stage covers individuals between the age of 11 and adulthood (Evans, 1973). The Formal Operational stage is when abstract thinking and more complex problem-solving using hypothetical premises is developed. McLeod, (2010) considers this to be the most significant step in cognitive development as "imagination and inferential reasoning" allows individuals to consider how various actions might affect an outcome, to explore mathematical and logical arguments, to create hypotheses, and to develop the ability to isolate variables, allowing determination of cause and effect. Kuhn, (2006) found that only about 30-35% of high school students in the US ever reach the Formal Operational level. In the Formal Operational stage, participation in sport is described by Robbins, (1983) as an "optimal cognitive development opportunity", allowing adolescents an opportunity to develop their enhanced cognitive thinking. In swimming, an example would be that individuals have to think strategically (e.g. pacing a race) whilst exercising, and at the same time being constrained by specific technique and competition rules. Enhancing progression through the Formal Operational stage of cognitive development may produce an academic benefit as adolescent swimmers may be able to grasp hypothetical concepts and mathematical/logical arguments either earlier or to a greater extent than their peers.

v. Sleep

Lack of sleep and poor quality sleep is known to have a negative effect on cognitive abilities. The US National Institutes of Health (NIH) published a report in the late 1990s exploring the lack of quality sleep in most adolescents resulting in their "permanent state of sleepiness" which is associated with negative mood, poor productivity, reduced short-term memory and reduced learning ability (NHLBI-NIH, 1997). Durmer and Dinges, (2005) describe that proper sleep patterns are required to allow the brain to consolidate memories and to memorise activities and Curcio et al, (2006) describe a correlation between lack of sleep and academic performance in adolescents. Adolescent swimmers may however be protected from many of these sleep problems. Yeung, (1996) states that exercise induced brain endorphins reduce stress levels and enhance sleep quality with Brand et al, (2010) identifying that chronic vigorous exercise in adolescents produces a significantly positive effect on both the quality and quantity of sleep, especially in males. Although relating to adults rather than adolescents, the National Sleep Foundation found that regular swimmers reported significantly better sleep patterns, including how long it takes to go to sleep and more unbroken sleep, than seen in the wider population (National Sleep Foundation, 2013). It seems highly likely therefore that swimming training is having a beneficial impact on the quality of sleep in adolescent swimmers, avoiding the negative cognitive effects of poor sleep described in the wider adolescent population.

6. Neurochemical theories

By far the greatest number of publications in recent years concerning the exercise-cognition interaction (both acute and chronic) are in the area of neurochemical impact on the brain. Several neurochemical theories have been proposed for how exercise-induced cognitive benefit occurs including: Catecholamine hypothesis (acute effect); Hypothalamic-Pituitary-Adrenal (HPA) and Hypothalamic-Pituitary-Gonadal (HPG) axis hormones (acute effect); and Brain-Derived Neurotrophic Factor (BDNF)/other factor-induced effect (chronic effect) (McMorris et al, 2016).

a. The catecholamine hypothesis/RAH Theory

The catecholamine hypothesis was proposed by Cooper, (1973) to explain the acute effect of exercise on cognition. Cooper suggested that circulating catecholamines produced by exercise cross the blood-brain barrier, increasing dopamine and noradrenaline levels in the brain which in turn activates the reticular formation, affecting alertness, excitation and arousal. Mason et al, (1973) identified that immediately before and during exercise, the sympathoadrenal system (SAS) is activated by the hypothalamus and brainstem resulting in catecholamines being released at postganglionic cells of neurones to activate or inhibit these as required. Green et al, (1982) found low levels of plasma catecholamines present with low level and low intensity exercise but an exponential rise in circulating levels of noradrenaline and adrenaline with exercise intensity. Podolin et al, (1991) described the threshold TCATS at which a significant rise in plasma adrenaline and noradrenaline concentrations are seen as being at an exercise intensity of approximately 75% V02MAX.

