From Department of Clinical Neuroscience
Karolinska Institutet, Stockholm, Sweden

EXECUTIVE FUNCTIONS AND SUCCESSFUL BEHAVIOR

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Stockholm 2021

Published by Karolinska Institutet.
Printed by Universitetsservice US-AB, 2021

ISBN 978-91-8016-244-9
Cover illustration: By Sofie Violett Pehrsson. The image is a painting using Monet's color palette by Frank Gehry's wiggle stool. Both Monet and Gehry highlight the importance of limitations for increased creativity, one of the themes of this project. Doesn't the chair resemble the brain?

Executive Functions and Successful Behavior

THESIS FOR DOCTORAL DEGREE (Ph.D.)

By

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The thesis will be defended in public at Karolinska Institutet, Stockholm, 3rd of September 2021

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To my beloved wife and all my inspiring children

POPULAR SCIENCE SUMMARY OF THE THESIS

Natural selection sometimes paraphrased as "Survival of the fittest" is a cornerstone in the theory of evolution. An important aspect of survival throughout evolution is the ability to adapt to the demands of constantly changing or novel environments. Such adaptation is associated with a more dynamic behavior and seems to be especially prominent in primates. A key component for human primates to meet these demands on adaptive behavior is self-regulation. Humans need to be successful in the competition with other species and with other humans in order to survive. Evolution seems to have favored the development of cognitive processes that are involved in self-regulation.

Self-regulation on a behavioral level should be mirrored in top-down regulatory mechanisms on an information processing level. Thus, the capacity of such cognitive regulation should be essential in order to accomplish different goals in a constantly changing environment. Especially when the flow of information is fast it becomes crucial that the brain has the ability to quickly regulate information processing.

The underlying functions of self-regulation are called executive functions. This umbrella term describes the top-down cognitive processes that control human thoughts and behaviors particularly in non-routine circumstances. Executive functions are involved in selecting stimuli that are attended to and in sustaining such attention as well as in cognitive flexibility and inhibition of an action or a thought. These cognitive processes are also important for problem solving and the ability to deal with novelty. Executive functions can be defined as mechanisms underlying self-governing actions necessary to select goals and to create and maintain actions to reach these goals. The basic principle behind this self-regulation theory is that executive functions have developed in the human species because of the need to survive and succeed in a constantly changing environment. Therefore, it may be argued that executive functions are particularly important in unfamiliar situations or quickly changing environments where previously learned behavior is not enough or even inappropriate to achieve the final goal. By orchestrating information processing and combining past experiences with the present situation, executive functions optimize our behavior.

Based on the idea that self-regulation is an important cognitive process in order to achieve a goal in quickly changing environments, the more general hypothesis for this project was that the capacity of the executive functions underlies successful behavior in such contexts. The aim of this project was to clarify the relation between executive functions and successful behaviors within several different contexts involving change and novelty in different age groups. We therefore hypothesized that individuals that are successful in situations that require dynamic adaptation have higher capacity of executive functions especially in terms of more complex executive functions as well as cognitive flexibility.

In the project, executive functions capacity was investigated in three different areas that included soccer, elite police forces and average occupational life in a mid-sized company. In three studies, male and female soccer players of different ages and different levels of play (semi-elite, elite, and national team levels) were assessed. In the fourth study, a police cohort was tested consisting of applicants for a police special forces unit and police officer trainees. In the last study a cohort consisting of forklift operators, sellers, operational managers and strategic managers were tested.

The results from the soccer studies showed that the capacity of executive functions, especially cognitive flexibility and creative fluency, correlated with successful soccer behavior, indexed by number of scored goals and made assists. Similar results were observed for junior and senior players as well as for players in lower divisions and those on the highest elite level. The results also showed that the capacity of executive functions and cognitive flexibility was in general higher for elite players than semi-elite players as well as for national team players compared to other elite players. Moreover, rated game intelligence, i.e., a general excellence in play, by the coaches correlated with the players' executive functions capacity. Finally, in the last study, cognitive flexibility and creative fluency correlated negatively with days of sick leave measured for the previous five years. This suggests that executive functions and cognitive flexibility may be of importance not only in quickly changing environments but also in ordinary life.

The conclusion of the project is that executive functions in general and cognitive flexibility specifically are of importance for successful behaviors in a quickly changing environment but also in everyday life. However, the results don't show if this correlation rested on innate individual differences or whether they merely are an effect of training. In order to better understand causality, longitudinal studies are needed where changes of executive functions are assessed in detail. Long term cooperation with soccer academies, where their players are followed from childhood to adulthood would make this possible. In regards to the special forces, it is of essence to better understand what happens with executive functions in stressful environments. Moreover, it is of interest to understand how executive functions affects risky behaviors and optimal outcomes. Finally, more research on the relationship between cognitive flexibility and sick leave could give a better understanding of how to minimize sick leave and allow people a healthier life.

ABSTRACT

Executive functions are the underlying mechanisms that drive top-down regulation of information processing. While suboptimal executive functions have been investigated in various groups of patients, their impact and contribution to behavioral success have not been clarified. It has been suggested that executive functions can be divided into simple executive functions, sometimes referred to as core executive functions, and more complex executive functions often involving other cognitive components referred to as higher order executive functions. Several cohorts of healthy individuals (in total 324 individuals) were investigated in five separate studies (**Study I-V**) to better understand how higher order executive functions are associated with successful human behavior.

Due to its similarity to evolutionary conserved behaviors that depend on well-developed executive functions, including cognitive flexibility and creative fluency, and as well as due to its global impact, soccer was chosen for the three first studies. Soccer is practiced in a strictly controlled area with clear and common rules all around the world. It involves fast problem solving with the aim to reach the same goal in different ways. Soccer is also played by individuals of both sexes of widely different ages and has a shared understanding of how success is defined by both professionals and the audience. Soccer is therefore a good research arena to better understand how executive functions impact human behavior in constantly changing environments where individuals act as free agents but with a common goal and specific restrictions.

Study I suggested that elite soccer players show significantly higher executive functions capacity than players on semi-elite level as well as compared to norms of the test. This result was conceptually repeated in **Study III,** in which national team players were compared with elite players from the same soccer clubs that had never been selected to play in national teams. The difference was especially evident when studying cognitive flexibility and creative fluency using the Design Fluency Test suggesting a better capacity for behavior adjustment. Moreover, this executive functions capacity was related to the number of scored goals and/or made assists under a prolonged measured period. Finally, cognitive flexibility correlated significantly on a moderate level with coach-rated game intelligence, i.e. the players' ability to "read the game", to anticipate the intentions of the opposite player and use that information to make successful decisions and actions.

The main results from **Study I** and **III** were also shown for junior academy players, age range twelve to nineteen years, in **Study II**. Working memory (a core executive functions) had the most prominent role, suggesting a relation of the results to the maturation of the brain. Both core and higher order EF, but not IQ-measurements, significantly correlated on a moderate level with the number of scored goals the players made during two sessions.

The next step was to assess the involvement of higher order executive functions in other non-sport situations where similar cognitive functions also may have a decisive role for success. **Study IV** showed that applicants for the Swedish counterterror intervention unit (Nationella Insatsstyrkan) had significantly better results in Design Fluency Test compared to average of the population and to police officer trainees mirroring the difference in level of play in soccer. Moreover, following the baseline tests, the applicants were re-tested after significant physical and psychological stress. The results showed that their re-test results declined compared to the expected result. However, there was still a significant correlation between the baseline results and the re-test results, indicating that higher capacity of executive functions could work as a resilience factor and safeguard adequate decision-making under stress.

Finally, in **Study V**, different occupations in a medium sized company including forklift operators, sellers, operational and strategic managers were studied. The results showed that the capacity of cognitive flexibility and fluent creativity (both on a perceptual and a verbal level) correlated negatively with the amount of sick leave for the previous five years. The results remained after controlling for age, work group, sex, and other different cognitive components. Since we adjusted for work group, education and socio-economic factors, these did likely not explain the results.

All together this thesis suggests that higher order of executive functions are important factors for success in several human behaviors and occupations. The results may need independent replication but this research project offers novel insights into how EF capacity is associated with behavioral success and that executive functions may represent a resilience factor to stress.

LIST OF SCIENTIFIC PAPERS

I. **Torbjörn Vestberg**, Roland Gustafson, Liselotte Maurex, Martin Ingvar, & Predrag Petrovic (2012). Executive functions predict the success of top-soccer players. *PLOS ONE* [1].

II. **Torbjörn Vestberg**, Gustaf Reinebo, Liselotte Maurex, Martin Ingvar, & Predrag Petrovic (2017). Core executive functions are associated with success in young elite soccer players. *PLOS ONE* [2].

III. **Torbjörn Vestberg**, Reza Jafari, Rita Almeida, Liselotte Maurex, Martin Ingvar, & Predrag Petrovic (2020). Level of play and coach-rated game intelligence are related to performance on Design Fluency in elite soccer players. *Scientific Reports* [3].

IV. **Torbjörn Vestberg***, Peter G. Tedeholm*, Martin Ingvar, Agneta C. Larsson, & Predrag Petrovic (2021). Executive functions of Swedish Counterterror Intervention Unit applicants and police officer trainees evaluated with Design Fluency test. *Frontiers in Psyhology* [4]. *co-first authors.

V. **Torbjörn Vestberg**, Henrik B. Jacobsen, Mats Lekander, Liselotte Maurex, Martin Ingvar, & Predrag Petrovic (2021). Executive function measures of cognitive flexibility are associated with days of sick leave. *Ready for submission* [5].

CONTENTS

LIST OF ABBREVIATIONS

ANCOVA	Analysis of Covariance
ADHD	Attention Deficit and Hyperactivity Disorder
ANOVA	Analysis of Variance
CEF	Core Executive Functions
CS	CogState Computerized Concussion Testing
CWI	Color Word Interference Test
DF	Design Fluency
D-KEFS	Delis-Kaplan Executive Function System Test Battery
dWM	Demanding Working Memory
HD	Higher Division
HEF	Higher Order of Executive Functions
IQ	Intelligence quotient
LD	Lower Division
M	Mean
NI	Nationella Insatsstyrkan (The Swedish Counterterror Intervention Unit)
NTP	National Team Players
PLP	Premier League Players
POT	Police Officer Trainee
SD	Standard Deviation
TMT	Trail Making Test
VF	Verbal Fluency
WM	Working Memory

1 INTRODUCTION

1.1 SURVIVAL OF THE FITTEST AND SELF-REGULATION

"Survival of the fittest", a concept created by Herbert Spencer, [6, 7] and adapted by Charles Darwin to describe the natural selection and the evolutionary theory, is sometimes confused with the assumption that "the strongest survive". However, when it comes to behavior, evolution is not solely about simple strength, physical power or speed. Instead, evolution is also about adaptation and the ability to adjust to the demands of constantly changing or novel environments. These factors, associated with a more dynamic behavior, seem to be especially important in mammals [8]. A key component for human primates to meet these demands is self-regulation [9]. Humans need to be successful in the competition with other species and humans in order to survive in such environments. Cognitive processes that are involved in self-regulation have therefore been favored in evolution [9].

One evolutionary important behavior involving a large amount of fast dynamic adaptions is hunting. Species that hunt in a group, including humans and other primates, often give each other different roles in the chase of a prey. Apart from the prey, each hunter needs to keep track of the position, behavior and intention of their hunting partners and adapt to the rest of the group. Previous experiences stored in long-term memory and future anticipated possibilities combine in working memory and are used in the ongoing operation. When something unexpected happens, the hunters have to stop their ongoing behavior and change tactics. In order to do so, they use inhibition and flexible adjustment but also fluent creativity. However, because of the environmental constraints, creativity needs to take the limitation of the context into account. Given the speed in a hunt, the information load per minute is high, increasing the demands on self-regulation. The hunters' dynamic and fast adaptation continues until they succeed to kill the prey. If they don´t succeed, their herd will perish. Thus, hunting in a group involves several cognitive self-regulatory processes that have been favored by evolution.

Evolution has driven the development of the brain in mammals, and particularly in primates [10]. It has, for example, influenced the size, volume and connectivity of the brain. In primates and humans, especially the prefrontal cortex - associated with flexible behavior and quick adaption, the ability to follow long term goals instead of immediate rewards, as well as with high complexity of social cooperation - has developed extensively throughout evolution [10]. In line with this, the prefrontal cortex seems to be related to how sophisticated and successfully different species of primates are able to cooperate in order to collect food and in their fight for survival [11-13].

Larger brain size also correlates with longer time for the brain to mature [14]. The maturation of the frontal lobes is especially slow in humans, and associated with learning how to collect food, how to protect the herd and to cooperate with other individuals for successful outcomes

[14] - behaviors that involve self-regulation [9]. However, the extended development period also puts a lot of pressure on the species, due to the demands for more protection and support of the offspring, as well as because young individuals do not participate in the survival of the group [15]. Another problem with a larger brain is that it requires more energy due to higher metabolic demands [16]. Despite these costs, evolution seems to prefer well-developed frontal lobes, which are related to delayed rewards and high ability of adjustment in social animals that live in changing environments.

1.2 CAPACITY OF TOP-DOWN REGULATION

Self-regulation on a behavioral level should be mirrored in top-down regulatory mechanisms on an information processing level. Thus, the capacity of such cognitive regulation should be essential to accomplish different goals in a constantly changing environment. Especially when the flow of information is fast, it becomes important that the brain has the ability to quickly regulate information processing.

Cognitive neuroscience has for decades focused on cognitive control and top-down regulation of information processing which give guidance to thoughts and actions to achieve desired goals [17]. The ability to use cognitive control is dependent both on genetics and on learning history [18]. It has been suggested that the capacity for information processing is normally distributed in the population for various different cognitive core functions, e.g. executive functions and their cognitive components [18] – see Figure 1 A. A low capacity may lead to functional disabilities. Such cognitive core capacities are mirrored in dimensionally distributed symptoms from the subclinical range to dysfunction – see Figure 1 B. ADHD-associated symptoms have such a normal distribution in the population [19] as indicated by Adult ADHD Self-Report Scale [20] – see Figure 2. The approach to study the full spectrum of a cognitive core capacity from variability within the healthy population to dysfunction is in line with the research domain criteria (RDoC) framework [21].

The information processing capacity in different domains will affect how effectively we solve problems, regulate our behavior and thoughts as well as our social relations. In other words, the cognitive capacities will determine how we function in life. For example, weak capacity in cognitive processes related to top-down regulation, may result in functional loss in a wide range of behaviors such as the ability to stay in focus, evaluate a behavior, inhibit a non-successful behavior, change direction of a behavior, etc. As mentioned above, it has been suggested that cognitive core capacity of such higher order regulation is directly related to the degree of ADHD symptom [18] and seems to correlate with employment status and financial situation of the individual [19]. Similarly, the capacity to regulate emotions is related to the degree of emotional instability symptoms in a dimensional way and may translate to clinical disorders such as borderline and antisocial personality disorder when the dysregulation leads to a functional loss [18]. However, the focus of this project is not the left tail of the core capacity but the right tail of this distribution for executive functions (i.e. above normal range) and how it relates to behavior.

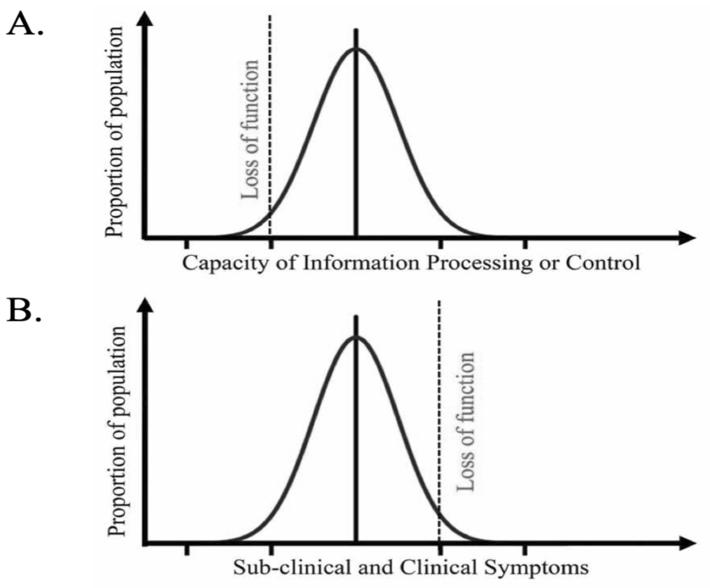

Figure 1. The cognitive core capacities theory. **A**. The normal distribution of cognitive core capacities. **B**. Cognitive core capacities are mirrored in dimensionally distributed symptoms from the subclinical range to dysfunction. Reprinted from *Top-Down Dysregulation — From ADHD to Emotional Instability*, Petrovic & Castellanos, (2016) [18]. Copyright©2016 with permission from Frontiers in Behavioral Neuroscience.

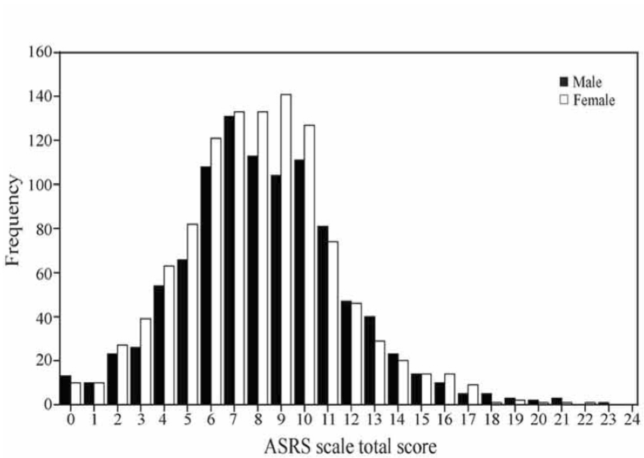

Figure 2. ADHD-associated symptoms and its normal distribution in the population. Reprinted from *Population-Based Study of Attention Deficit/Hyperactivity Disorder Symptoms and Associated Impairment in Middle-Aged Adults,* Das et al., (2012) [19]. Copyright©2012 with permission from PLOS ONE.

2 LITERATURE REVIEW

2.1 EXECUTIVE FUNCTIONS

The underlying mechanisms of behavioral and cognitive control are called executive functions (EF) [18, 22, 23]. This umbrella term describes the top-down cognitive processes that control human thoughts and behaviors particularly in non-routine circumstances [22-24]. EF are involved in selecting stimuli that are attended to and in sustaining such attention. EF also involve cognitive flexibility and inhibition of an action or a thought. Problem solving and the ability to deal with novelty are also included in EF [23, 25-27]. EF can be defined as mechanisms underlying self-governing actions necessary to select goals and to create and maintain actions to reach these goals [28]. The basic principle behind this self-regulation theory is that EF have developed in the human species because of the need to survive and succeed in a constantly changing environment [28]. Therefore, it may be argued that EF are particularly important in unfamiliar situations or quickly varying environments where previously learned behavior is not enough or inappropriate to achieve the final goal. By orchestrating information processing and combining past experiences with the present situation, EF optimize our behavior [17]. It has been suggested that the different EF show a pattern of both shared and distinct functions with large interindividual differences that are highly heritable at the latent level [29].

2.1.1 Core and Higher order of Executive functions

Executive Functions may be separated into *Core Executive functions* (CEF) and *Higher-order Executive functions* (HEF) [23, 30]. Inhibitory control, a part of the working memory (updating) and cognitive flexibility have been defined as CEF [23, 29, 31]. EF involved in more complex processes such as planning, reasoning, and problem solving, have been defined as HEF [23, 32]. Another way to emphasis the differences between CEF and HEF is to focus on the degree of difficulty of a task [30]. Keeping data on-line during simple decision-making is more closely linked to CEF (for example short term memory). However, manipulation of information with a purpose to reach a specific goal is more closely related to HEF.

2.1.2 Core Executive functions

2.1.2.1 Inhibition

Inhibition or interference regulation refers to the capacity to control thoughts, emotions, and behaviors, by overcoming internal processes or external distractions that may interfere with the main intention and goal [33, 34]. Inhibition involves suppression of learned behavioral responses that would not be successful in a given context [23, 33]. This also includes cognitive inhibition of thoughts and memories that may interfere with the goal directed behavior or problem solution. Inhibition supports top-down and goal driven behaviors by suppressing irrelevant information processing with the purpose of fulfilling a decided action [23, 35, 36]. Self-control is another term that involves inhibition through resisting temptations and not acting impulsively, in relation to what is expected of us [23, 35, 36].

