Chapter 7

Summary and general discussion

SUMMARY OF MAIN FINDINGS

The first aim of this thesis was to explore the relationship between physical activity and neurocognitive functioning in children. Especially the influence of organized sports was investigated, by comparing preadolescent children varying on the frequency and intensity in which they participate in organized sports. Also, dose-response relationships between physical activity, sedentary behavior and neurocognitive functioning were explored. The second aim was to investigate possible underlying capacities for superior performance of talented youth athletes as compared to less talented peers, on neurocognitive tasks underlying sport-specific skills. We examined executive functions, visuomotor coordination and explicit and implicit motor learning. Below, the main findings of the studies undertaken to address these aims are summarized. The findings will be discussed in the broad context of the relationship between physical activity (and sports in particular) and neurocognitive functioning. Next, study strengths, limitations, and implications of the findings are discussed. Finally, recommendations for future research are proposed.

Part A of this thesis, directing to the first aim, provides examination of the relationship between physical activity, sedentary behavior and neurocognitive functioning in youth.

Chapter 2 describes the effects of physical exercise interventions on executive functioning in a comprehensive meta-analysis of existing studies on children, adolescents and young adults. Meta-analytic effect sizes were calculated for the effects of acute physical exercise on the domain's inhibition/interference control and working memory, as well as for the effects of chronic physical exercise on planning. Across age-groups, a moderate effect size of acute physical exercise on executive functions was found (d=.52) in a sample of 586 participants derived from 19 studies, which indicates that a short bout (e.g. 30 minutes) of exercise may (at least temporarily) enhance executive functioning in youth and young adults.
It should be noted that the majority of the studies assessed the effects of physical exercise on inhibition/interference control. Consequently, the meta-analytic effect sizes for the other executive function domains that were studied

(i.e. planning, working memory, and set-shifting) were based on small numbers of studies. Especially the findings on working memory should be interpreted with caution, as the meta-analytic results are based on only four studies, derived from one publication.
Inconsistent results were found on the effects of chronic (regular) physical exercise on executive functions, which resulted in a non-significant meta-analytic effect size (d=.14) in a sample of 358 participants from 5 studies.

In Chapter 3, three groups of preadolescent children were compared: children who not participated in any organized sports, children who regularly participated in organized sports, and children who very frequently participated in organized sports. The groups clearly differed in terms of total time spent in physical activity (active transport, playing outdoors, physical education and sports) and the children who did not participate in organized sports also spent more time in sedentary behaviors (i.e. watching TV). The three groups were compared on motor inhibition, working memory, alerting attention, orienting attention, executive attention, and processing speed. Multivariate regression analyses examined the predictive power of physical activity and sedentary behavior for neurocognitive functioning. Results of the neurocognitive measures showed that the sedentary children had poorer motor inhibition and showed poorer working memory than the elite soccer players; moreover, they exhibited more lapses of attention (tau) as compared to both groups of children participating in sports. No group differences were found on alerting attention, orienting attention and executive attention, and processing speed. Regression analyses revealed a positive dose-response relationship between physical activity and the backward conditions of both verbal and visuospatial working memory, which indicated that children who spent more time in physical exercise performed better on the manipulation the central executive function of working memory. In addition, negative dose-response relationships were found between sedentary behavior and motor inhibition, as well as the central executive function of visuospatial memory, which indicated that more sedentary behavior predicted poorer motor inhibition and visuospatial working memory. As it is shown that lapses of attention (tau) might be related to frontal brain circuits, executive functions and white matter integrity, post hoc exploratory analyses were conducted to examine whether the relationship between group and dependent variables was mediated by tau. The mediation analyses on the measures that discriminated between groups showed a mediating role of lapses of attention (tau) on measures of accuracy, reaction time and working memory. This suggests a crucial role of lapses of attention when performing neurocognitive tasks, signifying that suffering from lapses of attention may lead to more errors and poorer performance on aspects of working memory and reaction time.