Hodgetts et al, (1991) demonstrated a negligible rise in plasma catecholamines at 30% V02MAX, even over prolonged periods (up to four hours exercising) but demonstrated that moderate intensity exercise (40-75% V02MAX) over 30 minutes triggered a rise in levels. In summary: low intensity exercise of any duration produces little or no increase in circulating catecholamines, but high intensity exercise over any time period, and medium intensity exercise over more than 30 minutes produces high levels of plasma adrenaline and noradrenaline. Cooper's 1973 theory that circulating catecholamines produced during exercise cross the blood-brain barrier is now believed to be inaccurate. Miyashita and Williams, (2006), state that the mechanism is now believed to be that circulating noradrenaline and adrenaline activate β-adrenoceptors on the afferent vagus nerve which in turn stimulates noradrenaline and dopamine synthesis in the brain. There is also considered to be a second pathway involving the autonomic nervous system stimulating the hypothalamus, reticular formation and limbic system, also resulting in brain catecholamine synthesis and release. This second system is associated with the "fight or flight" response (Sothmann, 1991). The fact that circulating catecholamines do not cross the blood-brain barrier in humans makes assessment of brain catecholamine levels difficult and research into brain catecholamine levels in animals during and post exercise have been very inconsistent. Kitaoka, (2010) found increased hypothalamic concentrations of noradrenaline during exercise but Goekint (2012) found no increase. The same inconsistencies were found for brain dopamine levels. These inconsistencies may be due to two factors. Firstly, Hattori et al, (1994) found that exercise needed to be of a moderate level or above to raise brain dopamine levels and many research protocols used a wide variety of exercise frequency, intensity and duration. Secondly, Bailey et al, (1993) found that brain concentrations of dopamine fell back to resting levels once fatigue was reached.

Davis et al, (2000), believe this to be due to an interaction between dopamine and 5-hydroxytryptamine (5-HT) which shows high concentration at fatigue. The hypothetical process is that dopamine is produced through the decarboxylation of L-DOPA (3,4-dihydroxy-L-phenylalanine) which requires aromatic amino acid decarboxylase (AADC). AADC is however also required to convert 5-hydroxytryptophan (5-HTP) into 5-HT. Frazer and Hensler, (1999) state that following heavy exercise of long duration, physiological conditions favour the finite amounts of AADC being used for the decarboxylation of 5-HTP rather than L-DOPA, resulting in reduced dopamine levels. Audiffren, (2016) describes the mechanisms behind how noradrenaline and dopamine are released in response to exercise and subsequently act on the brain, as described below.

Noradrenaline is released by the locus coeruleus, part of the brain stem with axons reaching into the hippocampus and neocortex. Niewenhuis et al, (2005) describe two different "activity modes" that cause this release of noradrenaline – tonic and phasic. Tonic release is stimulated by exercise and is prolonged whilst phasic release is short-lived and occurs in response to novel stressful or exciting situations. Noradrenaline is believed to produce its cognitive benefits by binding to adrenergic receptors where it reduces noise levels in the brain by stopping irrelevant/unnecessary signal processing, thus improving alertness and arousal. Noradrenaline is also known to have a significant role in energy modulation in the brain by controlling glycogen levels in astrocytes, increasing glucose availability to the brain (Berridge et al, 2003).

The effects of dopamine are more complex and less well understood. Three separate brain systems are believed to utilise dopamine produced in response to exercise - the nigrostriatal, mesolimbic, and mesocortical systems. As with noradrenaline, dopamine production also exhibits tonic and phasic release. Nigrostriatal dopamine is believed to enhance motor system readiness and response preparation (Robbins and Everitt, 1995), mesocortical dopamine enhances working memory and cognitive control (Floresco and Magyar, 2006), and also interacts in the reward and motivational processes (Robbins and Everitt, 1995). McMorris et al, (2016) in a review of the evidence for the catecholamine hypothesis concluded that on balance, there is support for acute exercise increasing brain noradrenaline and dopamine concentrations with resultant benefits for cognition, but that more research is needed in this area.

b. Reticular-Activating Hypofrontality (RAH) Theory

The RAH model of acute cognitive enhancement was first described by Dietrich and Audiffren, (2011) and is a variation of the catecholamine theory. This theory suggests that two separate mechanisms are activated by exercise, with a combined effect. Firstly, as the brain structures essential to maintain exercise are activated, those brain structures not needed to support motor activity are deactivated. This leads to a reduction in activity in the prefrontal cortex and in executive functions. At the same time, the increased noradrenaline and dopamine levels produce enhanced sensory and motor processes, and have a detrimental effect on prefrontal functions – see Figure 5 below.

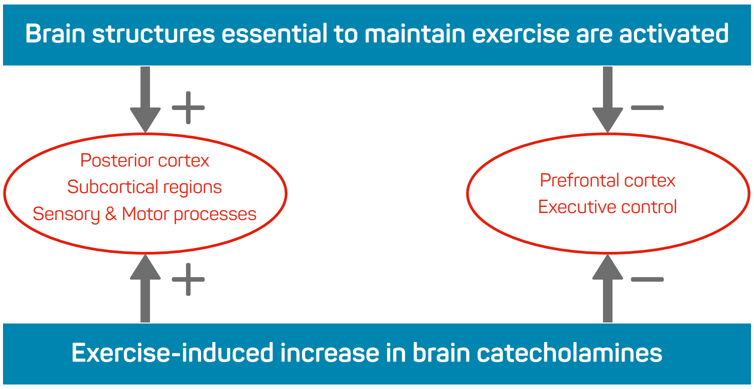

Figure 5: Reticular Activating Hypofrontality Theory (from Audiffren, 2016)

c. Hypothalamic-Pituitary-Adrenal (HPA) and Hypothalamic-Pituitary-Gonadal (HPG) Axis Hormones