2.1.2.2 Working memory

Working memory (WM) maintains information which no longer is present in one's perception [23]. Like short-term memory, WM is limited and temporary. There is no clear definition that separates short term-memory and WM [37] and they often overlap in the literature [37]. However, the concept of short-term memory is more commonly used when the purpose is to describe the process of temporarily storing information. The term WM is more commonly used when the focus is on the process to manipulate the temporarily stored information [38]. WM supports complex cognitive operations in reasoning associated with better understanding, learning and decision-making [29, 39, 40]. WM can be divided into a nonverbal (visual-spatial) and a verbal part [23, 41]. According to classical models of WM first described by Alan Baddeley, the visuo-spatial-sketchpad and a phonological loop are supported by an episodic buffer, a multimodal storage which integrates information into uniform representations [39, 41, 42]. It has been suggested that these subsystems are controlled by a central executive component [39]. This central executive is responsible for enabling manipulation of the information in WM, incorporating content of working memory to long-term memory (and vice versa), and protecting information in WM from other irrelevant processes [42]. In essence, although WM often is regarded as an EF, it may be argued that only specific aspects of WM, such as the central executive, belong to the core EF.

2.1.2.3 Cognitive flexibility

Cognitive flexibility (sometimes also denoted as cognitive shifting, mental flexibility or set shifting) has been suggested to be a CEF and refers to the capacity to mentally alternate between rules and tasks, as well as go back and forth between tasks, strategies, mental sets, or actions [23, 29, 43]. It is associated with the ability to adapt to changing requirements and is often regarded as the opposite of rigidity. Cognitive flexibility is related to the ability to alter views or methods to handle a situation, as well as being able to adjust to shifting difficulties, new procedures, or priorities [23]. It has been suggested that there is an overlap between cognitive flexibility and creativity [23].

Psychological flexibility is a psychological construct emphasized in several therapies such as acceptance commitment therapy, ACT [44-46]. Psychological flexibility relates to how flexible behavior an individual can use to adapt to the demands of different activities such as work and social interaction and is often assessed by self-report questionnaires [46]. Although the association between cognitive and psychological flexibility has been discussed [47] the relation has not been explored. EF and cognitive flexibility have also been suggested to be important components in other psychological models such as metacognitive theory [48], resilience, [49, 50], and locus of control [51].

2.1.3 Higher order of Executive functions

While CEF are defined by different specific cognitive abilities, HEF are defined by a combination of the different CEF abilities used simultaneously in planning, reasoning, and problem-solving in order to achieve a goal [23]. HEF are built on CEF that are required to resolve the most complex situations [52]. HEF promotes new behaviors when needed, by integrating reasoning, learning, and creative abilities in order to adapt and achieve a more successful outcome [53].

2.1.4 Executive functions and Fluid intelligence

Historically, Raymond Cattell [54], divided human intelligence in two components, *fluid intelligence* and *crystallized intelligence.* Fluid intelligence is the inherited capacity to solve reasoning problems that an individual has not been exposed to previously. Crystallized intelligence is the capacity to use previously learned knowledge to solve problems. It has been suggested that HEF and fluid intelligence are one of the same [23]. However, results from EF-tests correlate only to some degree with results from fluid intelligence tests [55-57] and more particularly when it comes to updating and working memory [24, 29, 58]. Tests of fluid intelligence like Raven's Progressive Matrices do not capture all capacities that are related to executive functions [59]. There is a more consistent view about crystalized intelligence in that the relations with EF are weak [55-57].

2.1.5 Executive function, General Mental Ability and IQ

IQ and/or General Mental Ability (*g*) are closely related to the theory of fluid intelligence and crystalized intelligence and are only weakly linked to EF [22, 24, 60-62]. General Mental Ability (*g*) is a concept created by Charles Spearman to capture and measure the cognitive capacity of humans [63]. The definition of *g* is broad and related to the capacity of reasoning, problem solving, decision-making, and higher order of cognitive skills [64]. However, since the concept is not well defined, it is also not clear which cognitive tests capture *g* [65]. General Mental Ability seems to be more related to the dimension it is used in (e.g. the industrial and organizational domain) than specific cognitive aspects measured by different cognitive tests. Studies have shown that common EF-factors that are included in working memory and cognitive flexibility (e.g. inhibition) only share 25% of its variance with *g*. *g* is also linked to a distinctive variance in working memory, also suggesting that EF and *g* differ [29]. An analysis with perceptual speed in focus likewise suggested that the EF factors were independent from cognitive speed [22].

Intelligence quotient, (IQ) is the average standard score based on results from a number of different tests included in a standardized test battery made to assess intelligence. An often used IQ test-battery is Wechsler Adult Intelligence Scale [66]. It measures the cognitive capacity in four dimensions: Verbal comprehension, Perceptual Reasoning, Working memory, and Processing speed [67]. Relationship between IQ and EF abilities, like inhibition, cognitive flexibility, and fluent creativity are generally low [32] and are the same across different age groups and sex. While IQ tests seem to capture knowledge associated with memorization technique based on repetition related to verbal and mathematical facts, executive function tests are more related to capturing open skills such as abstract thinking and problem solving [32]. IQ and EF represent such different cognitive domains that IQ tests cannot be used to measure an individual's full capacity for abstract thinking, planning, and execution [32]. However, some aspects of IQ (such as WM) and EF overlap extensively.

2.1.6 Executive Functions and Creativity

In order to reach a goal in a constantly changing environment, it is beneficial to have a working memory that makes it possible to analyze the present situation and compare it with earlier experiences. Inhibition of inappropriate behavior and flexibility allowing for a quick change of behavior when the initially anticipated outcome fails is also necessary. However, it is not sufficient with only such cognitive abilities. Instead, creativity involving the production of new ideas is also crucial for achieving many goals, especially in an unpredictable environment. Although, not the main aspect of creativity, the EF components discussed above play an important role in successful creative behavior [58, 68, 69]. Cognitive flexibility seems to be a stronger predictor for creativity than crystallized or fluid intelligence [58].

2.1.6.1 Creativity

Creativity may be defined as the capacity to construct original and valuable ideas in problem solving, as well as for developing processes and products [70, 71]. Creativity can be divided into divergent and convergent creativity [72, 73]. Divergent creativity involves the ability to search through information in different directions for multiple or alternative answers, and based on this generate novel and often unexpected combination of ideas. Convergent creativity involves the ability to evaluate the information in novel and original ways to reach a specific goal or answer a defined question [74-76]. Divergent creativity correlates strongly with fluency and flexibility [74]. If divergent creativity operates alone there is a risk that the results will be unrealistic [76]. Convergent creativity supports the creativity process by introducing a set of rules or a framework to the production of novel ideas. Limitations force creativity to become more effective through reasoning and execution [74, 76]. Divergent and convergent creativity may work together in order to be successful in a task that has many possible solutions but also has a range of restrictions. While divergent creativity contributes with fluency and originality, convergent creativity contributes with realism and frames.

2.1.6.2 *The importance of frames to promote a creative outcome*

As discussed above creativity seems to benefit from frames, boundaries and constraints, which increase and stimulate a higher level of planning and flexibility [77, 78]. Such rules seem to ease the integration of conflicting schemas and enhances the ability to integrate contradictions, which is proposed to increase creativity [77]. Frames seem to inspire and develop creativity [79, 80]. Frames, boundaries and constraints are essential for increasing creativity in business and entrepreneurship [81]. Great artists like Monet used constraints for the purpose of higher variability. For example, before starting a new painting, he decided which and how many colors he could use [82]. Frank Gehry, one of the most acclaimed architects of the 20th century, particularly recognized for the spectacular Guggenheim Museum and Walt Disney Concert Hall (placed in Bilbao and Los Angeles), talks about constraints and limitations as what really inspire his work [83].

2.1.7 Executive functions and Emotional regulation

It has been suggested that higher order emotional regulation resembles EF on a processing and behavioral level [18]. Both the non-emotional and emotional dimensions of information processing include several similar cognitive components of higher order control including cognitive conflict and monitoring, as well as behavioral adjustment processes. This can be exemplified in executive function tests that also involve an emotional dimension [84-87]. To separate the non-emotional and emotional variants of EF, they are sometimes divided between "cool" emotional EF and "hot" EF [18, 88-90].

2.1.8 Brain networks, neuromodulatory system and information processing underlying Executive functions

Although large-scale brain networks, consisting of both cortical and subcortical structures, are involved in the executive functions, prefrontal and anterior cingulate cortices have been identified as key structures underlying EF and cognitive control [17, 18, 91, 92]. Organization, reasoning, planning, and model testing with the purpose to predict the best behavior to reach a certain goal, involve functions of prefrontal cortex [92, 93]. Lateral prefrontal cortex is associated with several key aspects of executive behavior control [94]. For example, neurons are activated in lateral prefrontal cortex when selective attention for action takes place [94, 95]. Dorsolateral prefrontal cortex plays a crucial role for holding information on line, keeping focus on relevant data, selecting information and controlling the cognitive processing of the information [95-100]. Settings of rules to reach multiple behavioral goals have also been related to lateral prefrontal cortex [94, 100]. A line of primate and human studies also suggests its involvement in conflict induced behavioral adjustments [101].

Medial prefrontal regions, including the anterior cingulate, are related to the ability to monitor behaviors and initiate behavioral change, set shifting [92, 93]. More specifically, it has been suggested that this region is important in monitoring conflicts between different processes in the brain as well as in registering behavioral errors [86, 101]. Anterior cingulate cortex seems to play an important part when it comes to initiating and motivating actions. It is further involved in inhibition when it comes to controlling conflict related activities and goal-directed behaviors [86, 102].

Medial frontal cortex and lateral frontal cortex work in a network characterized by a mutual exchange of information. Sensorimotor, contextual, and episodic information influence this exchange of information based on motivational significance. The prefrontal cortex is thus important in integrating past experience with present influences in the guidance of goal-related behavior [17].

Top-down control of emotional processes is also dependent on the prefrontal cortex. Emotional behavior and experiences often include a combination of both emotional and non-emotional processes, and therefore the specific regulatory components are hard to disentangle [18]. However, it has been suggested that certain top-down regulatory networks are more related with emotional regulation than non-emotional regulation [18, 103]. For example, lateral orbitofrontal cortex has been suggested to be involved in a wide range of explicit emotional regulations associated with emotional expectation and rule construction including emotional reappraisal [104-106], reversal learning [107, 108], instructed learning [109, 110] and the placebo effect [111-114]. Orbitofrontal cortex is associated with impulse control and to utilized feedback control, important in social adjustment [93]. The rostral anterior cingulate cortex is involved in more implicit regulation of emotional processes [103, 115] including "hot" executive functions [84, 85].

It is important to emphasize that the prefrontal cortex, including anterior cingulate cortex, works in parallel with subcortical brain structures (e.g. basal ganglia) and specific neuromodulatory systems in order to achieve top-down regulation [116, 117]. Both the dopamine and the noradrenaline neuromodulatory systems projecting from the brain stem to these circuits are key components for such regulation [118, 119]. It has for example been suggested that while the noradrenaline system increases signals, the dopamine system decreases noise in prefrontal cortex [118, 119]. Thus, they both contribute to a better signal-to-noise ratio and a dysfunction in these systems may underlie ADHD [119].

2.1.9 Maturation of the brain and of Executive functions

Cross-sectional and prospective longitudinal studies on brain growth, cortical thickness, density, myelination and connectivity between different parts of the brain, show that the prefrontal lobes mature late compared to the rest of the brain [30, 120, 121]. The maturation process starts at the back of the brain to end with the frontal regions - see Figure 3. The frontal lobe maturation begins with the primary motor cortex followed by the superior and inferior frontal gyri, ending up with the prefrontal cortex [120]. The part of the brain involved with bodily movement and sensory experience shifts pattern of gray matter between 4 and 8 years of age [121]. Areas associated to spatial orientation, speech and language do the same between 11 and 13 [121]. The prefrontal cortex, a key area involved in EF processes, does not become fully developed until around the mid-twenties [120, 121] - see Figure 3.

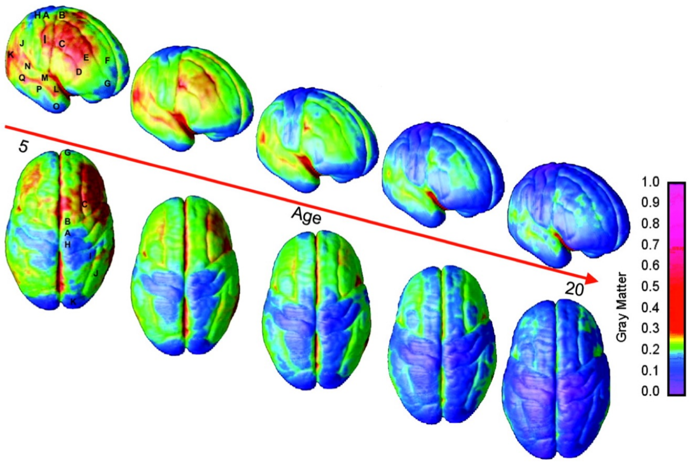

Figure 3. **Brain development.** The period for brain maturation where the prefrontal cortex develops last. Reprinted from *Dynamic mapping of human cortical development during childhood through early adulthood,* Gogtay et al., (2004) [120]. Copyright©2004 with permission from National Acedamy of Science.

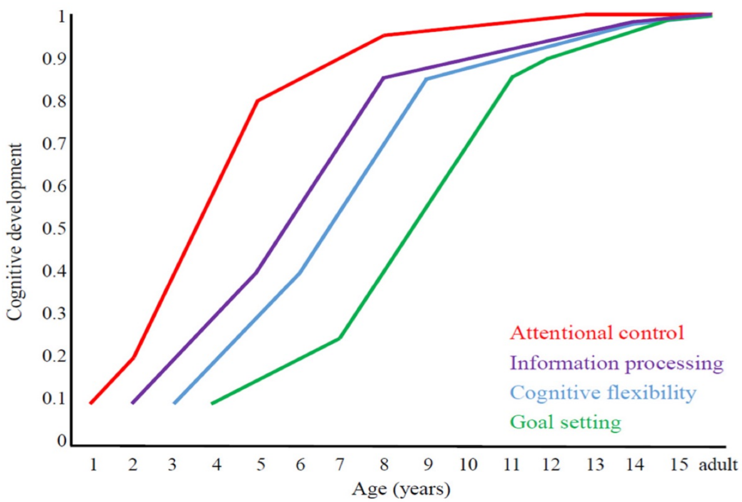

Figure 4. Development of executive functions. Reprinted from *Demystifying cognitive flexibility: Implications for clinical and developmental neuroscience*, Dajani & Uddin, (2015) [122]. Copyright©2015 with permission from Trends in Neurosciences.

Another way of describing brain development suggests that evolutionary older areas of the brain mature earlier than evolutionary younger parts, which constantly integrate information from the evolutionary older brain regions [121]. The human brain matures late when compared to other primates. This is mirrored in a long learning period for cognitive, practical, and social skills, making humans dependent upon others into adulthood [123]. This may be reflected in a higher fluctuating asymmetry of the brain in healthy human individuals compared to chimpanzees [124] indicating a greater level of environmental influence and higher plasticity of the human brain. This hypothesis is strengthened by the lower heritability of the human cortical organization as compared to chimpanzees [125].

In line with the different stages of brain development, EF also evolve gradually for many years and reach full capacity in the mid-twenties, allowing the child to become increasingly self-directed and less dependent on parents and environmental cues [126]. Different EF components have different developmental trajectories where the last functions develop in the late adolescence. In general, more complex cognitive processes develop last [122] - see Figure 4.

Cognitive functions associated with CEF develop during childhood, up through adolescence, to become fully developed at about twenty years of age [30, 31, 43, 127-130]. Cognitive flexibility seems to have the earliest maturation of the three main CEF (inhibition, working memory and cognitive flexibility), and adult capacity of cognitive flexibility is reached between eight and ten years of age [130, 131].

The performance of the working memory appears to be age-related in terms of both the visual and verbal ability [132]. This age-related performance affects the capacity to handle new information as well as retain previously stored information [132]. Working memory seems to develop in a step-by-step fashion. Simple recall of information develops until eleven to twelve years of age [30]. Holding data on line with the purpose to manipulate the information develops up to fifteen years of age [30]. The capacity to use working memory for self-organization related to information of strategic character, seems to develop until sixteen to seventeen years of age [30].

The adult level of inhibitory capacity is reached at fourteen-fifteen years of age [133]. However, childhood capacity of the inhibitory control seems to predict the capacity throughout life [134]. A child's ability to wait for its turn, and stay focused while distracted will in general - after adjusting for IQ, sex, social class and upbringing - persist throughout adolescence until adulthood [134]. If a child has a high capacity of inhibitory control it will likely have a high capacity of inhibitory control through adolescence and as a grown-up [134, 135]. A lower capacity of self-regulation as a child seems also to be lasting up to adulthood [136] especially when it comes to emotional regulation. Development of processing speed and attentional control occurs consistently with the ongoing myelination up to the age of fifteen [130].

Importantly, different CEF support each other [15]. The ability to inhibit interference from competing goals supports working memory capacities, and the ability to stay focused on goal-oriented actions, supports inhibition of irrelevant and distracting information. Because of this, each of the different executive functions are dependent on each other's development to reach their full capacity. Moreover, as HEF includes several CEF, HEF is last to develop fully. Strategic planning and the organization to achieve particular goals, functions related to HEF, appear to reach the peak level in-between twenty and twenty-nine years of age [23, 131].

2.1.10 Are suboptimal executive functions caused by psychiatric and neurological disorders - or are these disorders caused by suboptimal executive functions?

Deficits in EF capacity have been studied in relation to disorders like ADHD, autism, schizophrenia, bipolar disorder, depression, addiction, fetal alcohol spectrum disorder, traumatic brain injury, dementia etc. [137-143]. While weaker EF have been associated with different disorders, the question remains whether the weaker capacity is a consequence of the disorder or vice versa? EF are normally distributed among the general population and disorders like ADHD may be thought of as low EF capacity in this distribution when a functional loss is evident [18, 19, 87, 142, 144] - see also Figure 2. This opens up for the possibility that weaker EF capacity cause the clinical symptoms (at least partially), instead of being a consequence of the disorder. While this is evident for ADHD, it may also be partially true for other psychiatric and neurological disorder. Similarly, high EF capacity could function as a resilience factor by supporting information processing to achieve desired goals and thereby be more successful in specific tasks [87] both for individuals with different disorders and healthy individuals.

This project argues that research on EF capacity performed only in relation to different disorders does not give a full picture of their function and mechanisms. In order to develop a better understanding of EF and their importance for human behavior we also need to study EF in relation to successful behaviors in an environment where EF could play a decisive part of achieving a goal. By focusing on different EF components and the capacity of EF, an individual EF profile would not only be a diagnostic criterion but also provide a basis for more complex interventions and compensatory strategies in various life domains. This idea is in line with precision medicine in psychiatry [145] where treatment is tailored to the individual patient. A better understanding of the full spectra of EF would give new insights into how to help society to develop pedagogy, therapy and counseling based on individual cognitive profiles.

3 RESEARCH AIMS

Based on the idea that self-regulation is an important cognitive process in quickly changing environments, through evolution as well as in modern society, the main hypothesis for this project was that the capacity of the executive functions underlies successful behavior in such contexts. The aim of this project was to clarify the relation between EF and successful behaviors within several different domains involving change and novelty in different age groups.

A main hypothesis of the present thesis was that individuals that are successful in situations that require dynamic adaptation have different EF profiles compared to the average of the population, involving higher capacity of HEF and cognitive flexibility. Due to the maturation of EF, the optimal cognitive profile for successful behavior would be different in children compared to adults in that CEF should have a stronger impact than HEF in younger individuals. Another hypothesis was that increased ability of behavioral adaptation is also associated with increased resilience against stress and sickness.

3.1 CHOICE OF RESEARCH POPULATIONS

In order to investigate whether EF have a positive relation with successful behaviors in contexts that require adaption, this project included three different populations.

3.1.1 Soccer

Team sports, such as soccer, are in several ways similar to key behaviors that have developed throughout evolution in herds that hunt. Both situations involve fast behaviors in groups. Like the hunters, the soccer players cooperate in specific roles to reach an important goal. Moreover, in both situations the information input is large, and they change quickly. Thus, the need for a fast behavioral adjustment is obvious. Finally, both have a well-defined and highly desired goal with the behavior.

It may also be argued that soccer players comprise a good study population for understanding behaviors that requires adaption due to the highly controlled environment within the game, namely the limitation of the number of participants, the length of the match, the frames of the soccer field and rules defining what the players are allowed to do. At the same time, the players act as freely moving agents that take initiatives which can surprise the opponent. Success in soccer is well defined by goals and assists, and there is no uncertainty about which team has won. The game is played by both sexes, in all ages and all over the world. Moreover, the participants are often in physical and mental stress that puts their cognition and EF capacity under heavy pressure. Such frames are reminiscent of the test conditions that successfully have been used in experimental animal studies that include spatial and temporal restricted conditions [146, 147]. This further underlies the idea that soccer is a good choice for studying human behaviors in more detail.