Part B of this thesis directs to the aim to examine neurocognitive functioning, visuomotor coordination and motor learning in highly talented youth athletes (elite soccer players) as compared to less talented peers (amateur soccer players). In Chapter 4, elite soccer players, amateur soccer players, and children who did not participate in any organized sports were compared using a novel visuomotor coordination task in order to investigate whether elite soccer players have superior visuomotor coordination skills as compared to the other groups. The visuomotor coordination task in this study assessed visuomotor coordination in a dynamic environment, by using four difficulty levels and providing structured (predictable) and unstructured (unpredictable) conditions in which participants have to adapt their motor behavior. It was found that youth elite soccer players outperformed both other groups on the difference scores for variability at the highest speed levels, which means that at the most difficult, unpredictable trials, they were better able to maintain stability. This finding may be explained by high adaptability in the visuomotor system of highly talented athletes. Furthermore, no relationship was found between the amount of physical activity (i.e. active transport, physical education, outdoor play and sports), TV watching, time spent at the computer or gaming, on the one hand, and visuomotor coordination, on the other hand.

In Chapter 5, focus was on executive functioning in youth elite soccer players and age-matched amateur soccer players. The executive functions motor inhibition, attention and visuospatial working memory were examined and the findings indicated that on motor inhibition, the elite soccer players outperformed amateur soccer players. The analyses on the attentional networks revealed a group difference in alerting attention, indicating that the highly talented soccer players profit to a greater extent from temporal information to attain an alerting state, as compared to amateur soccer players. No differences were found on the orienting and executive network of attention, and results of the visuospatial working memory tasks indicated no group differences in visuospatial working memory. Furthermore, 89% of the participants were correctly classified being elite soccer player using a logistic regression model.

In Chapter 6, two groups of soccer players (i.e. youth elite and amateur soccer players) were compared to explore possible enhanced explicit and implicit motor learning in talented soccer players. Participants performed a modified serial reaction time task (SRTT) investigating explicit and implicit motor learning in parallel. Five test blocks were administered. Results of the explicit motor sequence suggest that when participants were explicitly instructed on learning the sequence, both soccer player groups showed similar performance, with equal learning curves and with a similar decrease in reaction times during the course of the task. It was found that elite soccer players learned more rapidly than the amateur soccer players on the implicit sequence, reaching asymptotic performance after the third block, with fast and stable execution of the motor sequence, whereas the amateur soccer players continued learning during the fourth block. Results provide evidence that when nothing is told about what should be learned, or even that something should be learned, the elite soccer players learn faster than the amateur soccer players. In other words, it may be suggested that elite soccer players are superior in the early learning phase, which allows quick implicit learning of motor skills.

GENERAL DISCUSSION

PHYSICAL ACTIVITY AND NEUROCOGNITIVE FUNCTIONING

As was found in the meta-analysis in Chapter 2, studies on the possible effects of chronic (regular) physical activity on executive functioning in youth are limited and results are inconsistent. The main challenge of intervention studies on the chronic effects of physical activity is the feasibility of such studies in terms of compliance to the training schedule and the difficulty to control for other confounding effects such as (natural) maturation of the brain and associated increases in neurocognitive performance during childhood. Therefore, many studies on chronic physical activity use a cross-sectional design, and compare children with different fitness levels in order to assess the association with physical activity and neurocognitive functioning (e.g. Buck, Hillman, & Castelli, 2008; Pluncevic–Gligoroska, Manchevska, & Bozhinovska, 2010; Chaddock et al., 2010). Findings on the immediate effects of physical exercise are more robust, although it is unclear what the optimal intensity and duration of a short bout of exercise is to enhance neurocognitive functioning, and, importantly, how long the effects last. For example a study by Joyce, Graydon, McMorris, & Davranche (2009) found that 30 minutes of moderate exercise enhanced motor inhibition for at least 50 minutes in young adults, but to our knowledge, this is not yet investigated in children and adolescents.