This hypothesis suggests that raised cortisol and testosterone levels as a result of exercise cause changes in the brain impacting on cognition. Exercise above a certain intensity, and psychological stress, are both known to activate the Hypothalamic-Pituitary-Adrenal (HPA) and Hypothalamic-Pituitary-Gonadal (HPG) axes. As Figure 6 (below) shows, this results in the hypothalamus producing corticotrophin-releasing hormone (CRH), arginine vasopressin (AVP), and gonadotrophin-releasing hormone (GnRH). These hormones act on the anterior pituitary gland with CRH and AVP causing secretion of adrenocorticotrophic hormone (ACTH) (HPA axis), and GnRH causing secretion of gonadotrophins including luteinising hormone (LH) and follicle stimulating hormone (FSH) (HPG axis). ACTH acts on the adrenal gland causing the production of cortisol which is the end point of the HPA axis stimulation and is known to be able to cross the blood-brain barrier. LH and FSH stimulate the gonads to produce testosterone and oestrogen which are the end points of the HPG axis (Koutsandreou et al, 2016). These authors describe a positive association between acute exercise, HPA and HPG axis hormones and improved acute cognition. The mechanisms behind how cortisol and testosterone may affect cognition have some similarities, but also some differences:

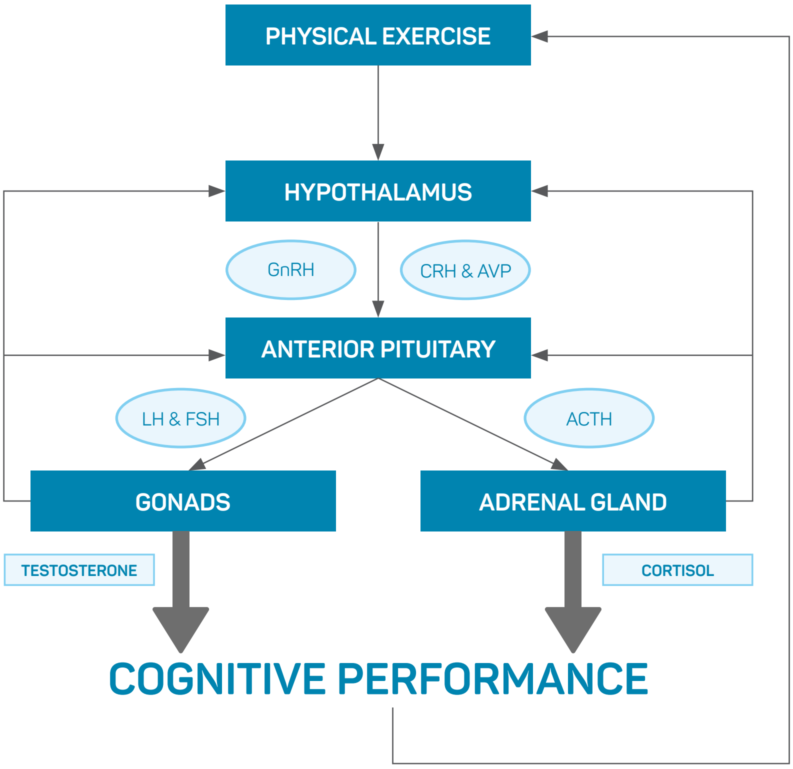

Figure 6: HPA and HPG axis activation pathways in response to physical exercise. (Modified from Wegner et al, 2012).

Cortisol - Heffelfinger and Newcomer, (2001), describe that cells in the cerebellum, neocortex and hippocampus all contain multiple cortisol receptor sites. When these receptors bind to cortisol, they are believed to affect cognition by enhancing the Long Term Potentiation process (Erickson et al, 2003). Lupien et al, (2005) demonstrated an inverted 'U'-shaped graph when cognition is plotted against cortisol levels in late adolescents/young adults. These authors believe this is due to there being two types of binding sites with different physiological mechanisms behind how they bind cortisol. One type of receptor (glucocorticoid receptors) bind cortisol with lower affinity than the other (mineralocorticoid receptors), and therefore at lower concentrations of cortisol, the glucocorticoid receptors remain unbound. As all the mineralocorticoid receptors bind cortisol (i.e. as cortisol levels increase to moderate levels), cortisol then starts to bind to the glucocorticoid receptors.