Importantly, the same cognitive processes are used in soccer as in many other aspects of daily life and professions. Thus, success in soccer also requires planning, flexibility, problem solving, adjustment and ability to deal with novelty - but in a stricter and more controlled environment.

3.1.2 Special forces

The second research population consisted of applicants for the special elite police forces, the Swedish Counterterror Intervention Unit (Nationella Insatsstyrkan, NIA). This group is perhaps even more comparable to herds that hunt than team sport players, due to the life-threatening situation and the terrible consequences of failure. The elite force officers also need to be physically well trained, deal with novelties and have the ability to make quick and successful decisions. However, compared with team sport players, the officers have less possibility for a second chance when they are in action. An intervention needs to be successful. If not, the results can be devastating. Another problematic aspect is that the "opponent" (equivalent of the opposite soccer team), doesn't need to "play by the rules", while the special forces are not allowed to use unnecessary violence. Theoretically, such stressful situations should be highly demanding for EF.

3.1.3 Corporate world

The third population that was studied in the present project was chosen from the corporate world and included different occupations such as forklift operators, sellers, operational managers and strategic managers. They represent a cross section of the society and the everyday life of people in modern society We argue that there are rules of what defines successful behaviors also in this population, although they are the not as clear as for elite soccer players and elite police forces. It is also more complicated to define successful behaviors due to difficulties in monitoring both the short- and long term outcome and because a greater dissemination of what could be objectively regarded as success. Our interest in this population mainly focused on the importance of flexible behavior for health, indexed by number of sick days, as similar ideas have been put forward [45, 46, 49-51] in several psychological models.

3.2 STUDY I

The focus for the first study was to investigate whether EF were related to successful behavior in soccer. We studied whether there was a difference between elite and sub-elite soccer players concerning their EF capacity, especially when it comes to HEF and a combination of creativity and constant adjustment, including cognitive flexibility. We also studied whether this capacity could predict the number of goals and assists in the coming two and a half years.

3.3 STUDY II

In the second study we aimed to test whether the results from **Study I** could be conceptually replicated in young players from an elite academy. We specifically tested how CEF and HEF were related to success (indexed by scored goals) in relation to cognitive development. We also tested whether a combination of creativity and adjustment including cognitive flexibility, would correlate with the number of goals the players scored during two years spent at an elite academy.

3.4 STUDY III

In the third study, we tested whether HEF abilities related to creativity and adjustment, including cognitive flexibility, also differ among the best soccer players in the world. We posed that national team players would have higher capacity than other elite players. We also studied whether the capacity of EF has an ecological validity by correlating the results with the players' game intelligence, rated by their coaches. We especially focused on creativity, fluency and cognitive flexibility mirroring the evolutionary need for fast and accurate adjustment, as this was predicted from study one and two. Finally, we tested whether there was a correlation between HEF, goal making and assists also at this level of play, as indicated by our previous studies.

3.5 STUDY IV

In this study we focused on a population consisting of the police special forces. As in the previous studies we investigated how HEF – mainly focusing on cognitive flexibility and fluent creative - correlates with successful behavior. First, we investigated whether there were differences between an elite group compared with a sub-elite group in regards to HEF capacity. In this case the elite group consisted of the applicants for the Swedish Counterterror Intervention Unit (Nationella Insatsstyrkan, NIA), the police resource in Sweden dealing with the most dangerous situations that require police intervention, which the ordinary police squads don't have the experience or capacity to resolve. The main task of Nationella Insatsstyrkan is to fight terrorism. Police academy students were selected as a control group where a lower level of performance on EF was expected. The aim was also to investigate how HEF capacity changes when the elite officers are under extreme physical and psychological stress. The hypothesis was that individuals with the highest HEF capacity at baseline would also have the highest HEF capacity under stress. We also wanted to investigate whether the results would remain after adjusting for other EF components including working memory and inhibition.

3.6 STUDY V

In the last study the goal was to investigate the role of HEF, with a focus on cognitive flexibility as well as creativity and fluency, in a more "normal population". A corporate world population was chosen that included forklift operators, sellers, operating- and strategic managers across several different socio-economic groups. Sick leave was used as a measurable behavioral outcome variable that we hypothesized would be dependent on behavioral adjustment and resilience. We then studied whether HEF would work as a resilience factor and contribute to decrease of sick leave across the socio-economic groups.

4 MATERIALS AND METHODS

4.1 MATERIALS

4.1.1 Delis-Kaplan Executive Function System Test Battery (D-KEFS)

D-KEFS is a performance assessment instrument that measures various aspects of EF. The primary measurement is often how fast the test subject completes the task, usually expressed in seconds. The secondary measurement is often accuracy, based on the number of right or false responses, although in some tests, such as Design Fluency, accuracy is the primary measurement. D-KEFS is used for clinical assessments in many countries around the world. It has well-described norms for the general population. The norm group of D-KEFS consists of a stratified sample of 1750 individuals and takes into account age, sex, ethnicity and education. The sample was collected in the US in the year 2000 [148, 149]. The D-KEFS results are normally distributed among healthy individuals [148, 150]. Test-retest reliability analysis for the D-KEFS shows a moderate to strong reliability [148, 149]. The test results, mirroring cognitive capacity, have been shown to be related to brain morphology [151, 152] in networks associated with executive functions [91]. The D-KEFS scores are positively correlated with the volume of the frontal lobes [151].

4.1.1.1 Subtests in D-KEFS

Main tests

Design Fluency (DF) – measures multi-processing in an ongoing situation with a focus on cognitive flexibility, creativity and flow [153-155]. DF also includes visual scanning, planning, working memory, and response inhibition [153-155]. It combines both divergent creativity and convergent creativity (see Literature Review for definitions). Thus, it involves the whole executive chain of decision-making, crucial for quick and correct acting. DF is a non-verbal standardized psychomotor test.

The task is to combine dots that are framed in a square on a paper using a pencil. Within the time limit of 60 seconds, the task in the first condition (Design Fluency 1; DF1) is to make as many different designs as possible by binding together four of five filled dots. The use of the same solution twice is not allowed. The test individuals need to use their working memory to remember what designs were already used. As a consequence of this, the participants need to constantly update their working memory. The test individuals also need to use their inhibition skills due to the fact that the test rules do not allow the participants to make a design more than once. Another cognitive capacity that is activated is visual scanning, due to a constant need for new solutions. Strategic planning is also of importance for a successful outcome, and may influence the number of solutions the test-subject can make.

At the next level, the second condition (Design Fluency 2; DF2), unfilled dots are added to the test box. The task is the similar to the first condition, but in this version, the test individuals bind together the unfilled dots. Although the filled dots are still present, the test individuals are not allowed to use them.

In the third condition, both the filled and unfilled dots are to be used. The task is to make designs in a similar way as in the previous tests, but continually shifting between filled and unfilled dots.

DF Total Correct is a score that combines the results of subtest one, two and three (DF1-3). DF Total Correct catches both "modest creativity" and more "innovative creativity" due to a higher demand of inhibition and cognitive flexibility in subtest three (DF3). Support for this notion has been shown using latent data analyses [150]. As DF Total Correct involves many cognitive processes it is not an optimal test for studying an isolated cognitive function. However, it reflects the ability of complex problem solving in real life situations where adjustment under time pressure is of essence. DF Total Correct was the primary test used through all the studies.

Since DF includes fluency and flexibility, it captures divergent creativity. However, as it also involves time pressure, spatial frames, and rules of how to make the designs, the test also captures convergent creativity. As it also involves many other different EF that act simultaneously in order to reach a goal, DF may be defined as a test of HEF involving creativity and behavioral adjustments. Thus, it mirrors the aim of the present project well and was therefore chosen as a main test in the studies.

As discussed above, latent structure analysis suggests that DF3 measures an additional component as compared to the fluency component in DF2 and 3, i.e. shifting [150]. Thus, it seems more focused on cognitive flexibility than the other conditions.

Verbal fluency test (VF) - In our last study we also used Verbal fluency (VF) as one of the two primary tests. In VF1-3, the participants are supposed to generate as many words as possible in 60 seconds either according to a specified initial letter or semantic category. Additionally, in VF3 test individuals are told to alternate between two different semantic categories. VF has many similar features as DF but in a verbal dimension instead of visuo-spatial dimension. In more detail, the category Switching (VF3) resembles DF3, as it has a focus on cognitive flexibility.

Additional tests

Two other sub-tests from D-KEFS were used for explorative analyses performed to capture how core executive functions influenced the results and, in some cases, adjust for them.

Trail Making Test (TMT) - TMT is aimed to capture visual attention combined with task switching using a pencil to connect circles in alphabetic and numerical order. The main test condition is TMT 4 measuring mainly cognitive flexibility in combination with WM and visuo-motor sequencing by switching between letters and numbers. Shifting is a major component as in DF3 but without the creativity component. The other conditions, TMT 2 to

3, were used to quantify and derive data that is necessary for performing condition 4, such as visual scanning, sequencing and motor speed.

Color Words Interference Test (CWI) - CWI is a test based on the original Stroop-task [148]. The test aims to measure the capacity to inhibit interference induced by mismatching information between words and colors [156, 157]. As long as the semantic information of a word is the same as the color of the word (for example blue is printed in the color blue) no conflict is present between the two processing streams (called a congruent stimulus). However, when the semantic meaning of a word is not the same as the color it is printed in, a conflict is present between the two processing streams (called an incongruent stimulus). It will make it more difficult to say the printed color of the word due to an over-learned semantic response of reading in favor of naming the printed colors. The test measures the ability to suppress the over-learned semantic response and the impulse to read the words instead of saying the color the words are printed in. Two baseline conditions are used: Condition 1 that includes naming of colors of a rectangle (no words are present), and Condition 2 that includes reading names of colors in black ink. Condition 3 is the traditional Stroop test where the task is to inhibit over-learned semantic response of reading in favor of naming the printed colors of the words. In Condition 4 a switching component is added where the subject needs to alternate back and forth by saying the printed color or read the words. Thus, although the capacity to suppress or inhibit an overlearned response is a central part of the task, cognitive flexibility is another important cognitive process involved in the task, especially in Condition 4.

4.1.1.2 The test result of D-KEFS and their correlations with structural and functional brain imaging

The results from the D-KEFS sub-tests CWI4, TMT4, and DF3, have shown to correlate positively with the thickness of cortex in medial superior frontal cortex/caudal anterior cingulate, inferior precentral cortex, caudal middle frontal cortex and parietal cortex [152] - see Figure 5.

A meta-analysis of fMRI-studies on executive functions in 173 experiments showed activations of a network that included caudal anterior cingulate cortex, superior medial prefrontal cortex, dorsolateral prefrontal cortex, insula and parietal cortex [91] - see Figure 6 A. Similar activations were observed when only including studies on the Stroop task in this meta-analysis - see Figure 6 B.

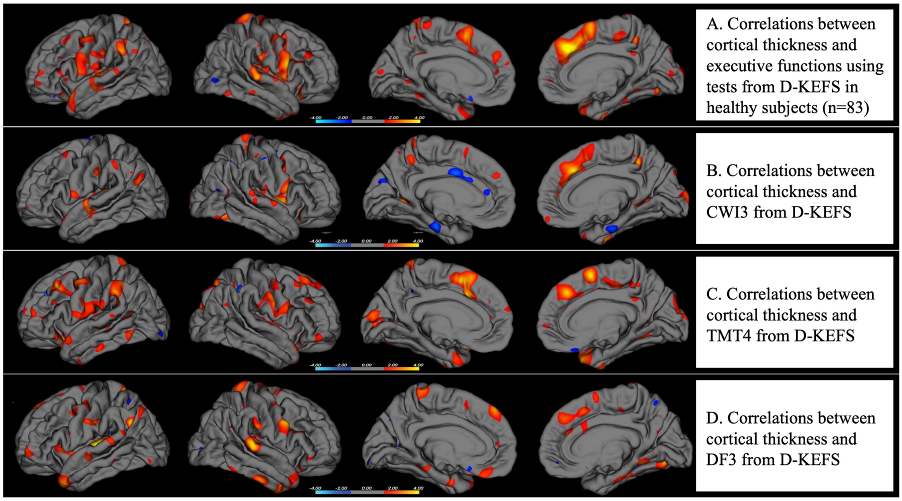

Figure 5. The relation between brain morphology and executive functions. **A**. A correlation was shown between cortical thickness in a distributed brain network (that included caudal anterior cingulate cortex, superior medial prefrontal cortex, dorsolateral prefrontal cortex and parietal cortex) and capacity on executive function tests from the D-KEFS test battery in healthy subjects (n=83) Abe' et al., (2018) [152]. Similar results were shown when only analyzing **B**. CWI3, **C**. TMT4, and **D**. DF3. The figure was produced and approved by the authors of the study.

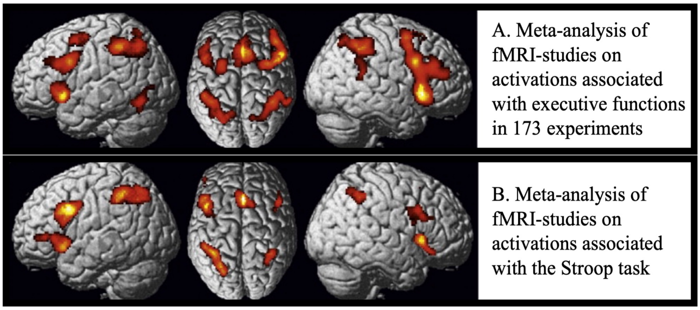

Figure 6. **The relation between brain function and executive functions.** **A**. A meta-analysis of fMRI-studies on executive functions showed activations of a network that included caudal anterior cingulate cortex, superior medial prefrontal cortex, dorsolateral prefrontal cortex, insula and parietal cortex. **B**. Similar activations were observed when only including studies on the Stroop task in this meta-analysis. Reprinted from *Three key regions for supervisory attentional control: Evidence from neuroimaging meta-analyses*. Cieslik et al., (2015) [91]. Copyright©2015 with permission from Neuroscience & Biobehavioral Reviews.

4.1.1.3 DF and limitations

DF, the main test in this project, has been criticized for involving different EF in the same task without differentiating between them. On the other hand, it reflects the reality of life better where a single EF component is rarely used in isolation

DF has also been criticized for its test norms because it consists of a relatively old US population sample [149]. It cannot be ruled out that the EF capacity in the population since the test was made is in line with the Flynn effect in IQ (the tendency of IQ scores to increase over time) [158]. However, the test results of the elite players from **Study III** showed no significant difference compared to test results of the elite players from the same division tested in **Study I** a decade earlier, suggesting that such change of the norm performance is not evident.

Finally the re-test reliability of DF shows in general a moderate to strong reliability but with lower test-retest reliability in subtest DF3 (r = 0,32) [149]. However since the re-test result is higher than the baseline, this effect suggests a learning factor rather than a consequence of weakness in capturing the capacity of an individual over time. When an individual has performed the test previously, it seems that the ability of DF to capture EF abilities over time becomes weaker due to lost novelty factor.

4.1.2 CogState Computerized Concussion Testing (CS)

CogState computerized concussion testing (CS) is a computerized test battery. It has a non-verbal psychomotor approach and the aim of the test is to capture different low-level cognitive aspects such as cognitive speed, attention, and decision-making. CS also measures the capacity of short-term memory and working memory when it comes to both speed and accuracy. Participants are shown playing cards on a computer screen. When a card is shown, the subject has to react correctly, according to the rules, and as fast as possible by using a specific key on the keyboard. In **Study II**, WM was used as the main test. Otherwise, the tests were used for explorative analyses performed to describe how specific core executive functions influenced the results and, in some cases to adjust for them.

Processing speed – This test assessed the reaction time by the time it takes for the participant to touch a key on the keyboard after a card is displayed on a computer screen.

Attention – This test measures the time and accuracy of responses to red cards, in a series of black and red cards that are displayed to the subject on a computer screen.

Learning - In this test, fifty-two cards of a normal playing deck are used and show up randomly (i.e., they may be shown twice). The participants should respond with a “yes” by pressing a key if they have seen the presented card previously in the test sequences. The test involves working memory (noting a card that has recently been displayed), short-term memory (noting the last card) and learning (noting a card that has been displayed earlier on in the presentation sequence).

Working memory - In this test the participants indicate, with a key press, whether a displayed card is the same as the card that was showed just before (i.e. one back memory-test). Despite its name this test is more of short-term memory test.

4.2 STUDY I. EXECUTIVE FUNCTIONS PREDICT THE SUCCESS OF TOP-SOCCER PLAYERS

4.2.1 Participants

In the first soccer study fifty-seven individuals participated (31 male and 26 female). Twenty-nine of them (male = 14, female = 15) represent the highest division (HD) in Sweden, called Allsvenskan (M^{age} = 25.3; SD = 4.2). Twenty-eight of them represent the sub-elite and lower divisions (LD). Seventeen of the LD group players were male players from a division two steps below the highest Swedish elite level (called Division 1). Eleven were females playing in the Swedish 2nd division. (M^{age} = 22.8; SD = 4.1). The educational level and age of the players showed no significant difference between HD and LD.

In the second prospective part of the study twenty-five male players were included (13 from HD level and 12 from LD level) that had played at least one game. Female players and players in division 3 were excluded because of lack of official information about scoring and assists.

When the season ended the assessed male HD teams held the ninth position (out of fourteen teams) and the assessed female HD teams held the sixth position (out of twelve teams) in their league on average.

The sub-elite players came from five LD teams and accounted for 20 % (male) respectively 17 % (female) of the total number of players in their teams.

When the season ended the assessed male LD teams held the fifth position (out of fourteen teams) and the female LD teams held the fifth position (of twelve teams) in their league on average.

The team managers selected the participants to represent the average soccer capacity of the team. The coaches were instructed to choose two representative players from each part of the team, i.e. forwards, midfielders, and defenders. The coaches were also instructed not to choose players that probably would be transferred to a lower or higher division in the near future.

During the period of two and a half years when data of goals and assists was collected the average participation in a game for each player was 70%.

Design Fluency Total Correct was used as the main test result. Additional tests were Color Word Interference Test and Trail Making Test.

Data concerning behavior of the players, measured by number of performed goals and assists, were obtained from the Swedish Football Association's official website from January 2008 till May 2010.

4.2.2 Procedure

One test leader assessed the players from 7 June to 30 October 2007. The tests were made in the training facility of the team. The assessments took forty minutes per player and were performed in standardized process.

4.2.3 Statistical analyses

A two-way full factorial ANOVA was used for the cross-sectional main analysis. Elite and sub-elite level of play (HD and LD) and sex were chosen as independent factors. The result on Design Fluency Total Correct was the dependent variable.

An additional ANCOVA-analysis was performed with the purpose to adjust for sex, age, division, team position, and education. The Design Fluency Total Correct measurement was the dependent variable.

A partial correlation was made for the prospective part of the study. The measurements from Design Fluency Total Correct and the square root of the points from goals and assists were correlated. Due to the different probabilities in goal making in different positions, two dummy variables were made to control for the positions of forward, mid-player or defender. Given that it is easier to score in a lower division, division level was also controlled for. Finally, due to a possible influence of age on physical and cognitive capability related to soccer, age was also controlled for.

4.3 STUDY II. CORE EXECUTIVE FUNCTIONS ARE ASSOCIATED WITH SUCCESS IN YOUNG ELITE SOCCER PLAYERS

4.3.1 Participants

From the beginning the group consisted of forty-nine players. Out of these players, thirty participants played at least one game and score at least once from February 2012 to February 2014. These thirty players made up the final test group with an age range from twelve to nineteen years. The mean age was approximately fifteen years. The players were from the same Swedish elite academy. The teams of this academy played at the highest division for each age group.

4.3.2 Material

CogState Sport and D-KEFS were used for the main analysis.

Learning from the CogState Sports (CS) was used and is denoted as demanding Working Memory (dWM). The choice to use dWM was based on the hypothesis that CEF are of most importance at a junior level due to the late maturation of the prefrontal cortex. Moreover, because dWM is more demanding than a simple short-term memory test it would better mirror the cognitive challenge on the soccer pitch, taking into account the constant information flow the players need to remember for more than a second.

We also used Design Fluency (DF) from D-KEFS, to capture the players' HEF capacity in relation to creativity and cognitive flexibility, as well as to simulate the executive chain of fluent creativity in combination of sustained attention, working memory, inhibition, and cognitive flexibility of decision making as in a real soccer situation. DF Total Correct was used with the purpose to capture the broad spectra of cognitive requirements in both modest and challenging contexts. Thus, this test also includes a higher demand of inhibition and cognitive flexibility and captures varied problem solving on the pitch.

As additional tests CWI and TMT were used.