Results of the regression analyses in Chapter 3 showed that physical activity was positively associated with performance on the central executive components of verbal and visuospatial working memory. Both aspects of working memory are crucial for learning, problem solving and reading (Melby-Lervåg & Hulme, 2013). Our results are in line with the study of Kamijo et al (2011) who investigated the effects of an afterschool physical activity program in preadolescent children and found positive effects on a working memory task. In addition, the study in chapter 3 also provides preliminary evidence for negative dose-response relationship between sedentary behavior and neurocognitive functioning in children. Specifically, it was found that that more sedentary behavior may result in poorer visuospatial working memory. This is in line with a recent study where a negative association was found between self-reported computer/video game playing and visuospatial working memory and shifting of attention (Syväoja, et al., 2013).

Furthermore, the study in Chapter 3 revealed no group differences regarding the attentional networks. However, our results demonstrated a possible highly important role of lapses of attention (tau) for neurocognitive functioning in children. Suffering from lapses of attention may lead to educational problems because there is less focus on (relevant) parts of the task or less time-on-task (e.g. Anobile, Stievano, & Burr, 2013). Physical activity might be a promising method to decrease lapses of attention: It has been shown that physical fitness is associated with improved stability in attention (Moore et al., 2013).

In short, it can be concluded that the studies in the first part of the present thesis add to the existing literature on the positive relationship between participation in physical activity and neurocognitive functioning. It is shown that being active during childhood predicts participation in physical activities later in life (Dik, Deeg, Visser, & Jonker, 2003; Middleton, Barnes, Lui, & Yaffe, 2010). Sport might play a specific role because studies show that organized sports activities such as soccer ensure a substantial part of daily moderate-to-vigorous activity (MVPA) in children (Wickel & Eisenmann, 2007; Leek et al., 2011). Furthermore, there is evidence that people with a physically active lifestyle have a higher 'cognitive reserve', which may delay progressive decline of cognitive functioning in healthy ageing and in clinical populations (Hamer & Chida, 2009; Nithianantharajah & Hannan, 2009).

NEUROCOGNITIVE FUNCTIONING, VISUOMOTOR COORDINATION AND MOTOR LEARNING IN TALENTED ATHLETES

In Chapter 4, it was found that the youth elite soccer players in our study were better able to adapt their motor response to highly unpredictable situations than amateur soccer players and sedentary children, which was particularly expressed in lower variability at the high speed unstructured (unpredictable) trials as compared to structured (predictable) performance at the high speed structured trials on a visuomotor coordination task. This is interesting because we used an eye-hand coordination task to measure visuomotor coordination, while eye-hand coordination is not specifically required during soccer. On the one hand, as Väntinnen and colleagues (2010) speculated, it is possible that the soccer players' training in fast-action sports explains the excellent adaptation to unpredictable situations. On the other hand, it may also be possible that highly talented athletes have an underlying capacity for excellent visuomotor adaptability.

In Chapter 5 it was found that especially motor inhibition as measured with the Stop Signal task could discriminate between youth elite soccer players and amateur soccer players. This result is in line with other recent studies using the same task to assess motor inhibition in open sports athletes. For example, the study of Alves et al. (2013) on elite volleyball players and the study on tennis players and swimmers of Wang et al. (2013) also reported better motor inhibition in open sports athletes as compared to closed sports (i.e. swimmers). However, because those two latter studies included only adult athletes, and similar to our study, no longitudinal or sport-specific performance measures were included, it remains unknown whether motor inhibition is a prerequisite for performance at the highest level. In addition, in the study in Chapter 5 it was found that the youth elite soccer players outperformed the amateur soccer players on alerting of attention, indicating that the elite soccer players were better able to attain and maintain an alert state. However, no group differences were found on orienting and executive attention or visuospatial memory. Although these results might be counterintuitive, both results receive support from other studies (Furley & Memmert, 2010; Voss, Kramer, Basak, Prakash, & Roberts, 2010; Alves et al., 2014). A possible explanation for the findings on orienting and executive attention is that elite athletes pay more attention to a wider visual angle (i.e. have higher peripheral awareness), instead of focusing on a small visual area as is required in the attentional tasks used in our studies. Visuospatial memory might be further explored using tasks more related to sport-specific situations such as assessing visuospatial memory from diverse visual angles or with simultaneously presentation of stimuli (Furley & Memmert, 2010).