Blair et al, (2005) demonstrated that as the amount of cortisol binding to the glucocorticoid receptors increases beyond a certain point, this results in "synaptic depression" which is thought to have a negative effect on memory. Low and high levels of cortisol in the brain therefore have either no effect or a negative acute effect on cognition whilst medium levels of cortisol have a positive acute effect (Heffelfinger and Newcomer, 2001). As previously discussed, exercise above a certain intensity and duration is necessary for the production of cortisol. Hackney et al, (2011) identified that for adolescents, intensity levels need to be above 60% V02MAX for a minimum of 10-15 minutes for cortisol levels to rise. Wegner et al, (2014) identified that exercising for 15 minutes at "medium intensity" (65-75% HRMAX) did not raise saliva cortisol levels in 14yr old adolescents. Although adolescents have been considered as a single cohort to date, Di Liugi et al, (2006) identified that early and mid-adolescents (Tanner stages 1-3) showed higher cortisol levels following 90 minutes of exercise than later adolescents (Tanner stages 4 and 5). Benitez-Sillero et al, (2009), also identified a difference in cortisol production between "high-fitness" adolescents such as our competitive swimmers who produced more cortisol after exercise than "average-fit" adolescents.

Testosterone - The acute effect of testosterone on cognition is less clear. Some studies have shown that a moderate increase in testosterone causes enhanced cognition, others that high levels of testosterone "impair spatial awareness", some that there is no relationship between testosterone and cognition, while others found a clear linear relationship. Given the absence of clear evidence, the suggested mechanism by which cognitive benefits from testosterone accrue can only be speculative. (Koutsandreou et al, 2016). Testosterone is known to bind to androgen receptors that are mainly found in the pre-frontal cortex and the hippocampus of the brain (Janowsky, 2006).

As previously described, these are the main areas of the brain responsible for memory and learning. Heemers and Tindall, (2007) describe testosterone binding to, and activating, the androgen receptor-complex in the brain resulting in up- or down-regulation of specific gene transcription. Up-regulation produces increased mRNA production which, following ribosomal translation, results in the production of specific proteins – e.g. for synaptogenesis. A second testosterone-cognition theory is that the enzyme aromatase, which is found in the hippocampus, converts testosterone to oestradiol which binds to oestradiol receptors in the hippocampus (Roselli et al, 2001). Similarly to cortisol, testosterone production occurs once a certain intensity-time threshold for exercise is passed, but this threshold is lower for testosterone than for cortisol (Koutsandreou et al, 2016). Budde et al, (2010) found that in 15-16 year olds, 12 minutes of exercise at 75-85% HRMAX produced an increase in testosterone levels, but not in previously inactive adolescents. The change in testosterone levels (pre to post-exercise) showed no gender differences (Budde et al, 2010).

d. Neurogenesis

Yau et al, (2016), describe the human brain as having the ability to "show structural and functional changes in response to environmental and experiential demands". Neurogenesis is an example of brain plasticity involving "the production of new neurons in the brain and integration into the existing Central Nervous System (CNS) circuitry throughout the [human] life span". Molina-Navarro et al (2016), describe neurogenesis as a continuation of the process of embryonic neurogenesis, but occurring only in specific regions of the brain. Altman (1962) identified the specific regions involved using radioactive thiamine as being the ventricular-subventricular zone of the forebrain and the sub-granular zone of the dentate gyrus of the hippocampus.

Kaplan, (1985), built on Altman's work by undertaking electron microscopy of these potential neurogenic sites and confirming neurogenesis in the hippocampus, the olfactory bulb, and the visual cortex. As previously described, the hippocampus is located in the medial temporal zone of the brain. According to Anderson, (2007) the hippocampus is the region of the brain where unique representations and memories are created as a result of the merging and mapping of sensory modalities. The critical role of the hippocampus in learning and memory was demonstrated by a well-known neurosurgical case (H.M.) recently re-reviewed by Augustinack et al, (2014). H.M. suffered from severe epilepsy and underwent a bilateral medial temporal lobectomy in an attempt to cure his fitting. This procedure resulted in H.M.'s total inability to commit any new events to memory whilst his previous memories remained unimpaired.

Moderate regular aerobic exercise such as swimming was demonstrated by Erickson and Kramer, (2008) to affect the physiology and morphology of many areas of the brain including increasing the volume and density of both the hippocampus and prefrontal cortex through neurogenesis. Herting and Nagel, (2012) explored this concept further, specifically in adolescents, and found clear correlation between cardiovascular fitness and hippocampal volume as a result of neurogenesis. The first to prove the link between hippocampal neurogenesis and learning were Burd and Nottebohm, (1985). These authors used electron microscopy techniques to identify the formation of synaptic terminals on newly formed neurons in birds. Using electro-physiology techniques, they identified integration of these new neurons into existing brain circuitry and a subsequent impact on functionality and learning. Hippocampal neurogenesis is believed to be the most significant in terms of cognitive benefit due to the critical role the hippocampus plays in memory and learning (Anderson, 2007).