To get a broader measurement both CEF and HEF were included in a composite measurement. The scaled scores from DF Total Correct and dWM were transformed to z-scores and then added, i.e., both measurements contributed equally to the index.

4.3.3 Procedure

The soccer players were tested from June until October 2013. The assessment took place in their training facilities. The test procedure was standardized and one assessor did all the tests. Data on the number of scored goals was provided from statistics of the academy for the period February 2012 to February 2014.

4.3.4 Statistical analyses

The analyses were made with IBM SPSS Statistics 23.0.0. Kolmogorov-Smirnov was used to test whether the data showed a normal distribution. A one-sample t-test was made to compare the test results with the norm population.

A Pearson product-moment correlation coefficient was used in order to study the relationship between the EF results and the number of scored goals per game. A partial correlation analysis was also performed to study the same relation (between the EF results and the number of goals they made in average per match) after correcting for possible confounders including height (as a proxy for maturation and physical advantage), year of birth and IQ.

4.4 STUDY III. LEVEL OF PLAY AND COACH-RATED GAME INTELLIGENCE ARE RELATED TO PERFORMANCE ON DESIGN FLUENCY IN ELITE SOCCER PLAYERS

4.4.1 Participants

Players in four teams from the Swedish premier league (Allsvenskan) were asked whether they would like to participate in the study. Fifty-one players accepted this invitation (nineteen men and thirty-two women). The age of the female players ranged from seventeen to thirty-five, with a mean age of twenty-four and a half years (SD = 4.6). The age of the male players ranged from eighteen to thirty-five years with a mean age of twenty-four and a half years (SD = 4.7)

Twenty-eight players of the total group of fifty-one participants had never played on a senior level for a national team. In the study they were called Premier League Players (PLP). Twenty-three players had participated in at least one game for a national team on senior level. This group was called National Team Players (NTP).

The NTP players had played in fourteen different national teams in total.

The ages of the NTP players ranged from twenty-two years to thirty-five years, with a mean age of approximately twenty-seven years (SD = 4.1). The ages of the PLP players ranged from seventeen years to thirty–three years old, with a mean age of approximately twenty-two and a half years (SD = 4.2). The difference in age between NTP and PLP was significant (t = 3.53, p = 0.001).

There were seven men (30,4% of the group) and sixteen women (69,6% of the group) in the NTP group. The PLP group consisted of twelve men (42%) and sixteen women (57%).

4.4.2 Material

As in the previous studies, Design Fluency (DF), from D-KEFS were used as the main test.

The combination score of DF Total Correct was used as the main variable of interest. Both the raw scores and the standardized score (normalized for age and sex) were used.

Apart from DF Total Correct, the separate tests DF1, DF2 and DF3 were used on an exploratory level to capture more specific cognitive components such as inhibition and cognitive flexibility.

The results from the CS-test battery were used to adjust the main results for more basic attentional capacities and CEF.

TMT and CWI from the D-KEFS were used as exploratory tests.

Even if there is no exact established definition of game intelligence it may be described as the player's ability to "read the game" [159]. The ability to anticipate the intentions of the opposite player and use that information to make successful decisions and actions is associated with game intelligence [160]. Despite the lack of an established definition of game intelligence, coaches and managers have a common opinion of what it is and how high the game intelligence capacity is of an individual player. Thus, coach rating of individual players could be used as a representative measurement of players' game intelligence level. In our study, the manager for each team that participated in the study was asked to estimate the game intelligence of the assessed players in comparison with the average level of the

Allsvenskan. They used a Visual Analogue Scale to rate game intelligence with five as average, one as the lowest value, and nine as the value for top rating.

The numbers of goals and assists, as well as the numbers of played games on the senior level for national teams were gathered from open data sources.

4.4.3 Procedure

The players that participated in the study were assessed from February till June 2018. The tested procedure was standardized, and the assessment of each player took forty minutes. Two test-leaders were involved in the assessments. To clarify if there was a difference between the assessment results of the two test-leaders, an analysis with the Mann-Whitney test was made on one team where both the assessors randomly tested the players. No significant differences between the test leaders assessments were discovered ($p = 0.39$).

4.4.4 Statistical analyses

The data analyses were made with IBM SPSS Statistics 25. Shapiro-Wilk and Levene's test were used to test for normal distribution as well as the homogeneity of variances.

A one-sample t-test was used to compare the DF Total Correct results between each test group (NTP or PLP) and the norm. An independent t-test was used to compare the two groups in regards to DF Total Correct. For further comparison between the groups, after adjusting for sex, age, lower level of cognition (processing speed), and CEF (short-term memory) an ANCOVA was performed. A Pearson correlation was used to investigate the relation between DF Total Correct and game intelligence rated by the coaches. A non-parametric analysis was also performed in order to test how robust the result was. Finally, a partial correlation test was performed in order to analyze the relation between DF Total Correct and coach-rated game intelligence after controlling for level of play (NTP or PLP).

4.4.5 Tests that were used in the exploratory analyses

Several exploratory analyses were made that are explained in detail in **Study III**. In short, we performed the main analyses above for each subtest of DF1-3 (including adjustments to better identify the main contribution of the differences). Moreover, we tested for the relation between DF Total Correct and number of performed goals and assists using an ANCOVA.

4.5 STUDY IV. EXECUTIVE FUNCTIONS OF SWEDISH COUNTERTERROR INTERVENTION UNIT APPLICANTS AND POLICE OFFICER TRAINEES EVALUATED WITH DESIGN FLUENCY TEST

4.5.1 Participants

Forty-five applicants to the elite police force "Nationella Insatsstyrkan" (NI) were recruited to the test group. Thirty police officer trainees were enrolled as a control-group.

The test-group, denoted as NIA (Nationella Insatsstyrkan Applicants), consisted of forty-four men and one woman with an age range of twenty-seven to forty-four and a mean age of approximately thirty-two (SD = 3.3). The NIA group included applicants who passed the first four screening tests to become a final candidate for the counterterror intervention unit NI. Some of the individuals of the NIA group failed in the physically and mentally very hard field assessment test that lasted for ten days. Due to this they had to leave the selection process prematurely which led to a gradual decrease in tested individuals for re-tests of EF capacity (base assessment: 45 individuals; re-test 1: 40 individuals; re-test 2: 38 individuals; re-test 3: 35 individuals).

The control-group denoted as POT (Police Officer Trainee), consisted of 30 individuals, and included twenty-four men and six women. The age range of the group was twenty-two to thirty-nine and the average age was approximately twenty-eight (SD = 4.70). The participants of the group were police officer trainees from the police academy of Stockholm. The POT-group was significantly younger than the test-group ($t(73) = 4.365$, $p < 0.001$).

4.5.2 Material

Design Fluency Total Correct and its subtests DF1, DF2, DF3 were used for the main analysis.

Process speed and Working Memory from CogState Sports were used to adjust for lower level of cognition.

CWI and TMT from D-KEFS, and Attention and Learning from CogState Sports were used as additional exploratory tests.

4.5.3 Procedure

A baseline testing of the NIA-group took place from May till June 2015. The POT-group was assessed from January till October 2016. The assessments were performed in a standardized procedure.

A re-test of the NIA group was performed approximately fourteen days after the baseline testing during a physically and psychologically demanding field assessment that lasted ten days. DF, TMT and CWI were tested in different days (DF was tested first, then TMT and finally CWI).

The NIA-group and the POT-group had different test assessors, but with the same instructions and preparation.

4.5.4 Statistical analyses

IBM SPSS Statistics 25.0.0 was used for the analysis. Shapiro-Wilk, and Levene’s test were used to test the normal distribution for the test groups and the homogeneity of variances.

An ANCOVA was performed in order to compare DF Total Correct results between the NIA group and the POT-group when adjusting for age and sex.

Further, a paired sample T-test was performed in the NIA-group to compare the baseline results with the re-test results during the field conditions. A Pearson's correlation test was also performed to investigate the relation between baseline and the re-test scores. Also, an ANCOVA was performed to study the relation between the results from DF Total correct (as well as DF1, DF2 or DF3) and the percentage difference of the results between the baseline test and the re-test, adjusting for attention and CEF including Processing speed, and Working memory accuracy from CS. We also adjusted for physical fitness indexed by resting state heart rate [161, 162].

The results of DF Total Correct and its three sub-tests were for both NIA and POT compared with the norm using a one sample T-test.

4.6 STUDY V. EXECUTIVE FUNCTION MEASURES OF COGNITIVE FLEXIBILITY ARE ASSOCIATED WITH DAYS OF SICK LEAVE

4.6.1 Participants

The study was made in cooperation with Derome-group, a mid-sized wood industry company with approximately two thousand employees. Derome's HR-department chose the employees who were offered to join the project. In order to capture the different categories of employees working in this company, the test individuals were stratified in strategic managers, operating managers, sellers and forklift operators. The participants were also chosen to represent the company regarding geographic location, age, and sex. Apart from the selection criteria above, the employees were chosen at random. One hundred eleven co-workers between twenty-two and sixty-seven took part in the study, and the average age was approximately forty-four (SD = 10.85). Ninety-four of the participants were men while seventeen were women. The four work groups consisted of twenty-seven forklift operators (M^{age} = 43.3, SD = 14.4; 24 males), twenty-five sellers (M^{age} = 42.4, SD = 11.4; 18 males), twenty-seven strategic managers (M^{age} = 46.6, SD=8.4; 22 males), and thirty-two operative managers (M^{age} = 44.5, SD = 8.7; 30 males). Age and sex showed no significant differences between the groups (age = $p > 0.6$; sex = $p > 0.15$)

4.6.2 Material

We combined the measurement of Design Fluency 1, 2, and 3 with Verbal fluency 1 (letters), 2 (categories), and 3 (switching) from D-KEFS into one index for the main analysis (the composite score was shortened DFVF). The purpose was to capture the creative abilities of generating solutions paired with cognitive flexibility on both a visuo-spatial and verbal HEF level.

As in previous studies, tests from CogState Sports test battery were used to adjust for lower level of cognition like Process speed, Attention, Short-term memory and Working Memory. Also, Color Word Interference Test (CWI) from D-KEFS (i.e. a Stroop-test) was used to adjust for inhibition skill.

Information from the HR-department concerning the employees' occupation, how long they had been employed in the company and how many days of sick leave they have had the last five years, was collected with permission from the participants. The days of sick leave were then divided by how many months they had been employed.

4.6.3 Procedure

The participants were assessed at their workplaces from March to June 2019 by six different test-leaders. Using standardized testing procedure and special training of the test-leaders minimized the test-leader bias. There were no significant differences in the test results between the test-leaders.

4.6.4 Statistical analyses

IBM SPSS Statistics 25 was used to analyses the results. Shapiro-Wilk and Levene's test were used to investigate the normal distribution of the group's results and the homogeneity of variances between the groups.

Due to a highly skewed sick leave data, a non-parametric correlation test was performed on the whole group to investigate the relation between DFVF and the amount of sick leave. A log10 adjustment of the sick leave data was performed for the participants with at least one day of sick leave in order to achieve a normal distribution for further analyses.

In the group with at least one day of sick leave, an ANCOVA was used to compare the correlation between sick leave (log10 transformed) and DFVF, adjusted for age, sex, and work group. In order to get a better understanding of how cognitive flexibility and creative fluency related to the results, several additional adjustments for lower level of attention and CEF were also performed (including attention, short-term memory and working memory).

Finally, a contrast measurement and a post hoc analysis were performed to investigate if there was a difference in DFVF and sick leave between the four work groups.

5 RESULTS

5.1 STUDY I. EXECUTIVE FUNCTIONS PREDICT THE SUCCESS OF TOP-SOCCER PLAYERS

5.1.1 Summary

- In line with the hypothesis, the first study showed that the elite soccer players out-performed sub elite players in DF Total Correct.
- Similar results were also shown in exploratory analyses for TMT and CWI.
- In the prospective part of the study, the results on DF Total Correct correlated significantly with the number of goals and assists that the players made during a period of two and a half years after they were assessed.

5.1.2 Cross-sectional test result from the main test DF Total Correct

The result from the DF Total Correct test showed that both HD and LD male and female players, performed well above the standard population on average (Male HD: +1.93 SD, Female HD: +1.76 SD, Male LD: +1.02 SD, Female LD: +1.12 SD) - see Figure 7. The results were in-line with the hypothesis that elite players have a higher EF capacity than the population in general, as expressed in normative data.

The results of the ANOVA showed a significant effect on DF Total Correct scores $F(3, 53) = 4.99$, $p = 0.004$, on level (HD: mean-score: 15.52, SD: 2.42; LD: mean score: 13.18, SD: 2.14; $F(1, 53) = 13.86$; $p < 0.0005$) but not on sex ($F(1, 53) = 0.03$; $p = 0.86$). When position, age and education-level were controlled for the effect remained (ANCOVA-analysis $F = 9.51$; $p = 0.004$). No other effects were significant. Thus, the result showed that elite players performed significantly better than semi-elite players on this test.

5.1.3 The result of the prospective part of the study

In the prospective partial correlation test the assessment result from 2007 showed a significant correlation between the players' results in Design Fluency Total Correct and the number of scored goals and made assists, expressed as the square root of the points due to a skewed distribution (cf = 0.54; $p = 0.006$; 1-tailed). The result of scored goals and made assists was collected from January 2008 till May 2010.

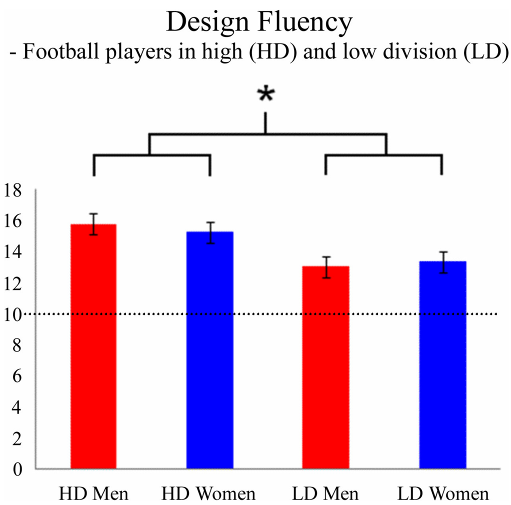

Figure 7. The results on Design Fluency Total Correct in elite and semi-elite soccer players of both sexes. The dotted line represents the mean of the norm. Reprinted from *Executive functions predict the success of top-soccer players*. Vestberg et al., (2012). Copyright©2012 with permission from PLOS ONE.

5.2 STUDY II. CORE EXECUTIVE FUNCTIONS ARE ASSOCIATED WITH SUCCESS IN YOUNG ELITE SOCCER PLAYERS

5.2.1 Summary

- In line with the hypothesis, EF capacity of the younger players correlated with successful soccer behavior measured as scored goals. Both results on dWM (CS learning) and DF Total Correct (D-KEFS) correlate moderately with the number of goals the players made on average per game during two seasons.
- A composite score of dWM and DF Total Correct showed a stronger correlation with the number of goals the players made over two seasons than only using one of the tests.
- The results remained after adjustment for year of birth, height and IQ.
- There was no correlation between IQ and the number of goals made during two seasons.

5.2.2 Descriptive tests

Main tests for the hypothesis testing were dWM (CS Learning) and DF Total Correct. The Kolmogorov-Smirnov test showed a normal distribution of the results.

In the dWM test (CS Learning) the test group performed significantly above average in normative data ($t(29) = 3.376$, $p = 0.002$).

The results from DF Total Correct also showed that the young soccer players performed significantly above the norm ($t(29) = 5.501, p < 0.001$.

Raven's Standard Progressive Matrices was used as a proxy to capture IQ of the players. The groups' average result was estimated to the 45.93 percentile (SD 24.6; Range 10-90), and did not deviate significantly from normative data ($t(29) = -0.407; p > 0.05$).

5.2.3 Main results

A significant correlation was shown between the players' test results on dWM (CS Learning) and the number of scored goals the players made on average per game during two years ($r = 0.437; p = 0.008$) - see Figure 8.

A significant correlation was also shown between the players' results on DF Total Correct and the number of scored goals that the players made on average per game during two years ($r = 0.349; p = 0.029$) - see Figure 9.

The composite measurement, derived from DF Total Correct and dWM, significantly correlated with the number of soccer goals the players made on average per game during two years ($r = 0.55, p = 0.001$) - see Figure 10.

5.2.4 Partial correlation test using goals as an outcome measure

When we controlled for age, height (as a proxy for physical advantage) and IQ, the significant correlation between the results on dWM and the number of scored goals still remained ($r = 0.449; p = 0.009$). This was also the case for DF Total Correct and the number of scored goals ($r = 0.366; p = 0.030$), as well as for the composite measurement and the number of scored goals ($r = 0.55; p = 0.001$).

5.2.5 Estimated IQ and scored goals

The results from Raven's Standard Progressive Matrices showed that the average IQ level of the test group was estimated to the 45.93 percentile (SD 24.6; Range 10-90). The test results did not deviate significantly from normative data ($t(29) = -0.407; p > 0.05$). There was no correlation between the player's results on the IQ-test and the number of made soccer goals ($r = -0.01; p = 0.48$) - see Figure 11.

5.2.6 Lower level of cognition and scored goals

Exploratory analyses suggested that the soccer players performed significantly above the norm in the Process speed test from CS, ($t(29) = 15.392, p < 0.001$, and in the Attention test from CS, ($t(29) = 13{,}461, p < 0.001$. However, there was no significant correlation between the players' results on Process Speed and the number of made soccer goals ($r = 0.18; p = 0.16$), nor between the results on Attention and the number of made soccer goals ($r = .10; p = 0.29$).

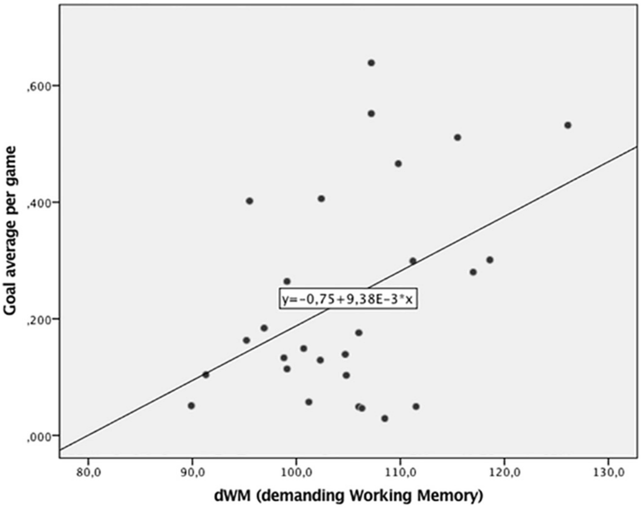

Figure 8. The correlation between working memory capacity (dWM) and the numbers of goals on average per game in elite junior soccer players during a period of two years. Reprinted from *Core Executive functions are associated with success in young elite soccer players.* Vestberg et al., (2017). Copyright©2017 with permission from PLOS ONE.

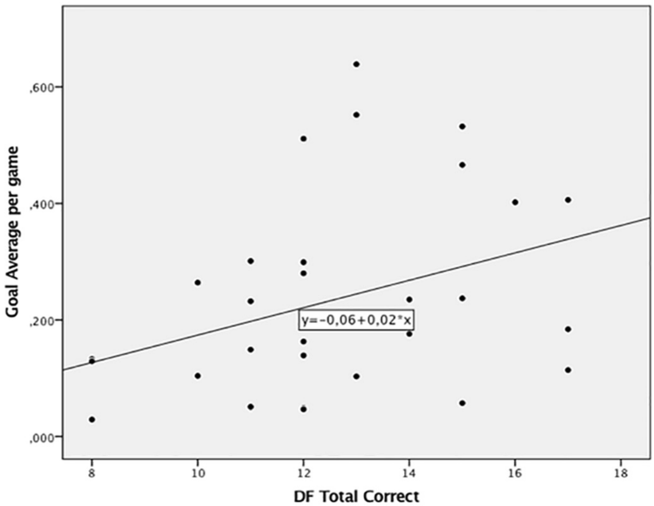

Figure 9. The correlation between the results on DF Total Correct and the numbers of goals on average per game in elite junior soccer players during a period of two years**.** Reprinted from *Core executive functions are associated with success in young elite soccer players.* Vestberg et al., (2017). Copyright©2017 with permission from PLOS ONE.