Findings on motor learning in this thesis are, to the best of our knowledge, the first showing better implicit motor learning of talents on a general motor learning task (Chapter 6). Results showed that the elite soccer players learned more rapidly on the implicit sequence, and reached asymptote performance earlier than the amateur soccer players. Results of the explicit motor sequence suggest that when participants were explicitly instructed on learning the sequence, both soccer player groups showed similar performance with equal learning curves. An explanation for the findings on implicit motor learning might be found in integrity or efficiency of the dentato-thalamo-cortical tract, which connects the lateral cerebellum and prefrontal brain areas and is associated with early motor sequence learning (Schulz, Wessel, & Zimmerman, 2014).

Taken together, findings of the second part of this thesis may therefore lead to the speculation that especially complex neurocognitive functions with a motor component may discriminate between highly talented and less talented young athletes because: (1) elite athletes showed lower variability at the high speed unstructured trials of our visuomotor coordination task, while there were no differences in visuomotor coordination in structured task situations between elite athletes and amateur athletes or non-players, (2) it was shown that motor inhibition could discriminate elite athletes from amateur athletes (Chapter 5; Alves, 2013; Wang, 2013), and (3) elite athletes showed faster implicit motor learning, suggesting earlier adaptation of the motor systems during learning as compared to amateur athletes (Chapter 6).

This interpretation of our findings is supported by other studies in adult athletes (e.g. Kida, Oda, & Matsumura, 2005) showing that elite athletes do not outperform amateur athletes or non-athletes on more simple tasks with a motor component such as two-choice reaction time tasks. In view of the findings of this thesis, complex neurocognitive functions with a motor component should be further explored in future research on sports talents.

When results of both parts of the present thesis are combined, it may be concluded that involvement in physical exercise could improve neurocognitive functions at least to a certain degree. However, not all functions seem to respond to physical exercise, as was also found in other research (Colcombe & Kramer, 2003). The diversity in results of the studies may be explained by differences between studies in terms of study designs used, such as intervention studies and correlational studies (which do not provide knowledge on causality), but also in terms of the populations studied, such as preadolescent healthy children, overweight children, low-performing young adults and athletes with different expertise and talent levels. In addition, methods differed in terms of the assessment of neurocognitive skills with traditional paper and pencil tests versus computerized tasks that isolate aspects of neurocognitive functioning and control for possible confounding neurocognitive demands. In addition, some neurocognitive skills may not only respond positively to physical exercise, but may be particularly well-developed in elite athletes already at a young age and therefore might contribute to the existing literature on defining a profile of a sports talent.

STRENGTHS AND LIMITATIONS

A strength of part A of this thesis is that groups, based on our selection procedure, clearly differed in the time spent on sports, with sedentary children spending no time on sports, amateur soccer players spending on average 253 minutes/week and elite soccer players spending on average 391 minutes/week on sports. The children classified as being sedentary in the study indeed showed more sedentary behavior (i.e. TV watching) than the children who participated in organized sports. Although physical fitness was not objectivity assessed (e.g. with a VO2max test), the study in Chapter 3 is among the first investigating neurocognitive skills in children varying in involvement in organized sports. Furthermore, sedentary behavior was not objectively measured, which may have led to socially desirable answers on the questionnaire used to assess TV watching and time spent on the computer and gaming. This, however, is unlikely because this would be the case for all three groups of children. In addition, assessment of sedentary behavior was somewhat limited, for example, the involvement in possibly beneficial sedentary behaviors such as reading a book or doing homework was not assessed.