It is impossible to evaluate neurogenesis using histological techniques in humans, except at post-mortem. The neuro-generative effect of exercise has, however, been demonstrated histologically in adolescent rats (Helfer et al, 2009), who showed that 12 days of forced running produced a significant number of new cells in the dentate gyrus of the hippocampus compared to a cohort of rats that did not exercise. The precise mechanisms behind why and how exercise causes hippocampal neuroplasticity and neurogenesis remains unknown (Hamilton and Rhodes, 2016), although several hypotheses exist and significant amounts of research are underway.

Brain Derived Neurotrophic Factor (BDNF) and other growth factors

BDNF plays a major role in neurogenesis and neuroplasticity, alongside a number of other proteins including insulin-like growth factor (IGF-1), fibroblast growth factor (FGF-2), and vascular endothelial growth factor (VEGF) (Cotman et al, 2007). Pareja-Galeano et al, (2015) also describe Nerve Growth Factor (NGF) as having a role in cerebral neurogenesis. Barde et al, (1982) were the first authors to isolate BDNF from brain tissue. Some thirteen years later, Rosenfeld et al, (1995) identified BDNF in serum and demonstrated a correlation between serum BDNF and BDNF levels in the brain. BDNF acts by binding to a high-affinity receptor (TrkB) in the brain where it stimulates "neuron sprouting and neural reorganisation". BDNF has also been demonstrated to support the "survival, growth and maintenance" of many different types of neurons including hippocampal cells (Huang and Reichardt, 2001). BDNF is known to be stored adjacent to synapses and is released as part of the hypothalamic response to exercise (Rothman et al, 2012).

Several studies have described increased serum concentration of BDNF in response to acute exercise including Ferris et al, (2007), although some have also shown no increase in BDNF following exercise, (Zoladz et al, 2008). McMorris et al, (2016) suggest that this variance may once again be due to differences in exercise intensity and duration between the studies. Ferris et al, (2007), showed that 30 minutes of cycling at 20% below TCATS had no effect on circulating BDNF levels, yet 30 minutes cycling at 10% above TCATS produced significantly raised serum BDNF levels. Peripheral and central IGF-1, FGF-2, VEGF and NGF production is also stimulated by exercise (Cotman et al, 2007). These growth factors work either alone, or in conjunction with BDNF to stimulate neurogenesis and neuroplasticity (Pajera-Galeano et al, 2015). VEGF has two roles relevant to neurogenesis. Firstly, it is believed to change the permeability of the blood-brain barrier allowing hormones (such as IGF-1 and FGF-2) to cross into the brain. Secondly, when necessary (i.e. when brain oxygen levels fall), VEGF stimulates angiogenesis in the brain, improving blood flow and therefore oxygen supply (Cotman et al, 2007). IGF-1 is released by active muscles and works in conjunction with insulin to deliver glucose to muscles as well as crossing the blood-brain barrier where it has a potent neuroplasticity effect on the brain (Dyer et al, 2016). The uptake of IGF-1 by the brain is facilitated by BDNF causing neurons to produce serotonin and glutamate, as well as stimulating the production of BDNF receptors on the neuron. These additional BDNF receptors then enhance the process of Long Term Potentiation to consolidate memories and learning. Ratey and Hagerman, (2013) suggest that this process goes back to the days of humans as hunter-gatherers where a linkage between exercise (i.e. hunting animals for food) and learning/remembering where and how to find and kill these animals was critical to survival. Figure 5 (below) modified from Cotman et al, (2007) describes the action of Growth Factors on the brain.