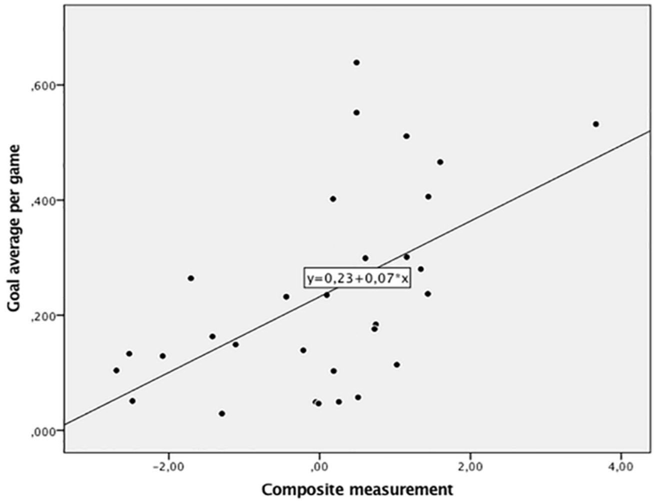

Figure 10. The correlation between the results on the composite scores (derived from DF Total Correct and dWM) and the numbers of goals on average per game in elite junior soccer players during a period of two years. Reprinted from *Core executive functions are associated with success in young elite soccer players.* Vestberg et al., (2017). Copyright©2017 with permission from PLOS ONE.

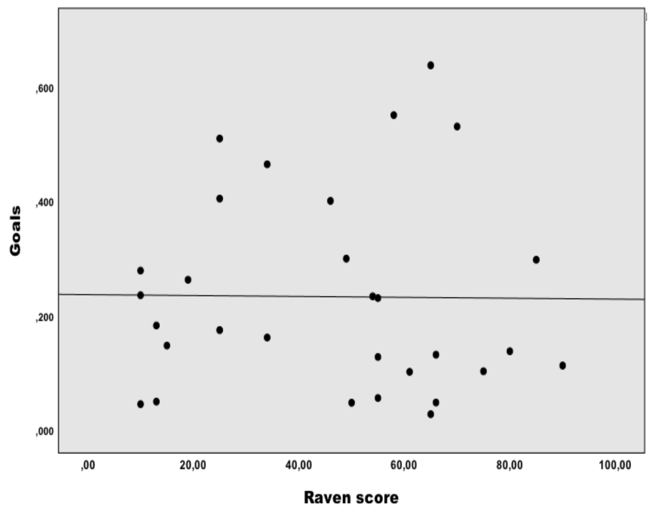

Figure 11. The correlation between the players’ results on Raven's Standard Progressive Matrices and the numbers of goals on average per game in elite junior soccer players during a period of two years.

5.3 STUDY III. LEVEL OF PLAY AND COACH-RATED GAME INTELLIGENCE ARE RELATED TO PERFORMANCE ON DESIGN FLUENCY IN ELITE SOCCER PLAYERS

5.3.1 Summary

- The third study conceptually reproduced the findings from **Study I** at a higher level of play in soccer. The result showed that National Team Players (NTP) significantly outperformed their teammates (PLP) not playing for a national team in the DF Total Correct test.
- Moreover, the result showed some ecological validity by inclusion of the coach rated-game intelligence of the players, i.e. an external judgment of the players' ability to read the game, in that rated game-intelligence correlated with the test results of DF Total Correct.
- The number of made assists during the season also showed a positive significant correlation with the players' results on DF Total Correct.
- Exploratory analyses using the sub-tests of Design Fluency (DF1-3) suggested that cognitive flexibility and creativity had an important impact on this performance.

5.3.2 Design Fluency – Group effects

Concerning the results on DF Total Correct, both the NTP and the PLP groups were far better than average of the normative data - see Figure 12 A.

In line with the hypothesis, the NTP group had significantly better results than PLP in DF Total Correct ($t(42.67) = 2.48$, $p = 0.017$, Cohen's $d = 0.71$) - see Figure 12 A.

In order to exclude confounding factors, an ANCOVA-analysis was performed that adjusted for process speed (to exclude that the results were not a consequence of faster response reaction), short-term memory (using a one-back memory task as a representation for CEF), sex, and, age. The ANCOVA showed that the NTP group significantly outperformed the PLP group, on the DF Total Correct test ($F(1,45) = 5.96$, $p = 0.019$, Cohen's d=0.73) even when adjusting for the factors above. The result suggests that the NTP players had better EF capacity - more specifically fluent creativity, flexibility and adjustment - than PLP players.

5.3.3 Relation between Design Fluency and coach-rated game intelligence

The results from the coach rating of game intelligence suggested that that the NTP group had significantly higher game intelligence than the PLP group, - see Figure 12 B.

To better understand how game intelligence relates to DF, a correlational analysis between the results on DF Total Correct and coach-rated game intelligence was performed. The results showed a significant relation between the two factors ($r = 0.37$, $p = 0.008$) - see Figure 12 C. An analysis made with a non-parametric test with the same factors produced a similar result (CC: 0.39, $p = 0.004$). To exclude the possibility that the coaches ascribed higher level of game intelligence to the NTP group, due to the fact that these players actually are national team players, a partial correlation analysis was made to control for level of play (NTP or PLP). Still the correlation continued to be significant (r = 0.3, p = 0.032). An exploratory analysis did not show any significant relation between the rated game intelligence and the other cognitive test results measuring inhibition (CWI 3 and 4), short-term memory or working memory (CS, working memory and learning). See the supplements to the study.

5.3.4 Subcomponent analysis of Design Fluency

There are three different subtests in DF (DF1, DF2 and DF3). The tests are designed to stepwise increase the difficulty level. DF1 represents a fundamental aspect of Design fluency paired with working memory and creativity. DF2 adds a component of behavioral inhibition. Finally, in DF3 the performance level is increased by adding a demand of shifting (see Methods), i.e. an increased need of cognitive flexibility. Using these subtests, several exploratory analyses were performed. The results showed that both the NTP group and the PLP group were significantly better on all subtests than the norm - see Figure 13 A, B and C.

The results showed no significant difference between the NTP and the PLP in DF1 or DF2 (Figure 13A and B). In parallel to this, there was no significant correlation between the results of DF1 and DF2, and the coach-rated game intelligence, although there was a trend effect in the later one (r = 0.24, p = 0.09). Nevertheless, in DF3, representing the highest demand of these three subtests on cognition in general and cognitive flexibility in specific, a significant difference between the groups was found in favor of the NTP group compared with PLP (t-value = 2.48, p = 0.017) - see Figure 13C. The result of DF3 also correlated significantly with the game intelligence rated by the coaches (r = 0.39, p = 0.004). Finally, the results remained in a partial correlation analysis between DF3 and rated game intelligence, controlling for DF1 and DF2, (r = 0.352, p = 0.013). This strengthens the suggestion that high capacity of cognitive flexibility is linked to game intelligence, even if a general increased task demand in DF3 also could be an explanatory factor of the results.

5.3.5 Relation between Design Fluency and goals or assists

In contrast to a subjective coach-rated game intelligence, the results from the DF testing was also related to a more objective measurement of behavior, i.e. the number of scored goals and made assists for the season 2017-2018, divided by the number of played games. An ANCOVA analysis was performed where adjustments were made for age and position, as done in our previous study [1]. The analysis also adjusted for sex and low-level cognition (to specifically study HEF). The results showed a significant correlation between assists and DF Total Correct, $F(1,40) = 4.94$, p = 0.032 Cohen's d = 0.70. This correlation was even more evident when specifically studying the group of players that had made at least one assist. This ensures that the players usually were in position to produce assists, $F(1, 20)$ =9.75, p = 0.005, Cohen's d = 1.4. To achieve a normal distribution, assists were square root transformed. In contrast, there was no such effect between DF Total Correct and scored goals using the same ANCOVA, $F(1,40)$=0.49, p=0.49, Cohen's d = 0.22.

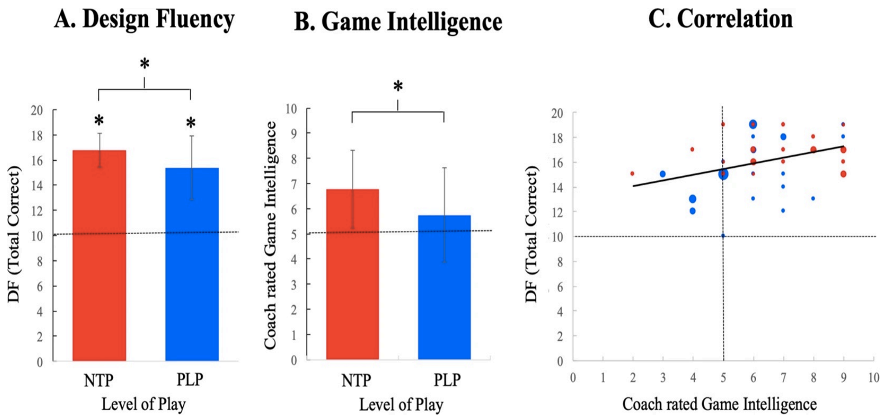

Figure 12. A. NTP and PLP compared with each other and the norm (dotted line). **B**. NTP compared with PLP in rated game intelligence in relation to a Swedish average premiere league player (dotted line). **C**. Results in Design Fluency of the tested players and its correlation with the coach-rated game intelligence. Reprinted from *Level of play and coach-rated game intelligence are related to performance on design fluency in elite soccer players.* Vestberg et al., (2020). Copyright©2020 with permission from Scientific Reports.

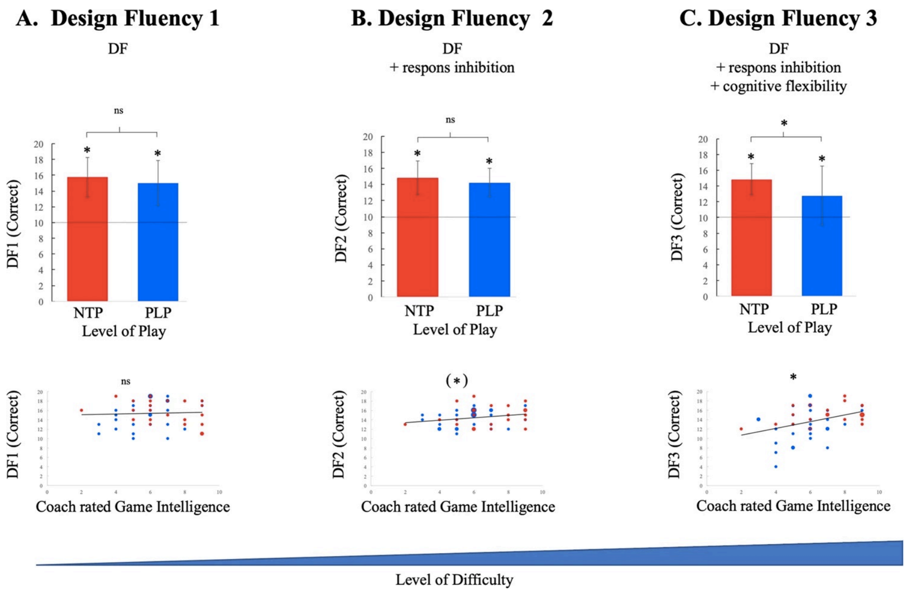

Figure 13. The group results of NLP and PLP on DF 1, 2, and 3 compared with the norm, each other, and in relation to coach-rated game intelligence (**A**, **B** and **C**). Reprinted from *Level of play and coach-rated game intelligence are related to performance on design fluency in elite soccer players.* Vestberg et al., (2020). Copyright©2020 with permission from Scientific Reports.

5.4 STUDY IV. EXECUTIVE FUNCTIONS OF SWEDISH COUNTERTERROR INTERVENTION UNIT APPLICANTS AND POLICE OFFICER TRAINEES EVALUATED WITH DESIGN FLUENCY TEST

5.4.1 Summary

- In the fourth study the hypothesis that HEF involving cognitive flexibility and creativity are of importance for success in a quickly changing enviorment, was reproduced in a different population, i.e. the special forces. The results showed that Counterterror Intervention Unit applicants performed better on DF Total Correct, including all its subtests, compared to police officers trainees.
- The study also showed that there was a significant correlation between baseline DF results perfomed in a relaxed enviroment and re-test DF results perfomed under physical and psychological stress in an extreme field condition.
- There was a significantly lower performance on the DF3 subtest performed in the stressful environment as compared to the baseline test-results.
- The individuals with the highest scores on DF3 had the most dramatic fall of the results in the re-test performed during the extreme field condition. However, in general, individuals with the best results at baseline also had the best scores when reassesssed.

5.4.2 NIA group compared with the POT group

The elite police force applicants (Nationella Insatsstyrkan Applicants; NIA) had significantly better results than the police officer trainees (POT) when including DF Total Correct, as dependent variable and group, age and sex as independent variables in a general linear analysis ($F(1, 71) = 18.98$; $p < 0.001$; $\eta_p^2 = 0.21$; Cohen's $d = 1.03$). Age and sex did not have any significant effect on DF Total Correct (Age, $F(1, 71) = 3.17$, $p = 0.079$, $\eta_p^2 = 0.043$; Sex, $F(1, 71) = 0.37$, $p = 0.55$, $\eta_p^2 = 0.005$). Levene's test indicated equal variances assumed for the dependent variable across the groups ($F = 0.488$, $p = 0.69$). The model assumptions were met using the Shapiro-Wilk test for normality of the residuals ($p = 0.11$). The mean of the NIA-group and the POT-group are presented in Figure 14.

5.4.3 DF subtests

The results of the three different sub-tests were similar to DF Total Correct. See **Study IV** for details.

5.4.4 Baseline assessment compared to the "field" assessment in NIA

5.4.4.1 DF Total Correct

A paired sample t-test was used to compare the baseline results of DF Total Correct with the results from the field assessment. There was no significant difference between baseline assessment (Mean = 14.98, SD = 2.44) and the "field" assessment (Mean = 15.30, SD =

2.27), *t*(39) = -0.86, *p* = 0.39. There was a significant correlation between the results of the baseline assessment and the results from the "field" assessment, *r*(40) = 0.49, *p* = 0.001.

5.4.4.2 DF subtests

DF1: A paired sample t-test showed a significant difference between baseline assessment (M = 13.95, SD = 2.84) and the re-test results (M = 15.25, SD = 2.84), *t*(39) = -0.2.53, *p* = 0.016, in that individuals performed better in the re-test (as expected due to learning effects associated with the DF-test). The correlation between the baseline assessment and the re-test result was significant (*r*(40) = 0.35, *p* = 0.029).

DF2: A paired sample t-test did not show a significant difference between baseline assessment (M = 13.68, SD = 2.67) and the re-test results (M = 13.98, SD = 1.78), *t*(39) = -0.8, *p* = 0.43. The correlation between the baseline assessment and the re-test result was significant (*r*(40) = 0.5, *p* = 0.001).

DF3: A paired sample t-test showed a significant difference between baseline assessment (M = 14.2, SD = 2.38) compared with re-test result (M = 12.83, SD = 2.23), *t*(39) = 3.79, *p* = 0.001 in that individuals performed worse in the re-test. The correlation between the baseline assessment and the re-test result was significant, (*r*(40) = 0.49, *p* = 0.001).

5.4.4.3 Relation between Baseline and Re-test of DF3

To better understand why the individuals performed worse in the DF3 re-test although an improvement is normally expected, a correlation analysis was performed. The baseline DF3 results were correlated with the difference in result in percent (baseline vs. re-test). Surprisingly, the result displayed a significant negative correlation *r*(40) = -0.46, *p* = 0.003. Higher result in DF3 at baseline gave a higher drop in the re-test result. When we adjusted for processing speed, working memory, and resting heart rate, the result remained, *F*(1, 35) = 9.16, *p* = 0.005, = 0.21 (Cohan's *d* = 1.03). Lower level cognitive capacity including Process speed and Working memory as well as resting heart rate, representing physical fitness [86, 87], did not have any impact on the score. Thus, the individuals with the highest scores on DF3 had the largest drop of the results in the re-test performed under hard physical and mental conditions. However, in general individuals with the highest baseline results still had the best scores in the re-test assessment – see Figure 15 and 16. The model assumptions were met using the Shapiro-Wilk test for normality of the residuals (*p* = 0.77).

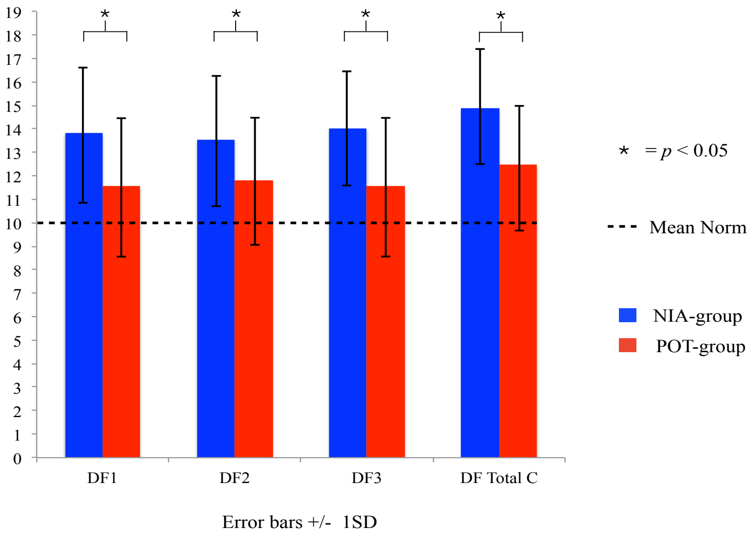

Figure 14. Mean and standard deviations of DF tests results in the NIA-group and the POT-group. Reprinted from *Executive functions of Swedish Counterterror Intervention Unit Applicants and Police Officer Trainees Evaluated With Design Fluency test.* Vestberg et al., (2021). Copyright©2021with permission from Frontiers in Psychology.

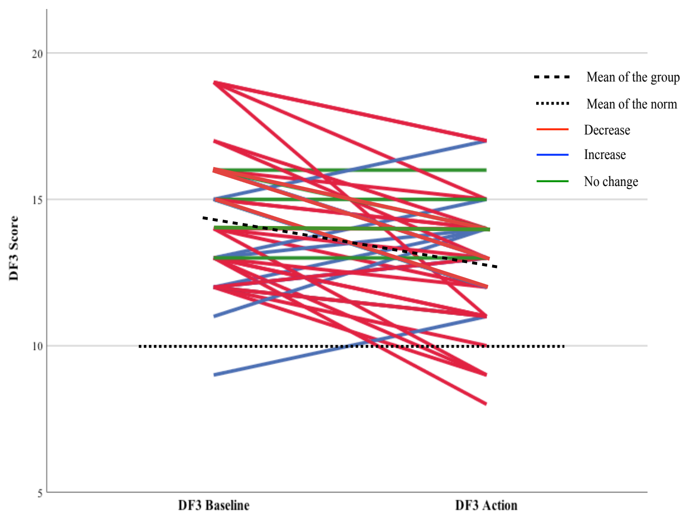

Figure 15. The results of DF3 during baseline assessment (DF3 Baseline) and during the stress test (DF3 Action) in all NIA participants. Reprinted from *Executive functions of Swedish Counterterror Intervention Unit Applicants and Police Officer Trainees Evaluated With Design Fluency test.* Vestberg et al., (2021). Copyright©2021with permission from Frontiers in Psychology.

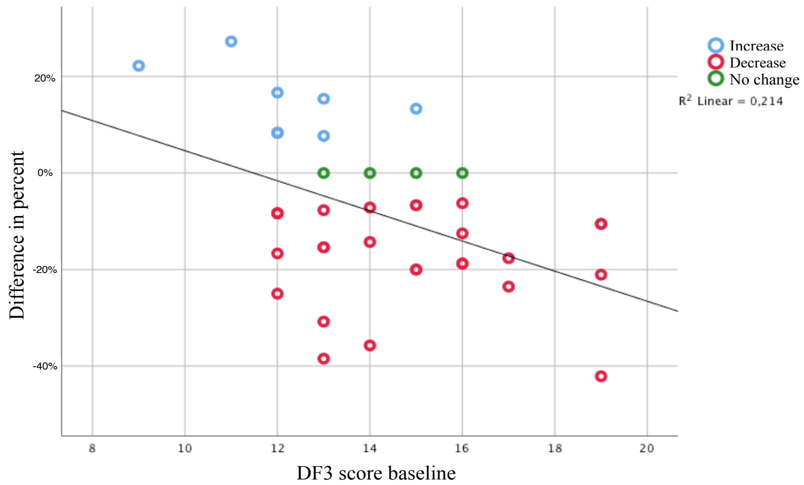

Figure 16. The difference in percent for DF3 results between baseline and the stress in all NIA participants between baseline and under pressure. Reprinted from *Executive functions of Swedish Counterterror Intervention Unit Applicants and Police Officer Trainees Evaluated With Design Fluency test.* Vestberg et al., (2021). Copyright©2021with permission from Frontiers in Psychology.