Concerning the studies in part B, a particular strength is that neurocognitive functioning was investigated in young athletes. The majority of previous literature is on adult and/or university athletes, which does not add to knowledge on talent identification in youth athletes. Although numerous studies investigated talent identification in young athletes on physiological and anthropometrical characteristics, the three studies in this thesis are the first examining neurocognitive functions in youth elite soccer players. Another great strength of part B of this thesis is the use of non-sport specific tasks, which allows comparing groups with different experience in soccer: When sport-specific tests would be used, athletes with more experience would be advantaged, which may not lead to measuring underlying (neurocognitive) capacities but rather to measuring the effects of (years of) training and experience in specific situations. Additionally, referring to Chapter 6, the elite soccer players were not familiar with the tasks and are not used to learn movements with their hands. Results of this study therefore provides some first evidence for possible underlying superior learning skills in sport talents.

Some limitations should be noted. First, no longitudinal data on the soccer players is available and second, correlations between executive functions and performance in soccer could not studied due to the lack of data on performance measures such as scored goals, assists and match playing minutes. For example for motor inhibition, it might be a possibility that this function develops earlier in highly talented athletes as compared to less talented peers. Second, a main limitation of both parts of the thesis is, however, that cross-sectional designs were used. Therefore no conclusions about the causal relationship between sports and neurocognitive functioning can be drawn: it is also possible that young athletes, who naturally (without training) develop strong neurocognitive functions are more likely to become elite athletes, as was also suggested by Jacobson and Matthaeus (2014).

IMPLICATIONS

CLINICAL RELEVANCE AND POSSIBLE INTERVENTIONS

Findings of the meta-analysis in this thesis clearly indicate that an acute bout of physical activity can benefit executive functioning in preadolescent children, adolescents and young adults. However, because the majority of the studies included in the meta-analysis examined inhibition, results on other domains that were studied (i.e. planning, working memory, and set-shifting) should be interpreted with caution. Nevertheless, the importance of inhibitory control for daily life activities is illustrated in many studies (e.g. Nigg, 2000; Karbach, & Unger, 2014).

It might be suggested that physical exercise may be especially beneficial for groups performing in the lower capacity ranges of neurocognitive functioning. A number of studies support this idea. First, a recent meta-analysis of Smith and colleagues (2011) revealed that children and adolescents with obesity show neurocognitive deficits which were most prominent for executive functions. Thus, it may be speculated that for overweight children, adolescents and young adults, physical exercise may be helpful. Indeed, this is supported by the study of Davis et al. (2011) on overweight children, which was the only study in our meta-analysis that found positive effects of a chronic physical exercise intervention in preadolescent children. Second, a study on young adults showed that only participants in the lower capacity ranges of working memory improved their working memory score after a single bout of aerobic exercise (Stroth, Hille, Spitzer, & Reinhardt, 2009). A recent study also supports the idea that a single bout of exercise may enhance inhibition in the lower capacity ranges: In that study it was found that only children performing in the lower ranges of an inhibition task improved accuracy after a single bout of aerobic exercise (Drollette et al., 2014).

Third, it may be suggested that neurocognitive deficits observed in clinical groups may be particularly vulnerable to the beneficial effects of physical exercise. For example, it has been shown that patients with attention deficit/hyperactivity disorder (ADHD) often show impaired inhibition, which is thought to lead to a cascade of adverse developmental outcomes including impaired performance on other neurocognitive functions, disruptive behaviour, impaired social skills and poor academic performance (e.g. Biederman, et al., 2004;

Scheres et al., 2004). Interestingly, some positive effects of physical exercise interventions on executive functions and behavioural symptoms in ADHD have been reported (e.g. Medina et al., 2010; Pontifex, Saliba, Raine, Picchietti, & Hillman, 2013). Similarly, preliminary beneficial effects of exergaming on neurocognitive functions are reported for patients with an autism spectrum disorder (Anderson-Hanley et al., 2011), multiple sclerosis (Sandroff, Klaren, Pilutti, Diugonski, Benedict, & Moti, 2013) and young adults with intellectual disabilities (Pastula, Stopka, Delisle, & Hass, 2012). Although these are all promising findings, more research is necessary to investigate underlying mechanisms and clinical relevance of effects in clinical groups.