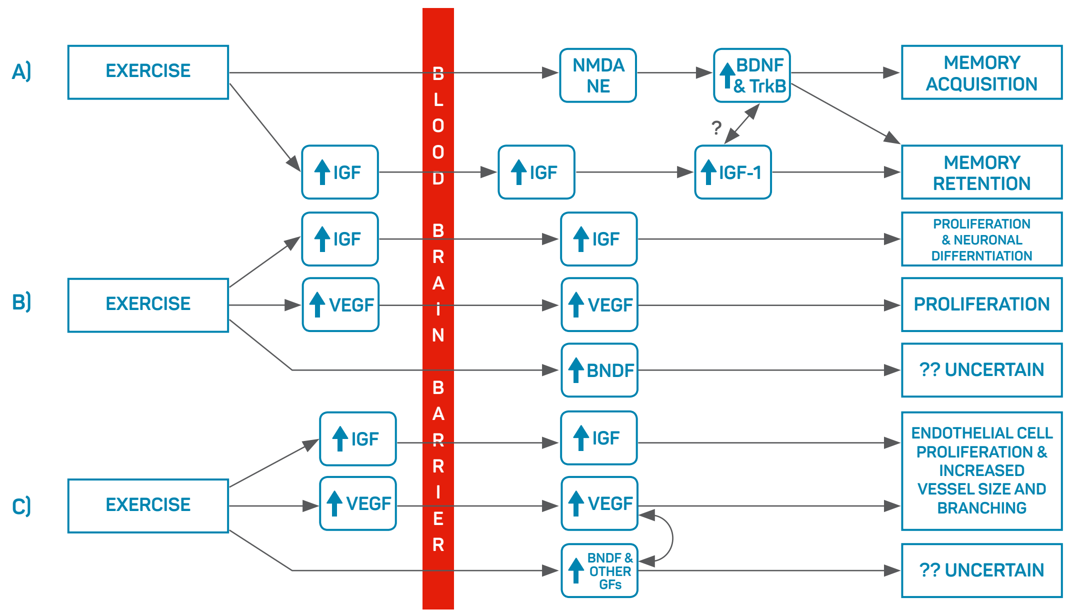

Figure 7: Exercise and Growth Factors (modified from Cotman et al, 2007)

Circulating FGF-2 levels are also increased during exercise and cross the blood-brain barrier where it is believed to have a critical role in neurogenesis. NGF is also released within the brain by the newly formed brain cells and has a key role in the differentiation and growth of neurons in both the peripheral and central nervous system (Holtzman and Mobley, 1994).

Swimming training and special populations of adolescents

Much has been published about the neuro-cognitive benefits of exercise for people with a range of long-term conditions including Parkinson's Disease, ADHD, Alzheimer's Disease, Breast Cancer, Type II Diabetes, Obesity, and Heart Failure (McMorris (Ed), 2016). Many of these conditions fall outside the scope of this report as they do not typically affect adolescent swimmers. However, the cognitive impact of exercise in adolescents who are obese or suffer from Attention Deficit Hyperactivity Disorder (ADHD) may be relevant.

a. Attention Deficit Hyperactivity Disorder

O'Neill et al, (2016) define ADHD as a neurodevelopmental disorder in which individuals display elevated levels of inattention, impulsive behaviour and hyperactivity. ADHD has both an environmental and a genetic linkage with a heritability estimate of 0.76. Several genes have been identified as increasing the risk of ADHD (Faraone et al, 2005). Visser et al, (2014) estimate that 11% of American adolescents have received a diagnosis of ADHD, with Polanczyk et al (2014) suggesting that the global prevalence is about 5%, making it one of the most prevalent disorders of childhood (O'Neill et al, 2016). Although neuroanatomical differences have been identified between those with ADHD and the wider population, reduced levels of brain catecholamine are believed to play a key role in this disorder (Minzenberg, 2012).

Swimming could therefore offer a non-pharmacological approach to managing ADHD due to its proven role in raising acute levels of brain catecholamines and other exercise-induced benefits. Swimming is often a sport of choice for people with ADHD. For example, Michael Phelps took up swimming following a diagnosis of ADHD at age 11 (Diller, 2016).

O'Neill et al, (2016) state that young people with ADHD display a range of other impaired "neural factors" such as "executive functions (inhibitory control), processing speed, motor persistence, and academic achievement" all of which can be positively affected by exercise through many of the pathways and factors already discussed. Several authors including Hoza et al, (2014) evaluated the benefit of chronic exercise on ADHD symptoms in children (rated by self, parents and teachers). Only one of the many published studies failed to find any benefit from chronic exercise. O'Neill et al, (2016) conclude that when considered together, these studies provide evidence that young people with ADHD show "improvement in core ADHD symptoms and in social functioning", including cognition and academic performance following regular exercise. These authors stress that more research is needed into the type, intensity and duration of exercise needed to provide benefit as well as any exercise-pharmacological interaction.

b. Obese adolescents

Although it could be considered to be outside the scope of this review (as trained competitive swimmers are not obese), the impact of obesity on cognition and the potential corrective effects of exercise has been included as research in this area reinforces the link between physical fitness and cognition. Swimming training may also be a route for obese adolescents to improve their fitness and their cognitive function. Adolescent obesity has tripled in the US between 1980 and 2011 (Ogden at al, 2014). Davis and Cooper, (2011) demonstrated a clear correlation between being overweight/obese and reduced cognition/academic performance in children. Whilst this is an interesting and controversial finding, it is difficult to unpick cause and effect.