5.5 STUDY V. EXECUTIVE FUNCTION MEASURES OF COGNITIVE FLEXIBILITY ARE ASSOCIATED WITH DAYS OF SICK LEAVE

5.5.1 Summary

- In the fifth study a more general population was included - consiting of forklift operators, sellers, operational and strategic managers - as it has been suggested that cognitive flexibility and creativity is also associated with better outcomes in contexts that do not involve quick changes. One such outcome is health status, which can be indexed with days of sick leave. The result showed that there was a significant negative correlation between the number of sick leave days and a combination score of DF 1-3 and VF 1-3 (denoted as DFVF).
- When specifically studying individuals that had at least one day of sick leave the results remained significant.
- These results also remained significant after adjusting for sex, age, working group, processing speed, attention and CEF (including short-term memory, working memory, and inhibition). Importantly, as we adjusted for work group socio-economic conditions did not explain the results.

5.5.2 The relation between DFVF and sick leave in the full group

First an analysis was performed with all individuals. Since approximately a third of the total group of the participants did not have any days of sick leave for the last five years, the data was highly skewed. Therefore only a non-parametric test was performed on this group. This analysis showed a significant negative correlation between DFVF and sick leave (r_s (111) = -0.25, p = 0.007). Two individuals had a sick leave of more than 3 SD above the mean. After removing these individuals, the results remained (r_s(109) = - 0.23, p = 0.018).

5.5.3 The relation between DFVF and sick leave in individuals with sick leave

To further investigate the quantitative relationship between the degree of sick leave and DFVF, an analysis was performed in the group that had at least one day of sick leave during the last five years (n=74). A non-parametric test showed a significant negative correlation between DFVF and degree of sick leave (r_s (74) = -0.305, p = 0.008). Due to the skewed distribution of the data, a log10 adjustment was made on the sick leave data. When using the log10 transformed data, the significant negative correlation between sick leave and DFVF remained (Pearson's r; r = -0.34, p = 0.003) - see Figure 17.

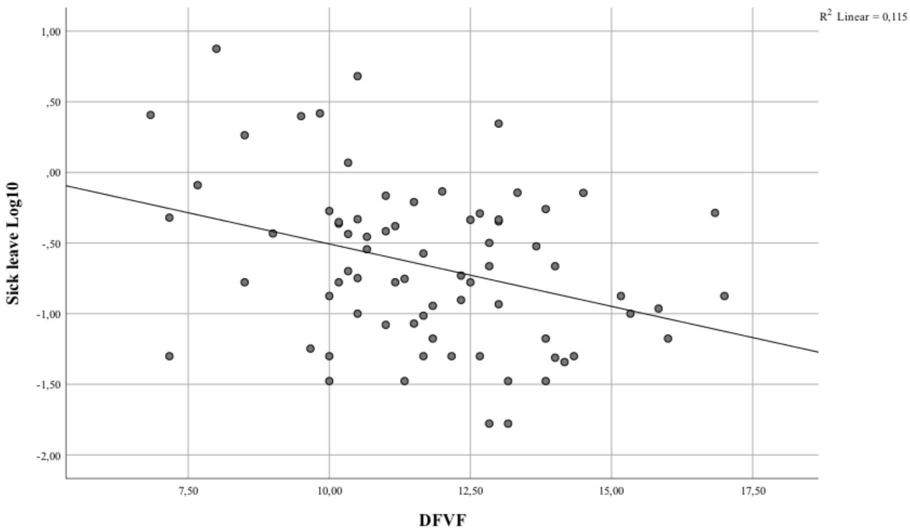

Figure 17. The correlation between DFVF and average number of sick leave days per month in the last five years (log10 transformed).

5.5.4 The relation between DFVF and sick leave when adjusting for other parameters

To study the relation between sick leave and DFVF after adjusting for sex, age, working group, processing speed, and CEF (including attention, short-term memory, working memory and inhibition), an ANCOVA was performed. The main effect of DFVF on sick leave was still significant (F(1, 62) = 10.84, p = 0.002, η_p^2 = 0.15, r = 0.39, d = 0.84), suggesting that better results on DFVF correlated with lower sick leave duration. We also found a significant effect of group ($F(3, 62) = 5.27$ p = 0.003, $\eta_p^2 = 0.20$, $r = 0.45$, $d = 1.00$) and inhibition ($F(1, 62) = 7.91$, $p = 0.007$, $\eta_p^2 = 0.11$, $r = 0.33$, $d = 0.7$), indicating that better inhibition capacity also correlated with fewer days of sick leave. The other independent variables (sex, age, working group, processing speed, attention, short-term memory, and working memory) did not show a significant effect on the score of Sick-leave Log10. The model adjusted R squared was 0.26. The model assumptions were met according to Levene's test of equality of residual variances ($p = 0.22$) and Shapiro-Wilk test for normality of the residuals ($p = 0.24$).

A contrast measurement showed a significant lower amount of sick leave among the strategic managers (p = 0.002, 95% CI [-0.96, -0.22]) as well as the operating managers ($p = 0.004$, 95% CI [-0.81, -0.16]) compared with the forklift operators. There was no significant difference between sellers and forklift operators ($p = 0.67$, 95% CI [-0.47, 0.30]).

5.5.5 Post hoc analyses of result of DFVF in the different working groups

Using Tukey's HSD test for a post hoc analyses on the whole group (n = 111), showed that the results of DFVF were significantly higher for the strategic managers ($p = 0.002$), operating managers ($p = 0.017$), and sellers ($p = 0.022$) compared with forklift operators.

A post hoc analysis made with Tukey's HSD on the group with at least one day of sick leave (n = 74), showed that the results of DFVF were significantly higher for the operating managers ($p = 0.031$) compared to forklift operators. Sellers ($p = 0.062$), and strategic managers ($p = 0.14$) did not have significantly better results than forklift operators.

5.5.6 The relation between sick leave and DF or VF separately

To examine if there was any difference between the verbal and the visuo-spatial part of the fluency measurement the same ANCOVA as above was performed separately for DF (Design Fluency) and VF (Verbal fluency) in relation to log10 sick leave.

The analysis showed that DF was significantly related to sick leave ($F(1, 62) = 5.97$, $p = 0.017$, $\eta_p^2 = 0.088$, $r = 0.30$, $d = 0.62$). A significant effect was also observed for group and inhibition ($F(3, 62) = 4.87$ p = 0.004, $\eta_p^2 = 0.19$; $F(1, 62) = 5.06$, $p = 0{,}028$, $\eta_p^2 = 0.75$). The other variables (sex, age, working group, processing speed, attention, short-term memory, and working memory) did not show a significant effect on the score of Sick-leaveLog10. The model adjusted R square was 0.2. The model assumptions were met according to Levene's test of equality of residual variances ($p = 0.17$) and Shapiro-Wilk test for normality of the residuals (p = 0.18).

The same ANCOVA analysis using VF instead of DF, also showed a significant effect on sick leave ($F(1, 62) = 7.08$, $p = 0.01$, $\eta_p^2 = 0.10$, $r = 0.32$, $d = 0.67$). There was also a significant effect of group ($F(3, 62) = 5.6$, p = 0.002 $\eta_p^2 = 0.21$) and inhibition ($F(1, 62) = 6.55$, $p = 0.013$ $\eta_p^2 = 0.096$). The other variables (sex, age, working group, processing speed, attention, short-term memory, and working memory) did not show a significant effect on the score of Sick-leaveLog10. The model adjusted R square was 0.22. The model assumptions were met according to Levene's test of equality of residual variances ($p = 0.16$) and Shapiro-Wilk test for normality of the residuals ($p = 0.41$).

6 DISCUSSION

The evolution of the human species has favored adaptation and the ability to adjust to the demands of a constantly changing environment as it increases the ability to compete successfully with other individuals and groups. A key feature to meet these demands has been self-regulation [9]. More specific cognitive processes such as *working memory*, *inhibition*, *flexibility* and *fluent creativity* are cornerstones for self-regulation and have been favored in evolution [9]. These cognitive mechanisms are called *executive functions* (EF). While much previous research has emphasized how behavioral function deteriorates when EF do not work optimally, the present project aims to show that they also are of immense importance for human success, especially when pursuing a goal in quickly changing environments.

There are many factors and skills that influence human behavior in a way that may lead to a successful outcome, including education, training and social cooperation. However, in a quickly changing environment unplanned adjustments are also crucial for a successful outcome. This project suggests that EF regulate information processing in such environments and thereby adjusts behavior in a way that leads to increased achievement of the behavioral goals.

Studying the impact of cognitive processing on successful behavior is difficult because many nuisance factors interact and interfere with real life behavior. To deal with this problem, many studies have been performed using various behavioral experiments, trying to control for all aspects except for the variable of interest. But this way of studying human behavior is far from how the brain and decision-making works in reality. By only studying one aspect at a time, there is a risk that we miss how different cognitive processes interact, as well as how they compensate for specific weakness in order to reach a goal.

A compromise is to study human behavior in a semi-controlled environment closer to real life behavior, but with a restricted framework that provides multifaceted opportunities of problem solving. Such an experimental setting would give a better understanding of the relationships between successful behavior and the underlying cognitive processes.

Soccer is performed in a strictly controlled area with clear and common rules all around the world, and involves problem solving with an aim to reach a goal that may be accomplished in many different ways. It also involves a quickly changing environment. Soccer is played by young and old individuals of both sexes, and has a commonly shared understanding by professionals, spectators and the public, of how success is defined. Therefore, this project regards soccer as an excellent opportunity to study successful human behavior in a context where adjustment is a key aspect. This makes it possible to use cognitive findings from soccer players to better understand how EF forms successful decision-making and behavior. Soccer has an obvious connection to the evolution of primates including humans as it has many resemblances to hunting a prey by a group of hunters. To be successful both in soccer and in hunting a prey, an individual needs to have a high capacity in behavioral adjustment. Soccer reflects the interaction between physical strength, speed and the adjustment derived by cognitive abilities.

EF are often measured as a part of a diagnostic assessment of different psychiatric disorders. The underlying idea of such assessments is that psychiatric disorders lead to a decline in the capacity of different EF subcomponents (as in schizophrenia and bipolar disorder) or have a low initial capacity (as in ADHD). A low EF capacity may therefore support a diagnosis. The results and cognitive profile may also suggest how serious the problems are and the nature of the behavioral problems that the patient may encounter in real life. Similarly, cognition has often been measured in connection with suspected concussion in sports [163-166]. For example, EF measurement assessed on the athlete in a baseline testing can been compared with the test result assessed after a suspected concussion. A significant decline provides support for the concussion diagnosis. By testing EF again, for example after fourteen days, it is possible to assess if the capacity has been restored. This can be used as an indication whether the athlete is ready to participate in the game again. Such use of EF measurement gives good support for both diagnosis and treatment [167].

In contrast, the purpose of the present project was to present a new angle on how to understand EF. Instead of treating EF as a passive set of variables surrounded and influenced by many different environmental factors, the aim was to investigate how EF supports real life behavior. This project therefore chose to study circumstances in real life where EF may be especially important, including human behaviors where a high capacity of adjustment through a mix of both divergent and convergent creativity paired with cognitive flexibility is needed to accomplish a goal. This project also studied whether age and the maturation of the brain were of importance for what types of EF were used in such behaviors, whether different sub-components of EF play different roles depending upon the situational demand and how EF work when humans are under physical and psychological pressure. Finally, this project also wanted to examine whether high EF capacity might be a resilience factor in everyday life.

In this project, EF capacity was assessed in altogether 324 individuals in relation to successful behavior. It is worth mentioning that each assessment takes approximately one hour to perform and each scoring of the results takes approximately two hours to complete. Thus, in total almost one thousand hours were spent on only performing the tests and calculating the results. Assistants under supervision by the PhD student performed approximately half of the tests, while all final scoring was always performed by the PhD-applicant.

Below the findings of this project are discuss and comment in a chronological order followed by specific key aspects including 1) the relation of our results to other studies on sport and cognition, 2) research on concussions and sport in relation to EF, 3) cognitive flexibility and 4) learning. Identifying limitations of this research project ends the discussion.

6.1 COMMENTS ON THE STUDIES IN THE PROJECT IN A CHRONOLOGICAL ORDER

In **Study I** [1] twenty-nine elite soccer players from the highest division in Sweden were tested. They were compared with twenty-eight semi-elite players from lower divisions. The players consisted of both men and women and were chosen by their coach to represent the average player's capacity in the team.

In line with our hypothesis, the results showed that elite soccer players were significantly better in their EF capacity than the semi-elite players. This was especially evident for higher-level EF (HEF) when cognitive flexibility, fluent creativity and cognitive adjustment were used together in problem solving (as a part of the Design Fluency test; DF). The result remained after adjusting for age, playing position and level of education. The results of the elite players were on average close to one SD above the average result of semi-elite players and there was no effect of sex.

In part two of the study, twenty-five players were followed for two and a half year in regards to the number of goals and assists they performed during this period. The results showed a medium strong and significant correlation between their results on DF and the number of goals and assist the players made during this period. Thus, their HEF capacity could predict their future performance, a finding that has been reproduced in several studies both on soccer [168-173] and other ball sports [174-182].

The result from **Study I** strengthens the project hypothesis that adjustment derived by self-regulation through HEF, plays a vital role both for the individual and for the team to act successfully. It also opened up for **Study II** [2] where we wanted to investigate the importance of EF in younger individuals. This was especially interesting since there is a fast development of EF during adolescence, in which HEF develop late [23, 131]. Again, we chose to study soccer for the same reasons as in the first study, and to be able to compare the results with the adult players. We hypothesized that EF also are important for successful behavior in children and teenagers during similar environmental constraints (large amount of information that is quickly changing), but that HEF are of less importance since their brains have not fully developed (which is mirrored in more simple play). Instead, CEF should be of greater importance in this group of soccer players. Since the players are sorted based on their age, they also differ in their physical maturation including the brain maturation. This leads to a hypothesis that EF should play a lesser role for success on a junior level than on a senior level.

Based on the assumption that soccer played in younger age is simpler compared to soccer played on senior level and therefore less dependent on assists, we primarily measured goals as a proxy for successful behavior. The coaches from a Swedish soccer academy chose a group of forty-nine players (12 to 19 years old) representative for the performance level of their age group. From this group, thirty players were selected through the qualification of having played at least one game and scored at least one goal over a period of two years (since some players that did not score goals did not play many matches).

The study showed a moderate relation between the capacity of the working memory, representing CEF, and the number of scored goals in average per played game during a period of two years. In line with the hypothesis, there was a weaker but still moderate correlation between HEF, represented of DF Total Correct, and the number of scored goals compared with the result from **Study I** and soccer behavior on senior level. The results remained when adjusting for age, IQ, and height (as a proxy for physical maturation).

The data showed no correlation between IQ and scored soccer goals. This suggests that IQ, in this case, has a weak relation to successful soccer behavior where there is a need for fast and accurate decision-making – at least in junior players.

The result from **Study II** conceptually reproduced the outcome from **Study I** in that HEF in the form of cognitive flexibility, creativity and flow are important for success in soccer. This strengthens the hypothesis that self-regulation through EF also is important for successful behaviors in younger age. Due to the maturation of the brain CEF seem to play a more prominent role than on senior level. This likely contributes to a less complex game with fewer assists.

In **Study III** [3] we investigated whether self-regulation capacity also has a pivotal role at the highest level of play, i.e. in the performance of national team soccer players. In this study, we wanted to explore the role of EF in successful soccer behavior in more detail and address some of the limitations in our previous studies. For example, we aimed to address whether learning could have had a role in the difference between levels of play as observed between elite and semi-elite players in **Study I** and whether cognitive flexibility was the main driver of their success. We also wanted to have a better quantification of successful play than measurements of scored goals and made assists.

In the study, we compared premier league players that had played in national teams to premier league players that had not played in national teams on senior level. National team players exercise, compete and practice together with their teammates who do not play for a national team. The only environmental difference between the two groups consists of some weeks each year when the national players represent their nations in international tournaments. Thus, the effect of learning due to more training hours is less of a confounder in **Study III** than in **Study I**, where this is a true concern (as premier league players train significantly more than lower league players). Yet, on a whole, national team players are regarded as more proficient than other premier league players. As in previous studies we used DF as the main test due to its combination of convergent and divergent creativity, cognitive flexibility, and fluency as well as other EF components such as working memory and inhibition, mirroring a mix of cognitive processes that are used in real life situations with large information load and fast changes. Out of the fifty-one men and women that were tested, approximately half had played for a national team. Some of the best soccer players in the world were a part of this group. The results showed significant differences between the two groups in favor for the national team group concerning their DF capacity. The results correlated with the coach rating of game intelligence and the number of assists the players made during the latest season.

Moreover, the results suggested that in the EF chain of different but interacting EF components, cognitive flexibility was especially crucial for success on this top level. Namely, the DF3 showed a significant correlation with the coach rating of game intelligence, even when adjusting for DF1 and DF2. This suggests that cognitive flexibility may be the most predictive variable for game intelligence. However, it is possible that other factors such as ceiling effects contributed to the result. The finding of the prominent role of cognitive flexibility highlights that adjustment plays a significant role for a successful behavior in a context consisting of much information that changes quickly.

The purpose of **Study IV** [4] was to generalize the findings from soccer to other real life situations, in line with the hypothesis that EF are critical for behavioral adjustments and have developed under an evolutionary pressure to increase survival of the species. Especially, such adaptive behavior would be central in any situation where there is a large amount of quickly changing information and a need to reach a goal with a high value. Thus, the importance of EF for successful behavior should be observed in many different situations with a similar context. A logical step would therefore be to study areas that resemble soccer in terms of information processing.

Given these general ideas, we chose next to study police officer applicants to the Swedish Counterterror Intervention Unit. As in soccer, their assignments include a large amount of information and quick changes, as well as working together in a group. Moreover, the contexts they work in include real risks and life-threatening situations. On an evolutionary level this resembles hunting in a group because some situations involve the use of weapons and the risk of devastating consequences if the behavior fails.

Seventy-five police officers were recruited in total. Out of these, the test group consisted of forty-five applicants to the Swedish Counterterror Intervention Unit who had passed tough psychological and physical tests for over a half year which most of the initial applicants had failed at some stage. The final step included a decisive field-assessment before being considered to become a part of the counterterror intervention unit. The field-assessment consisted of ten days of extremely difficult and stressful tests. The control group consisted of thirty individuals from the police officer training academy.

The baseline result showed that the applicants for the counterterror intervention unit performed significantly better than the police officer trainees in the DF Total Correct, mirroring the results from the earlier studies in soccer where a difference was observed between elite and sub-elite soccer players.

The applicants were also tested with DF (as well as a Stroop test) after several days in the field assessment. Several findings emerged. First, there was a correlation between the baseline test and the field assessment results. High results in the baseline test were significantly associated with high results in the re-test performed when the test group was under extreme physical and psychological stress. Second, the results were significantly weaker on the re-test compared with the baseline test, which was unexpected. Taken into account the loss of the novelty factor, the re-test results of DF Total Correct should have been higher than observed [149]. Even a drop in performance was observed for DF3. This result suggests how sensitive EF capacities are when humans are under stressful pressure. Finally, the individuals that showed the highest capacity in the baseline DF test, showed the greatest reduction of the results in the re-test performed during the extreme field condition (although individuals with higher results in baseline still had the best scores at the re-test assessment in general). The same reduction of results was not seen for the Stroop test. The fact that the best performers had the largest percentage decrease in results may be attributed to that many prefrontal functions have an inversed U-shaped curve of functional capacity [183]. Thus, those individuals that are at the top of their performance during baseline will worsen when more is required of them and those individuals that are not at the top of their performance at baseline will perform better than their baseline performance in such a situation. However, the differences in results may also be attributed to a “regression to the mean effect” [184]. In sum, hard physical and psychological pressure had an extensive impact on the cognitive flexibility.

Study IV generalizes the previous findings in **Study I, II,** and **III** by suggesting that EF are important for successful behavior in other situations than ball sports (e.g. soccer) that are characterized by a large information load and fast changes. Also, the results suggest that cognitive flexibility is especially vulnerable when humans are under heavy pressure.

In **Study V** [5] we wanted to test whether HEF in general, and cognitive flexibility in specific, also have relevance in a normal population. Many psychological therapies and constructs (including acceptance and commitment therapy [44-46], metacognitive therapy [48], resilience models [49, 50], and locus of control models [51]) emphasize the importance of executive functions in theory and psychological flexibility measured by self-rating instruments for health and well-being. However, the link between EF-capacity and such health outcomes has not been explored in a general population. We wanted to investigate if we could show a link between measured cognitive flexibility capacity and well-being and set out to test this relationship in an experimental study.