Results of the study in Chapter 3 in this thesis have important implications for sedentary children. Findings on the poorer working memory scores and more lapses of attention in sedentary children are highly relevant given the significance of these functions for academic achievement (Bull, Espy, & Wiebe, 2008). For example, it has been shown that working memory can predict future reading and spelling achievement (e.g. Nevo, & Breznitz, 2007). Likewise, lapses of attention may lead to educational problems because there is less focus on (relevant) parts of the task or less time-on-task (e.g. Anobile, Stievano, & Burr, 2013).

These results suggest that children who do not participate in sports should be encouraged to participate more in moderate-to-vigorous physical activity (MVPA). Several types of interventions have been studied to increase participation in physical activity in youth. A first intervention that showed promising results is offering extra-curricular organized physical activities. With this method, children are offered sports activities immediately after school, which is referred to as a critical period for an intervention because the time after school contains a considerable proportion of the total leisure time (Atkin, Gorely, Biddle, Cavill, & Foster, 2011). A meta-analysis of quasi-experimental studies and randomized controlled trials showed that after-school programs increased daily MVPA, physical fitness and decreased blood lipids (Beets et al., 2009). Second, school-based interventions could be related to physical education classes by lengthening the lessons, and hiring certified physical education teachers to increase quality and quantity of MVPA (Kahn et al., 2002; van Sluijs, McMinn, & Griffin, 2007).

Because effects of school-based interventions are often not observed outside school, several family-based programs have been developed to increase overall physical activity in children and adolescents (for a meta-analysis, see Kriemler, Meyer, Martin, van Sluijs, Andersen, & Martin, 2012). Those family-involved interventions typically consist of education material, “challenges” on not-watching TV as well as stimulating playing physical activity games (van Sluijs et al., 2007). It is shown that interventions solely based on the family were not beneficial in increasing daily MVPA, but combined approaches with family and school-based interventions show the best evidence for increased MVPA levels (Kriemler et al., 2012). Additionally, children should be encouraged to become member of a sports club because being member of a sports club is associated with lifelong higher levels of psychical activity (Tammelin, Näyhä, Hills, & Järvelin, 2003). Notably, a recent systematic review showed that sport club membership, and team sport in particular, is also associated with social health: Children participating in team sports have better emotional control, conflict resolving and relationships with others (Eime, Young, Harvey, Charity, & Payne, 2013).

Given the findings on negative effects of sedentary behavior on neurocognitive functioning as shown in Chapter 3 of this thesis and because the sedentary children in that study also extended the guidelines of the maximal amount of screen time per day (Tremblay et al., 2011), interventions are recommended to decrease daily sedentary behavior. A growing body of research investigated the effectiveness of interventions aiming to decrease sedentary behavior in youth (e.g. Salmon, Tremblay, Marshall, & Hume, 2011; van Grieken, Ezendam, Paulis, van der Wouden, & Raat, 2012). A recent review of reviews reported small but significant effects of interventions to reduce sedentary behavior in children and adolescents. These interventions focused on education, social support and changing family habits such as watching TV while having dinner, or driving to school instead of cycling (Biddle, Petrolini, & Pearson, 2014)

In conclusion, in view of the importance of executive functions in daily life, studies in the first part of this thesis clearly point out that it may be useful to exercise for a short time period (e.g. 30 minutes) to enhance (at least some) neurocognitive functions temporarily. This may especially be relevant in groups with poorer neurocognitive functions, such as overweight children and children with ADHD. Furthermore, as sedentary children perform poorer on several highly important neurocognitive functions, it is recommended that children, parents and schools encourage involvement in physical activities with high levels of MVPA. Several suggestions are provided to increase MVPA and decrease sedentary behaviour (i.e. screen time) in school-aged children. It is important to make a distinction between interventions aiming to increase physical exercise participation and interventions aiming to decrease detrimental sedentary behaviors since it was shown that the health effects of physical activities and sedentary behavior are unrelated (e.g. Biddle et al., 2004).