For example, is the obesity linked to lack of exercise when we know that exercise has a positive effect on cognition, or was the reduction in cognitive functioning due to weight/adiposity having a direct effect on cognition? (Bustamante et al, 2015). Davis et al, (2015) compared measures of cognition between the following different age/gender/socioeconomic matched groups: active normal weight; sedentary normal weight; and sedentary obese children. Obese sedentary children scored much lower on measures of cognition than active normal weight children, particularly in measures of complex executive function. A specific difference was noted between the scores for both active and sedentary normal weight children, and the scores for obese children in measures of attention. Earlier research from Davis and Cooper, (2011) does however suggest that a having a lower executive function, especially inhibition, to start with might lead to obesity as a result of overindulgence and unhealthy lifestyles.

How much exercise produces cognitive benefit?

In 2008, the US Federal Physical Activity Guidelines Committee posed the question "Do the effects [cognitive benefits] of physical activity vary according to features of the physical activity, including type, intensity, or timing (i.e. session duration, weekly frequency, and length of participation)?" (US Department of Health and Human Services, 2008). To date there appears to be no clear evidence-based answer to this question for adolescents. In obese children, a study identified a linear relationship between increasing activity and performance in mathematics tests and executive function (Davis et al, 2011), however the transferability of this to non-obese populations remains unproven. Concern has also been expressed that other factors in the Davis study (including behavioural incentives, adult contact, social interaction etc.) may have produced bias in the data.

We do however have information from research detailed previously that may address this question. Moderate but not excessive exercise produces the highest levels of brain dopamine (Hattori et al, 1994); exercise needs to be at an intensity of 75% HRMAX for at least 15 minutes for cortisol and testosterone levels to rise (Koutsandreou et al, 2016); and BDNF and other neurotrophic factors are produced after 30 minutes of moderate and above exercise (Ferris et al, 2007). Moderate exercise for at least 30 minutes on a regular basis therefore produces optimal conditions for inducing cognitive benefit on both a short and long-term basis. Swimming training intensity, duration and frequency for adolescent competitive swimmers is typically delivered as recommended by both the UK Long Term Athlete Development Pathway for swimmers (Lang & Light, 2010), and the Australian Swimming Development Model (Richards, 1997). A typical adolescent competitive swimmer (aged 12-18) will swim train between 5-20 hours per week over 3-6 days (8-50 km swimming per week). Although all energy systems are trained by competitive swimmers, in excess of 75% of their pool training will be aerobic at around 50-75% HRMAX, or in the moderate band described above. In addition, most swimmers will also undertake some form of 'land training'. Although it seems impossible on the basis of currently available evidence to produce a dose-response curve, the volume, intensity and frequency of the exercise being undertaken by our adolescent swimmers will almost certainly be delivering the maximum benefit for cognitive function.

Ratey and Hagerman, (2013) believe, on the basis of their literature review, that the maximum cognitive benefit of exercise is achieved by undertaking "some form of aerobic exercise" for a minimum of 45-60 minutes per day on 6 days of the week, with some high intensity exercise included on at least 2 days per week. This exercise profile also correlates closely with the training our adolescent swimmers undertake. These authors add an additional 'rule of thumb', that the better your fitness level, the better your brain works.

Without question, adolescent competitive swimmers can be considered to be extremely fit as a result of their intense training regime. Neuroscientists will undoubtable continue to research the exercise-cognition dose-response curve issue, but on the basis of the current evidence it seems that swimmers are gaining the maximum benefit.

Cause and Effect?

One factor not yet discussed is whether people who have greater cognitive ability or who have better self-discipline are attracted to competitive swimming as a sport thus creating a skewed population of "high performing" and "hard-working" students that the headmaster referred to – i.e. swimming training is not causing the effect seen, rather that these individuals are choosing swimming as a sport as a result of their personality type. Consideration of the role of psychology in an individual's choice of sport goes back over 125 years. Dudley, (1888) described "the mental qualities of the athlete" as being a key factor in their success. More recently, Raglin and Hale, (2006) describe the influence of psychology in sport as being very complex with a massive array of variables such as established personality traits and transient psychological states both interacting with each other and acting independently causing a huge amount of "contradiction and confusion" regarding the impact of pre-disposing psychological factors on participation in a given sport. Personality is defined by Spielberger et al, (1983) as "enduring……specifiable tendencies to perceive the world in a certain way and in dispositions to react or behave in a specified manner".