We chose to work with a mid-sized company and tested one hundred eleven individuals consisting of equal parts of forklift operators, sellers, operational and strategic managers. The same tests were used as in the previous studies. Once again we used DF as our main test representing a mixture of convergent and divergent fluent creativity in combination with a highlighted demand of cognitive flexibility and fluency as well as several other EF-components. Since verbal language is more important in everyday working life than in soccer and in the special forces, a verbal fluency test was included as well, and a composite score was constructed of Design Fluency and Verbal Fluency Test (denoted DFVF).

A common outcome measurement for health and well-being for the four working groups was difficult to find. However, the amount of *sick leave* may represent such a common variable suggesting a health outcome that is important in all groups. The theoretical idea was that although it is difficult to avoid sickness, cognitive factors that impact decisions when to go on sick-leave and when to return to work would be related to the ability of cognitive flexibility and behavioral adjustment.

The results suggested a significant negative correlation between DFVF and the amount of sick leave of the employees during the last five years. Even after adjusting for sex, age, working group, processing speed, and other cognitive capacities as CEF (like attention, short-term memory, working memory, and inhibition) the results remained. Thus, the results mirror previous theoretical considerations in different psychological models and self-ratings of behavior that suggest that EF [48-51] in general and flexibility in specific may be seen as a resilience factor for health.

6.2 THE RESULTS OF THIS PROJECT IN RELATION TO OTHER STUDIES IN THE RESEARCH FIELD OF SPORTS AND EF

Before this project, few studies had focused on how general EF relate to successful sport behavior including soccer. However, other aspects on sports and cognition have been studied previously [185]. For example, processing speed among junior soccer players [186] as well as the importance of sport-specific perceptual focus for success has been investigated before this project started [185, 187]. Also, a study on general attention has previously shown that elite volleyball players made fewer errors than sub-elite players and rowers [188]. Core executive functions, such as working memory have been studied as well before our first soccer study, but only on basketball players from lower divisions compared to non-athletes. The results showed no significant difference between the groups [189]. To our knowledge, research on how general EF – including inhibition, cognitive flexibility and HEF – relate to successful sport behavior in elite athletes has not been performed or published before this project started.

6.2.1 Soccer

Following our first study on EF and soccer behavior [1], a number of studies on how general EF capacity relates to a variety of different sports, including soccer, have been published. Three Dutch studies focusing on soccer and EF [168-170] performed on young non-athletes, semi-elite players and top academy players, with an age range of eight to seventeen (n=126; n=88; n=168), showed that the elite players had significantly higher inhibition capacity than the sub-elite and non-athletes. One of these studies also used Design Fluency which was the main test in all studies of this project and confirmed the results from **Study I** [1] showing that the elite players had significantly better cognitive flexibility and HEF compared to sub-elite players [169].

A study made on applicants to a Japanese soccer academy (n=383) studied junior players with an age range between eight to eleven [173] and used a Stroop test to measure inhibition and CEF as well as a short version of the Design Fluency test. The players were also tested for their emotional state, social support, grit and resilience. After the applicants were tested for their EF capacity, eight coaches with extensive soccer experience studied the applicants when they played soccer in three short games. Through consensus between the eight coaches, 196 of the applicants were accepted to the academy. The study showed that the successful players, tested for their EF capacity before the coaches evaluated the players, (with no knowledge of the EF test-results) had significantly better results on the Stroop test and the Design Fluency test than the rejected players. Interestingly, there were no significant differences between the two groups of players concerning mental health and social support. Moreover, the rejected group had higher self-rated scores for grit score and resilience than the accepted players. This suggests that the EF capacity is more important than applicants' mental strength for successful soccer behavior. Finally, repeated errors in the Design Fluency test (i.e. using the same solution twice) was the main error in both groups, suggesting that it was not the capacity of the working memory that was the main factor for the results [173]. Instead, the success factor for the accepted players was cognitive flexibility and creative capacity resulting in more design solutions according to the researchers. The results from the Japanese study was in line with the results from **Study II** [2] suggesting that HEF that includes cognitive flexibility, creativity and fluency is of importance for success also in young players. However, in our study we also showed that working memory is of equal, if not larger importance for success in young players. On a more general level the Japanese study is in line with all three of our studies suggesting that Design Fluency captures successful behavior in soccer [1-3].

A recent soccer study from Germany, yet available only as a preprint, [190] is of particular importance since it also includes senior elite soccer players (as **Study I** and **Study III**). The players' age ranged from twelve to thirty-four and included a fairly large number of individuals (n=156). The measured EF were working memory, inhibition and cognitive flexibility (TMT). The results showed a significant correlation of a moderate effect size between game intelligence and working memory as well as cognitive flexibility, confirming the main outcome from **Study III** [3]. Importantly, in this study game intelligence of the individual players was also assessed as in **Study III** [3]. Eight main coaches from the players' different teams rated the game intelligence. As in our study [3] a correlation was observed between rated game intelligence and the EF capacity. Moreover, the German study took one step further by showing that EF correlate with the players' rated game intelligence already on a junior level.

Apart from the soccer studies, research that focuses on general EF and sport behavior has been performed in a variety of other sports. Below are some examples.

6.2.2 Tennis

A study on junior tennis players [182] that included twenty boys and twenty girls (of age 9 to 15) showed that the results from a modified version of the Design Fluency test could predict the players tennis ranking level 18 months after the assessment. This result was in line with the results from all of our soccer studies [1-3] showing a correlation between Design Fluency and successful sport performances.

6.2.3 Table tennis

Table tennis players have also been studied in relation to their EF capacities [191]. The tests that were used to capture the athletes' EF abilities included CWI, TMT and Design Fluency, i.e. the same tests that were repeatedly used in this project. Thirty elite players vs. thirty semi-elite players were compared (M^{age}=16). The results showed that the elite table tennis players had significantly higher scores on the tests than semi-elite players. In CWI 3 and 4, when adjusted for training hours, the results remained in relation to number of made errors, where the elite players still were better. As table tennis is considered as a less open sport compared to soccer, ice hockey, and basketball, the need for EF and cognitive flexibility, inhibition and creativity could be different depending on the fact that more open sports provide a larger number of opportunities for solutions and thus could require better executive abilities. However, the study indicates that inhibition in table tennis could play a significant role for a successful adjustment, in line with the results from this projects **study I, II** and **III** [1-3].

6.2.4 Basketball

A small study on elite basketball players [180] (n=12), semi-elite players (n=12) and amateur players (n=10) showed that the elite players had significantly higher scores on the Stroop-test and the Design Fluency test than the two other groups. This result confirms the results from the **Study I** and **Study III** [1, 3] by showing significant differences between elite and sub-elite players.

6.2.5 Ice hockey

A study that tested elite and semi-elite ice hockey players [174] (n=48) with the Design Fluency test showed that center forwards had significantly higher scores than players in other positions. An ice hockey performance measurement based on number of scored goals of the team while the players were on the ice, was calculated. The result showed a significant correlation between TMT 4, measuring cognitive flexibility and scored goals. The study confirmed our finding of an association between successful sports behavior and EF. Moreover, it moved the research field further ahead by indicating that there could be a specific EF profile depending on the position, responsibility, and mission a player has on the team.

6.2.6 American football

A study on 280 semi-elite American football players [175] from five university teams, division 1 (M^{age}=19,9), also highlighted that a specific EF component could be more or less important for a specific position in the team. The focus of the study was to test inhibition skills. The football players were compared with 35 age-matched controls (university students with no experience of sporting participation at university level). The results showed that there was no significant difference in reaction time between the players and the controls. However, the football players had a significantly better inhibition ability than the controls. Further analyses showed that defenders had better inhibition skills than the offensive players on a group level. The researchers suggested that the players' inhibition ability could be important when it comes to the selection of players for the team and for the development of cognitive control during games. The results from this study confirmed the results from **Study I, Study II, and Study III** [1-3], showing that inhibition is an important ability in sports and that reaction time/processing speed have no significant impact for successful sports behavior.

6.2.7 Badminton

A study has also been performed on badminton players [177] and their inhibition skill which showed similar results as the American football study discussed above. Forty-two badminton players from ages 19 to 26 and fifteen non-athletes from ages 23 to 27 participated in the study. The results showed no differences in reaction time between the groups. However, when it came to inhibition skills the badminton players had significantly better results than the non-athletes. Moreover, the higher ranking the badminton players had in the national ranking system (i.e. Taiwan) and in the world ranking system, the better they performed in the test ($r = 0.442$, $p = 0.003$). This result confirms the results from **Study I**, **Study II**, **and Study III** [1-3], showing a significant correlation between the athletes EF capacity and their sport performances. The results from the Taiwanese study also confirmed the results from **Study II and Study III** [2, 3] that showed no significant impact of reaction time/processing speed for successful sports behavior.

6.2.8 Deviating results

Out of a large group of studies that support our initial hypotheses, two studies have shown deviating results [189, 192]. A basketball study, previously mentioned [189], showed no significant differences in spatial working memory between basketball players and individuals not playing basketball. However, as the basketball players were not playing on an elite level, the study did not properly mirror our first and third studies' research performed on elite players in the highest divisions and national team level. Also, only CEF-related abilities were tested, which may not be decisive in basketball. Finally, it should be noted that the test used in the study (Corsi block tapping measuring the ability to mimic and reverse movement sequences of the test leader) might not capture executive function components that are relevant to basketball. Notably, no test of cognitive flexibility or inhibition was included. Importantly, the study did not show an opposite result, i.e. that the basketball players had lower capacity than the control group.

The other study that did not support our findings was an investigation of the cognitive capacity in a cohort of rugby players [192] where elite players were compared with semi-elite players (n=79; elite=55, semi-elite=24). This study better mirrored the hypothesized model of this project, by comparing elite with semi-elite players. However, the rugby study measured different cognitive aspects such as verbal memory recognition, digit span recall, and simple reaction time. The only test that was related to the tests we used in this project was the Stroop test, i.e. a CEF-test. No HEF capacity was investigated. Also, as the rugby study performed the assessment in the traditional experimental way by trying to adjust for all variables except one, it may fail to identify the whole executive chain needed for a successful behavior. One test in the rugby study showed a small but not statistically significant difference between the groups. It was the verbal recognition memory test in which the semi-elite group performed better than the elite group. Given that rugby is a distinct contact sport, it would be of interest to test elite rugby players on Design Fluency, and especially DF3 due to its special focus on cognitive flexibility since this cognitive process has been suggested to be particularly sensitive to concussions [164].

Study	Main Test	Co-tests	Level of play	Correlation	Norm	Age	Number of subjects
Soccer							
Vestberg et al 2012	DF*	CWI*, TMT*, CS	Yes* (E/SE)	Goals & Assists*	Yes*	Adults	n=57 (M/F)
Vestberg et al 2018	DF*	CWI, TMT, CS	No (FA)	Goals*	Yes*	Junior	n=30 (M)
Vestberg et al 2021	DF*	CWI*, TMT, CS	Yes* (E)	Goals^{ns}, Assists*, GI*	Yes*	Adults	n=51 (M/F)
Verburgh et al 2014	SSRT*	ANT*, WM	Yes* (E/A)	No	No	Junior	n=124 (M)
Huijgen et al 2015	SSRT*	DF*, TMT*, WM	Yes* (E/A)	No	No	Junior	n=88 (M)
Verburgh et 2016	SSRT*	STM*, WM*, ANT	Yes* (E/SE/Non)	No	No	Junior	n=168 (M)
Sakamoto et al 2018	DF*	Stroop*	Yes*(App/Rej)	No	No	Junior	n=383 (M)
Scharfen & Memmert 2021	WMC*	TMT*, SST	No	GI	No	Junior/Adults	n=156 (M)
American Football							
Wylie et al 2018	FlankT*		Yes* Off/Def/Non	No	No	Adults	n=315 (M)
Vollyboll							
Alves et al 2013	Tswitch *	FlankT*, ST*, AT	Yes* Athlete/Non	No	No	Junior/Adults	n=154 (M/F)
Ice Hockey							
Lundgren et al 2016	DF*	TMT4*	Yes (E/A), Position*	Statistics*, GI	Yes*	Adults	n=48 (M)
Table tennis							
Wang et al 2016	ANT	Congru, Ingru*	Yes* Athlete/Non	No	No	Adults	n=65 (M/F)
Elferink-Gemser et al 2018	DF*	CWI*, TMT*	Yes*, (E/SE)	No	Yes*	Junior	n=60 (M/F)
Basket ball							
Alarcón et al 2017	DF*	CWI	Yes* (E/SE)	No	No	Adults	n=34 (M)
Tennis							
Ishihara et al 2019	DF*		No	Yes*, Ranking	No	Junior	n=40 (M/F)
Badminton							
Liao et al 2017	SST*	SSRT	Yes* Athletes/Non	Yes*, Ranking	No	Adults	n=57 (M/F)
Mixed ball-sports							
Faubert et al 2013	3D-MOT	WM	Yes* (E/SE/Non Socc/Rug/Hock)	No	No	Adults	n=308
Wang et al 2013	SST*		Yes* Tenn/Swim/Non	No	No	Adults	n=60 (M)

DF=Design Fluency; CWI=Color Word Interference; CS=CogState Sport (low level attention); TMT=Trail Making Test; SST=Stop-Signal-Test; GI=Coach-rated game intelligence; F=Female players; M=Male players; *=Significant

Table 1. Studies showing a significant relation between executive functions and performance in ball sports.

Study	Main Test	Co-tests	Level of play	Correlation	Norm	Age	Sex and number of players
Rugby							
Kruger et al 2019	WordMem*	Att/DigSpan/Reaction	Yes*	No	No	Adults	n=79 (M)
Basketball							
Furley et al 2010	SpWM		Athletes/Non	No	No	Adults	n=112 (M)

*=Significant

Table 2. Studies not showing a significant relation between executive functions and performance in ball sports.

6.3 CONCUSSION, SOCCER AND CONSEQUENCES FOR COGNITION

Studies on how concussions impact the cognition of soccer players suggest that professional soccer may be associated with cognitive decline and neurodegenerative diseases. The death cause of 7,676 former Scottish male professional soccer players born between 1900 and 1976 were investigated and matched against 23,000 controls from the general population [193]. The results showed that the soccer players were three and a half times more likely to suffer from dementia and other serious neurological conditions, as well as a five-fold increase for Alzheimer's disease, a four-fold increase for motor neuron disease and a two-fold increase for Parkinson's disease. These negative outcomes are thought to be a consequence of concussions and possibly ball headings, but the study was unable to establish a link between these. Other reports have suggested that some cognitive functions such as memory can be negatively altered in professional and amateur soccer players [194, 195]. However, other studies have not been able to find such effects, at least related to ball heading [196]. Also, the studies in this project were not able to identify lower capacity in age-normalized executive functions, which would be expected if concussions throughout the players' active history would have had an additive negative effect on cognition. Notably, most studies so far have been cross-sectional, using simple measurements of cognition and not relating the findings to brain morphology. In sum, research suggests that the relation between higher order cognition and soccer is not straightforward and there is a need to study large samples of individuals on an elite level longitudinally with both complex HEF tests and brain imaging. Also, at present, measures of cognition performed acutely after concussions are often specifically studying low level cognitive processes or CEF [197], missing out on HEF including cognitive flexibility, creativity and fluency – processes that are likely sensitive to brain damages.

6.4 COGNITIVE FLEXIBILITY

In several studies of this project we claim that we measured cognitive flexibility. However, do we? And what is cognitive flexibility? This section takes a critical account on these questions in relation to the discussed studies.

A common thread in all five studies presented in the thesis is that Design Fluency was used as the main test. Design Fluency is often interpreted as a measure of cognitive flexibility [23, 148]. However, it is essential to keep in mind that DF is an assessment of higher order executive functions (HEF) involving several cognitive processes including low level processes such as general attention and processing speed as well as core executive functions (CEF) such as working memory and inhibition. DF capacity is also highly dependent on creativity and fluency. Finally, other information processing variables such as basic perceptual processing and motor planning components may impact the test results [155]. In several of our studies we have tried to adjust for such confounding factors.

In **Study I,** we only adjusted for non-specific factors that could indirectly affect the results (e.g. age, sex and educational factors) when we compared levels of play, and we adjusted for age in the prospective correlational analysis (only performed in men). Both level of play and future success were still significantly related to the measured DF capacity. The adjustment for age and sex has already been performed in the normalized scores for D-KEFS [148]. However, we also tried to account for an interaction between these variables and type of play. The adjustments tried to narrow down the cognitive factors that are important for successful behavior in soccer, but still a variety of components in DF (presented above) could explain the behavior.

In **Study II**, we also adjusted for an approximation of IQ assessed with Raven's Standard Progressive Matrices [198] in the correlational analysis. Both DF and dWM were still related to success in terms of scored goals. However, as in **Study I**, many cognitive components apart from cognitive flexibility could have explained the results.

A more careful approach to test whether the cognitive flexibility was a main factor for successful behavior in soccer was applied in **Study III.** Here, we adjusted for several general cognitive factors (perceptual speed and low level attention) and other core executive functions (e.g. working memory) in the comparisons between levels of play. The results showed that a difference for level of play survived such adjustments. As we reasoned that the Stroop test also contains a cognitive flexibility component, we did not adjust for performance in this task.

We also used another approach to test for the same question in **Study III**. Namely, out of the three DF subtests (DF1-3), DF3 has been shown to contain a specific cognitive process that is thought to be related to switching by alternating between black and white dots. This finding was observed by applying latent variable analysis to a large dataset [148]. Building on this result, DF3 has been suggested to be even more specifically related to cognitive flexibility than DF1 and 2 [150]. In our study, we could show that only DF3 was related to a difference between the two levels of play. Moreover, it was the only one of the subtests that correlated significantly to the coach assessment of cognitive flexibility, a result that survived after adjusting for DF1 and 2. These results further suggest that cognitive flexibility is a main factor in successful soccer behavior, as DF1 and 2 contained all other cognitive processes including creativity and fluency. However, it should be acknowledged that possible ceiling effects in DF 1 and 2 could have contributed to such differences. Moreover, as elite players scored significantly higher than the norm in all DF subtests, the results suggest that other cognitive aspects measured with DF are also important for success in soccer.

Although **Study IV** is about requirements to become an elite police officer, many similar components are of importance as in soccer. For example, the ability to act precisely and goal oriented in quickly changing environments where both level of stress and fatigue are high, as well as the ability to cooperate in a group. Here, DF was also compared between two putative levels (police officer trainees were defined as a lower level group in regards to the requirements). In a similar fashion as in **Study III**, we adjusted for perceptual speed and working memory. Also, here the results were significant when the two levels were compared.

Another way to understand the involvement of cognitive flexibility in success of the behavior associated with elite soccer and police force requirements is to study the results from other tests that involve cognitive flexibility such as the Stroop task, i.e. Color Word Interference Test (CWI) in D-KEFS [148] and Trail Making Test (TMT4) [148]. A main cognitive factor in the Stroop task is behavioral inhibition. However, cognitive flexibility is also an important aspect of the Stroop task. While CWI3 is a standard version of the Stroop task including some cognitive flexibility, CWI4 also contains a task-switching component (different rules apply when there is a square around the word) making it especially demanding in regards to cognitive flexibility. Interestingly, both in **Study I** and **Study III** only CWI4 (but not CWI3) explained the difference between levels of play. In regards to TMT4, this test showed a difference between levels of play of soccer in **Study I**. In **Study IV** the elite police force group outperformed the control group significantly in all tests, except in one, where the two tested groups were compared. Thus it is not possible to discuss specifically cognitive flexibility.

The results above suggest that cognitive flexibility is of importance for elite performance in soccer and special forces. But even if we were able to isolate cognitive flexibility, this cognitive process actually contains several subcomponents supported by different processes including 1) a need to detect a novel stimulus (determined by its salience), 2) a need to allocate attention to the new stimulus (an attentional factor that may be of both bottom-up and top-down nature), 3) working memory components to remember the rules and 3) inhibition of allocating attention to the previous stimulus [122, 199].

It is important to acknowledge that DF, the test that showed the clearest association in our studies, also involves a creativity aspect and a cognitive flow component [23]. In theory, these variables, especially creativity, should be key factors for successful behavior in order to reach a goal in a quickly changing environment. Thus, it is likely that also these cognitive components, that are not included in CWI or TMT, are of importance. Studies with more power could therefore compare tests involving cognitive flexibility that differ in creativity and flow to better elucidate these specific components. Also, other tests that measure cognitive flexibility that include other cognitive aspects, such as the Wisconsin Card Sorting Test [200], would be interesting to test in relation to DF in elite ball sports and police forces.

Although cognitive flexibility seems to be a key aspect, our studies and theoretical considerations suggest that it is the combination of several executive function components that best mirror a successful behavior in a quickly changing environment. Therefore, a perfect test for measuring only cognitive flexibility would probably not be the best test to predict success in the behaviors that we have studied. In line with this idea, in **Study II** we have shown that an index score had the best explanatory value for behavioral success (as least in children).

Study I - IV all try to understand which executive function components are important for adapting in a quickly changing environment. However, we argue that similar functions are central in other aspects of life. For example, cognitive flexibility should be of importance to integrate several lines of information processing channels if the information content is complex and information load is large, especially when an individual needs to view information from several angles and adjust to new ideas. Leadership may be an example of a position that involves such aspects of information processing. In line with this idea, it has previously been shown that EF and cognitive flexibility are key features of transformational leadership [201]. Other studies have suggested a relation between behavioral regulation or EF capacity and academic achievement [136, 202, 203].

Behavioral and mental flexibility has also been suggested to be key features for health outcomes and well-being in several psychological constructs such as metacognitive theory [48, 204-206], psychological flexibility [45-47, 207], resilience [49, 50, 208], and locus of control [51]. However, studies of the relation between these psychological models and capacity of EF in general and cognitive flexibility in specific, in regards to health outcome, have been scarce. In **Study V**, we directly tested whether better results on DF also mirrored a better health outcome indexed by days of sick leave. We found that, over a range of positions from managers to blue-collar workers, both Design Fluency (DF) and Verbal fluency (VF) capacity were inversely related to days of sick leave (in combination and independently). This effect was not dependent on socio-economic status, as the results remained after adjusting for the various work positions. The results also remained after adjusting for several confounds including processing speed, low level cognitive processes, simple attention as well as short-term memory, working memory and inhibition. Also, CWI was related to number of sick days. This may indicate that cognitive flexibility is specifically related to health outcomes. However, DF3 and VF3, associated with most cognitive flexibility, did not differ notably from DF1-2 and VF1-2, suggesting that general creativity and flow may be of importance. Also, even though previous studies suggest a relation between EF capacity and sick leave in patients [209, 210], our study is novel in suggesting a similar relation between EF capacity and health outcomes in an ordinary workforce. Therefore, replications with even more detailed adjustments of confounds are needed (several such possible confounds are discussed in the article). Also, it would be of interest to better understand how cognitive capacity measured in a lab setting translates to psychological flexibility, which deals with real life behavior, often on a much more prolonged time scale. Finally, it is of interest that managers showed higher EF capacity than forklift operators, in line with the idea that leadership positions require more adaptation [201].

6.5 GENES AND ENVIRONMENT

The purpose of this project was to explore the relation between successful behaviors and EF. We did not aim to study whether these functions are innate or acquired. However, nearly everyone that has been in contact with this project has asked the question: "Is it possible to improve the EF capacity or are these abilities genetically predetermined?". Even if the project was not designed to study this question some of the results could be used as a basis for a discussion of this topic.

Studies have suggested that it is possible to develop some EF capacities through training, an effect that seems to be larger among children with lower baseline capacity than children who are performing on an average level [211, 212]. Working memory seems to have a greater benefit from such training than other EF abilities [213]. The effect of EF training can be divided into near transfer effects and far transfer effects [211, 212, 214]. Near transfer effects refers to improved results on the task that is practiced or similar tasks as a consequence of regular training. For example, the individuals successively increase the score on a working memory test week after week due to regular training of this task. Far transfer effects refers to an indirect consequence of improvement in other areas of life rather than on just a specific behavior that is targeted in a training program. For example, such an effect could be equaled to if a person becomes better at driving a car after regular training of working memory on a computerized test on the subject [211, 212, 214]. While near transfer effects have been found [211], indirect influence from cognitive training on other behaviors is weak [211] and even doubtful [214]. There are many different methods that attempt to develop the EF capacity [212] such as computer games, aerobic practice, martial arts and other physical activities, mindfulness, educational programs etc. [212]. Out of these different methods, physical training seems to have a small but significant impact on improving the EF capacity [215]. The effect seems to be present in all age groups [216] with a special benefit for children and older adults [217]. But the results are not unequivocal [218]. Meta-analyses have also been performed with the purpose to investigate the relation between cognitive training and the development of EF as well as their transfer effects [219]. Even if results suggest that the effect is not particularly strong, it seems that cognitive training of working memory has some transfer effects and improves the EF capacity also in ”everyday functioning” [219]. However, using coping strategies, counteracting stress and emotional imbalance, increasing self-confidence, and experiencing social belonging may increase EF capacity even more than focusing narrowly on developing specific aspects of EF [212].

With these meta-analyses as a backdrop for our project, the results from **Study I** showed a significant difference in the EF capacity between the players from the highest division and the players from lower divisions. However, it is not possible to delineate if the results were consequences of an impact on EF due to more regular training (involving both physical and cognitive components) for the higher division group or if it is an innate factor that drives the difference.

In **Study III,** we tried to control for the training factor by only including players from the same division, playing in the same teams, led by the same coach and having the same regular exercise. The only difference was that some of the players also played for a national team during a short period every season. The results from **Study I**, suggesting a better EF-capacity in higher-level players, were still reproduced. The players that were ranked as the best in the world had better EF, despite that they trained and practiced regularly in the same way as their teammates not representing a national team. Thus, when the training factor was kept more constant between the individuals, the differences in EF capacity still remained between the best elite players and elite players that are not on a national team level. The finding does not exclude that physical or cognitive training influences the capacity of EF, but suggests that training is not the only factor that contributes to the difference observed between levels of play.

In **Study IV** the elite police force applicants were tested under an extreme field condition to mirror a real combat situation. In order to adjust for the influence of physical fitness on the EF we used resting heart rate as a proxy. The effects remained even after such adjustment in that the results from the baseline still correlated with results from the field assessment. Although, this analysis cannot exclude the impact of physical fitness on EF it suggests that it is not a main driver of high EF capacity stability observed in this group.

In **Study V** four diverse work groups were included (forklift operators, sellers, operational managers and strategic managers). In this cohort it is likely that the manager groups had higher education and a better socio-economic status than the forklift operators, although the study did not formally measure these variables. The results suggested a higher EF capacity for managers than for forklift operators, a difference that could be a consequence of education and/or socio-economic background. However, when we adjusted for work group it didn't change the within group findings regarding the relation between number of sick days and EF capacity. Thus, even if education and socio-economics could have an impact on EF it did not influence the relation between EF and sick leave.

The results from this project cannot exclude that cognitive and physical training, education or socio-economic background has an impact on EF [212]. But it seems that these environmental aspects are not strong enough to be the main factors that explained the differences in EF-capacity. Taken into account the results from **Study II**, that the capacities of EF have a significant and strong correlation to successful behavior already at a young age, the idea that the capacity of EF is mainly something that we inherit as has been suggested previously is strengthened [22, 220, 221]. However, as previously mentioned, other studies have shown that it is possible to influence the EF capacity both positively and negatively throughout life. Future studies will have to further reveal the degree to which environment and genes determine the high EF capacity in successful behavior.

6.6 ALL STUDIES

With a theoretical model built on evolution theory and the idea of the importance of successful adjustment through self-regulation to survive and thrive, each of the five studies have shown that EF are related to successful performance in contexts where there is a need to adjust behavior. The interaction between working memory, inhibition and cognitive flexibility together with fluent creativity has shown to be important for successful behaviors in novel and changing environments. The studies suggest that especially creativity in combination with cognitive flexibility contribute to successful behaviors. However, the fourth study suggests that these cognitive processes also seem to be more vulnerable to stress than other EF components. Although, cognitive flexibility and fluent creative are of a special importance for adjustment in order to reach a goal, a range of EF-components are needed to complete the executive chain. However, it is likely that weaker capacity in one EF-component can be compensatory of another one.

6.7 LIMITATIONS

A weakness of this project is the small samples in each of the five studies. However, the results have been reproduced in each of the included studies, in different cohorts and in various contexts. Moreover, as mentioned previously, the results of the first study published in 2012 has been conceptually reproduced in several other studies performed by different research groups, in different cohorts, on different continents, in different sports, exercised in groups or as individuals [168-182, 190, 191]. In total, more than 2,200 individuals have been included in these studies. Some of these studies have also used the same test battery with the same results on their cohorts as in this project [169, 173, 174, 180, 182, 190, 191]. Together these studies strengthen the hypothesis of the importance of EF for successful behaviors in contexts that quickly change and where there is a need for fast adaptation in order to reach a goal (such as ball sports).

Even if all participants in **Study III** had approximately the same training schedules which partially controls for physical and soccer skills, we did not adjust for physical abilities or technical soccer skills in **Study I** and **Study III**. However, in the second youth study we controlled for the height of the players as a proxy for physical size and strength. It didn’t interfere with the correlation between EF and number of scored goals. In the “special forces study”, i.e., **Study IV**, we adjusted for resting heart rate, considered as a proxy for physical fitness, in some analyses which did not influence the results. Future studies focusing on the relations between physical ability, skills and EF will hopefully shed more light on this question.

This project did not control for any psychological aspects such as motivation or grit (defined as perseverance and passion for long-term goals) [222]. Therefore it cannot be excluded that these variables drive the results. However, it may be difficult to separate motivation from EF. A Japanese study on soccer and successful play mentioned above [173], also used Design Fluency as the main tests, and assessed their individuals with a self-evaluation test for grit, resilience (defined as the ability to successfully cope with change or misfortune), social support and profile of mood state. While Design Fluency predicted successful soccer behavior, grit, resilience, social support or mood state did not. Actually, the players that were not accepted to the academy had higher grit-score and resilience than the players who were accepted. Future studies about the relations of different psychological aspects and EF will hopefully shed more light on this relation.

Another weakness of this project was that the norms of some of the tests are relatively old [148, 149] and it can't be excluded that the EF capacity in the population has changed since normative data was constructed. However, the results of elite soccer players tested for the third study in 2018 [3] were in line with the results in the first study in 2007 [1]. The 51 elite players from Swedish premier league (Allsvenskan) tested 2018 (M = 15,98, SD = 2,186) compared with the 29 elite player from Swedish premier league (Allsvenskan) tested 2007 (M = 15,52, SD = 2,42) were not significantly different in DF Total Correct ($t(78) = 0.87$, $p = 0.39$.)

The norms for the main test were based on a US population sample and it cannot be excluded that the EF ability is different in various populations and cultures. However, studies made in different cultures and cohorts using the same or similar test, observed similar results [169, 173, 174, 180, 182]. Even if the norms are relatively old and built on a US population, they still seem robust in relation to age, cohorts and cultures.

6.8 ETHICAL CONSIDERATIONS

In this research project The Helsinki Convention has been followed. The participants have chosen to freely take part in the studies and the individuals have been coded to avoid the possibility of being identified in relation to their results. The assessment tests used in these studies have been used in clinics and research for several decades and no harm has been reported. Due to this there have been few ethical or moral issues in the present project.

Out of all individuals that were tested in this project, less than five showed an overall result that indicated possible function deficits. These individuals were informed that their results were low and asked if they felt that they were well and if they functioned as usual. If not, they were asked to see their doctor for further medical and psychological assessment.

During this project one ethical concern has been raised: could the results of a project like this be misused in relation to future selections of children to elite sports? This is possible, but we argue that one should not moralize over acquiring knowledge. Instead, it is important to raise the question for further discussions and debate of how society chooses to use this knowledge.

Although our project is not about selection in sports, some comments on this issue are worth noting. The results from this project can probably be used in selection processes as a complement to tools that are used today (e.g. strength or technical skills). For example, in this project we have found that cognitive flexibility is crucial for success on the highest level of soccer, the national team level. Knowing that the final capacity of cognitive flexibility reaches its top already in early age and that cognitive flexibility is easy to measure opens up for cognitive testing of the applicants to soccer academies to ensure future national team level. However, as our results are relevant only on a group level and cannot predict the future on an individual level, such use cannot be supported in isolation. More studies would be needed to successfully transform the results to be used in selection processes. However, this project can give guidance and ideas about how to use measurements of executive functions in future studies on selection processes. In a similar way, although it is possible that individual profiles of EF capacity may guide tactics and training of established players, our project cannot scientifically prove that such use is optimal for the success of a team.

7 CONCLUSIONS

It is beneficial to be strong and fast for survival in a quickly changing environment. However, this project adds to previous research that suggests the control of behavior is as important in order to be successful in such contexts. The results of this project are in line with the idea that evolution has favored self-regulation of information processing such as EF. More specifically, adjustment and flexibility paired with creativity seem to be especially important aspects in quickly changing environments for survival of the fittest. Added to this, our research suggests that similar cognitive functions are of importance for health and well-being.

8 POINTS OF PERSPECTIVE

8.1 META-ANALYSES

Meta-analyses on studies that have the same aim as this project, i.e. describing the relation between EF and successful behaviors in quickly changing contexts, would give further understanding of how EF are important in environments that require behavioral adjustment in order to achieve a goal. Especially, such meta-analyses would emphasize robust relations and disregard accidental results.

8.2 SOCCER

The results in this project showed a significant relation between EF and some successful soccer behaviors. However, in order to understand if these successful behaviors are innate or an effect of training, longitudinal studies are needed. Long term cooperation with soccer academies and their players from the age of approximately ten years to adulthood would make this possible. By measuring EF capacities and soccer skill when the players start at the academy and re-test the players at several time points, a deeper understanding about whether EF and the different components such as cognitive flexibility and fluent creativity drive the growth of successful behaviors would be possible. Since most players do not end up as professional elite players, it is essential to test a large number of players, possibly as an international multi-site project. This would also allow for studying possible effects of concussions and ball headings on cognition, and preferably on a brain level as well. In order to be able to control for age, expected cognitive development and common environmental aspects for these age groups, a control group should also be followed, e.g. consisting of ordinary school classes from the same admission area as the football academy.

8.2.1 Soccer, Electronic tracker system, and EF

Like the studies on neurons that constitute a positioning system in the brain, awarded with the Nobel prize in medicine 2014 [146]), it is also possible to start using the electronic soccer field tracking system that all soccer clubs in major leagues already use, with the purpose of gathering “big data”. Complex analyses of such big data increase the understanding of why some individuals are on the “the right place at the right time”, a concept that often is loosely used when assessments of game intelligence are made. A derived measure of that sort would be of great interest to correlate with the results from EF testing of the players. This has the potential to dramatically increase the knowledge of how the executive functions drive information processing and to predict in a more specific way successful behaviors and broaden the understanding on the theory of evolution and how the fittest survive. It may also better describe optimal characteristics of different positions in the soccer team.

8.3 SPECIAL FORCES

In regards to the special forces, it is of essence to better understand what happens with higher order cognition such as different EF in stressful environments. Moreover, it is of interest to understand how this change also affects risky behavior and optimal outcomes. At present, testing of EF in police applicants is not done. By implementing EF assessment on a regular basis in the selection procedure to the police academy or to the Swedish Counterterror Intervention Unit, a norm may be constructed that can be used for research of how EF relate to key behavior in these groups and for following long term development of the police force.

8.4 FLEXIBILITY, STRESS PREVENTION, AND SICK LEAVE

Several psychological treatments and models (such as acceptance and commitment therapy, metacognitive therapy, resilience models, and locus of control models) have suggested that flexible behavior is a key component for health, as well as suggesting a relation between flexible behavior and EF including cognitive flexibility, a relation which has not been proven. The data from this project suggests a relationship between the capacity of cognitive flexibility and health status. Future studies need to both measure cognitive flexibility and flexibility in real life (e.g., flexible behavior/psychological flexibility) associated with health outcomes in order to better understand this relation. Such a study could be performed in collaboration with a sufficiently large consumer retail company. Individuals could first be both evaluated in regards to their psychological flexibility and assessed for cognitive flexibility capacity using standardized test such as Verbal and Design Fluency. In a second step both measures of flexibility could be compared to sick leave and how the employees experience the working day before, during and after peak hours. This measurement could be complemented with the employer's judgment of the co-workers' ability to handle stress. In order to get more objective data on how stressed the co-workers become in different contexts, their heart rate could be measured constantly during a working day. A study like this could give information about the relation between psychological and cognitive flexibility. It could also give information about how these factors are associated with stressful real life events.

8.5 COMPENSATING STRATEGIES - NOT SELECTION

It is common to use tests in work life for selection purposes. While it may be practical and also offer an equal opportunity on a surface level, it is extremely important that the used tests have a valid capacity to predict future successful behavior. The common use of IQ tests in these circumstances does not seem to meet those criteria [223-225]. While we have found a seemingly robust correlation between EF and successful behavior for some professions, more research is needed before EF tests could be recommended as a selection tool. While EF results may stand out in the high-end tail the predictive strength of EF on the level of the individual within the normal range is unknown. Without more longitudinal data there is no strong basis for the use of such tests in selection procedures.

Instead, compensating strategies are of high interest. Traditionally, the results from EF assessment have been used in healthcare to help patients with deficits to build compensating strategies. When a patient, who is assessed in the clinics is informed about weak areas of their behavior that are dependent on a specific suboptimal cognitive process capacity, they can be better prepared for the unknown future and build behaviors to avoid earlier mistakes often with the help from a psychologist or psychotherapist. A similar approach can be used in non-patients. By building cognitive maps of EF and giving guidance on alternative strategies, work groups or sport teams may become more successful on both an individual and a group level. Individuals may also become better at coping with stress and increase their health status in the longer run.

8.6 GENERAL REMARKS ABOUT FUTURE RESEARCH ON THE RELATION BETWEEN EXECUTIVE FUNCTIONS AND HUMAN BEHAVIORS

In order to use EF to better predict behavior, and help individuals to be more successful and satisfied with their life, we need to increase the understanding of how EF developed during the course of evolution. One way is to study primates and their interaction in more detail with a focus on behavioral adjustment in their natural environment, then study humans in environments having similar constraints, and finally moving towards how such cognitive processes regulate thinking and coping with stressors in modern life. We also need to study the full spectrum of cognitive core profiles and capacities both on a behavioral and a mechanistic level. We believe that in this quest it is always important to stay close to how EF developed under an evolutionary pressure and avoid solely reductionist research.

9 ACKNOWLEDGEMENTS

First I would like to thank my supervisor, Predrag Petrovic. For giving me the opportunity to transform my interest for neuropsychology and behaviors into a real research project and an exciting journey. You have been a great supervisor. We have had lot fun together. We have been traveled together to other countries to meet and assess some of the best soccer players in the world. We have been interviewed by the most influential sport journalists in the world and have had our results published in newspaper like The Times, The Guardian, The Independent, Daily Mail, The Sun, The New York Times, The Wall Street Journal, Gazzetta dello sports, Huffington Post etc. DN and SvD have covered our project and we have been visited TV-studios during prime time. In parallel with this, you “forced” me to write a book about our findings together with the journalist Thomas Learner. The idea was crazy to me, that I, a dyslexic, would write a book?! But it has not only been success and glory. Our project has been met with strong opposition from some people and institutions. Due to misunderstandings and malicious rumors about our project, spread through the media I have been close to giving up. But when you kept believing and didn’t give up, I could not do it.

Thank you Martin Ingvar for believing in my theories and in me. Thank you for your great support. I have never met anyone that so quickly understands my thoughts and ideas. I will never forget when you, Predrag and I were sitting on a small sofa waiting to meet the Head of the institution. We had recently gotten into a fight with the “armed special forces“ about the right to our results and were waiting for the Heads feedback. Thank you for the opportunity to relive a dear old school memory of sitting on an uncomfortable bench waiting for the principal’s scolding.

Liselotte thanks for your help to make this topic clearer to me. Mats, thanks for your encouraging me to finish this project. Christoph, Orestis, Frida, Lars, Alexander, Mimmi and others, your help with my data, data programming, and other academic struggles and difficulties, were invaluable. Thanks for letting me be one of the team. Rita Almeida, with you help I was able to manage the statistics, thank you.

Gustaf and Reza, your help with assess the players was invaluable.

Ola Andersson (AIK, Sirius), Christian Krigström Gentile (Djurgården’s Academy), Bosse Pettersson (Vi Lirare), thank you for your enthusiasm, support and interest in the project.

Håkan Nyman, you opened the door to neuropsychology and Christine Bedinger you made me understand that everything is "neuro". *PRIMA Barn & Ungdomspsykiatri*, your financial support helped me to complete this project. *Derome*, with your effort and support with individuals and the opportunity to let me train and educate assessors of your HR-staff, you made it possible to develop this project from soccer to the corporate world, a great thanks to Peter Larsson and Urban Forsbring. Thank you *Huvudsta Vårdcentral,* who made it possible for me to summarize and finish this project.

Thanks to all soccer players, police officers and employees at Derome for letting me assess your executive functions, which made this project possible.

Sofie, your cover image is fun and smart, thank you! Claire, more than thanks for your proofreading.

Finally, the greatest thanks of all will go to my wife and family. Thank you for your fantastic support and tolerance with my mood. Lotta, thank you for following me through the whole project, supporting me with proofreading and making it possible both time-wise and financially to implement and complete everything. We not only support each other, we make each other better.

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