Research by Morgan, (1985) explored the personality traits in a variety of athletes, including swimmers and concluded that successful athletes tended to be less introverted, suffer from less depression, neuroticism and trait anxiety than both unsuccessful athletes and the wider population. Cause and effect was however not addressed in this study.

All these traits are factors that could be influenced by either the physiological impact of exercise on the brain or the psychological aspects of greater self-affirmation through sport participation (as previously discussed). Although difficult to undertake, there is a significant gap in the literature for a longitudinal study of personality traits at a young age (IE pre any effect of exercise) and later participation and success in sport.

Discussion

It seems clear that "the benefits of chronic exercise on learning, academic success and working memory are overwhelming" (McMorris, 2016). Hamilton and Rhodes, (2016) are also clear that "exercise clearly.....promote[s] enhanced cognitive function" in both the short and long-term. Whilst other ways to improve specific cognitive performance through 'brain training' are known (e.g. regularly solving Sudoku puzzles may result in you becoming good at Sudoku), these do not produce the wider transferrable cognitive benefits that exercise such as swimming produces (Redick et al, 2013). The pro-cognitive effects of exercise are both short and long-term. The short-term effect of exercise on cognitive functioning lasts for between 1 and 3 hours post exercise and is derived from exercise induced physiological and biochemical changes, mainly liked to the concept of enhanced arousal, and predominantly associated with the speed and accuracy of task processing rather than memory and learning. This is an important point for adolescent swimmers as many may stop training for a period before important exams to help prepare, including on the day of the exam itself - when in fact an early swimming morning training session may be beneficial. Kim et al, (2013), also demonstrated that sudden cessation of exercise in regularly exercised mice results in a transient decline of brain function, specifically in short-term memory and spatial learning. The observed decline was to levels below the baseline for the control (non-exercising group). These transient effects are believed to last for several weeks, again reinforcing the view that sudden cessation of training to prepare for exams may be completely the wrong strategy. The long-term effects of exercise on cognition accrue due to a number of factors including exercise induced neurogenesis and neuroplasticity in the brain, especially in the hippocampus, which produces enhanced executive functions, learning and cognition.

There still remain, however, a number of areas in which the evidence for any benefit, or the mechanism behind how the benefit accrues remains inconclusive, including what are the specific cognitive benefits of exercise to adolescents as opposed to mature adults or children? This question remains difficult to answer as the physiological changes to the brain associated with development are immense and will interact with any exercise induced effects. More studies are critical to allow us to fully understand the exercise-cognition pathways in adolescents. Adolescent participation in competitive swimming has also been demonstrated to have significant psychological benefits that may impact on academic performance. When compared to non-athlete peers, adolescent athletes tend to be more grounded and focussed, have enhanced self-esteem, and self-confidence and better social networks. These enhanced traits support the headmaster's hypothesis that adolescent swimmers are "hard-working", due to their increased psychological and psycho-social maturity. The evidence that swimming training and competition provides an "optimal cognitive development opportunity" (Robbins, 1983) for adolescents to progress more quickly through Piaget's Formal Operational stage is strong. This enhanced progression allows the development of complex problem-solving abilities and the ability to hypothesis, both of which are key skills in an academic environment.

The long-term effects of early year's benefit from swimming may also play a factor in the cognitive abilities of adolescent swimmers. The vast majority of competitive swimmers will have learnt to swim in early childhood and will have gained the linguistic, social, cognitive and physical benefits that are described by Jorgenson, (2013a). These early year's benefits have been described as producing benefits many years later, i.e. in adolescence (Nuffield Foundation, 2015).

How much exercise and how often to gain cognitive benefit remains unclear. Although this question has no definitive answer in the literature, it is clear that adolescent swimmers who are training at even the minimum recommended levels will be significantly exceeding the reported thresholds for frequency and duration to produce cognitive benefit. Those thresholds that have been described suggest that benefits accrue from moderate intensity exercise on a regular basis for a minimum of 30 minutes at a time or, according to Ratey and Hagerman, (2013), the maximum cognitive benefit comes from undertaking aerobic exercise for a minimum of 45-60 minutes per day on 6 days of the week, with some high intensity exercise included on at least 2 days per week.

Conclusion

The overwhelming majority of the reviewed literature supports there being cognitive benefits accruing from competitive swimming training in adolescents. These exercise-cognition benefits are both short and long term, and accrue through a multiplicity of mechanisms. The volume and type of exercise that our adolescent swimmers are undertaking exceeds all the suggested thresholds for the cognitive benefits to accrue. Additional psychological and psycho-social benefits also accrue for adolescent swimmers from being part of the squad/participating in competitive swimming.

The headmaster's hypothesis that adolescent "*competitive swimmers.....are all hard-working and perform highly academically*" would seem to be strongly supported by the evidence.

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