IMPLICATIONS FOR TALENT IDENTIFICATION

An important conclusion of the findings in Chapters 3-5 of this thesis is that knowledge of neurocognitive functions of soccer players may be of value for talent identification in open sports. Effective talent identification is a major challenge for many sports organizations, and a complete profile of talented children may enhance efficiency of identification as well could provide a possibility for individual training programs. Nowadays, this is already applied for physical and technical skills. For example, when it is known that a soccer player performs poorer than expected on free kicks or jumping height, there will be specific focus and individual training on these skills. The same may hold for neurocognitive aspects, such as motor inhibition, visuospatial memory or concentration: players may follow adapted training programs, either in the lab or with practical on-field exercises.

As was described in Chapter 5 of this thesis, motor inhibition may facilitate other skills which are a key factor for performance in open sports such as agility. The ability to quickly react on, for instance, an opponent which results in a change of direction, is thought to be a key requirement for performance (Lloyd et al, 2013). Interestingly, data are available of 59 elite soccer players (aged 11 to 17) who performed a 30-meter agility sprint test within a two-month period around the neurocognitive testing. These unpublished data show that motor inhibition is significantly correlated ($r=.28$, $p=.03$) with the agility tests and, interestingly, in particular with performance in the unpredictable condition of the visuomotor coordination task ($r=.44$, $p=.001$), where high adaptability is required.

Results of the study in Chapter 6 may also have implications for talent identification. In that chapter, we provided the first evidence for superior implicit learning in young talented athletes as compared to amateur athletes, and it may be speculated that efficiency of implicit motor learning in young athletes can be a promising predictor for future elite performance. Furthermore, a practical implication of the current findings is that in young athletes, implicit motor learning should be encouraged. Gabbett and Masters (2011) described several possible effective strategies for improving implicit learning, such as the use of errorless learning (learning without mistakes through step-by-step introducing of parts of a new skill), random practice (flexible working on skills, instead of a logical structure during training), or using dual-tasks to avoid step-by-step learning of a specific skill.

Clearly, more knowledge is required on the relationship of neurocognitive functions and performance in elite sports as well as trainability of these functions, but the findings are promising for talent identification. It could be valuable to include computerized neurocognitive tests as a scouting instrument in addition to field tests, which are rather time-consuming and often are less standardized and subject to external influences (e.g. weather circumstances).

FUTURE DIRECTIONS

While findings of this thesis have added important knowledge to the literature on the relationship between physical activity and neurocognitive functioning in children who are not involved in organized sports at all, and in children at the high end of the physical activity continuum, several important research questions have also been raised.

First, it is still unknown which duration, frequency and intensity of exercise has the most optimal effect on health (e.g. Kistler et al., 2011; Sayers et al., 2011; Sabia et al., 2012). For example, several studies suggest that a minimum of exercising three times a week is needed to benefit health and some studies show detrimental effects of vigorous exercise on neurocognitive functions (Tomporowski, 2003), but results are inconclusive (see for a review, Powell, Paluch, & Blair, 2012). Future research on duration, frequency and intensity of exercise is thus highly important, because that would allow practical advices on frequency and duration in terms of physical activities (e.g. physical education and playing outdoor).

Second, it may be interesting for future research to focus on prevention of sedentary behavior and the feasibility of increasing physical activity in the school system. During the last decade, several promising projects have been initiated, such as “Vignet Gezonde School” (‘license healthy school’), a certificate for schools devoting extra attention to health. Furthermore, school-based interventions have been to developed aiming to promote physical activity and sports participation (e.g. de Meij, Chin A Paw, van Stralen, van der Wal, van Dieren, & van Mechelen), although effects of neurocognitive functioning and consequently, academic achievement await investigation. However, as was described in the implications section above, effects of school-based additional physical activity alone have demonstrated mixed results on long-term participation in physical activity. Therefore, it may be suggested to investigate effects of structurally changing the school system, not only by providing extracurricular exercise, but for instance also by increasing physical activity during academic lessons. For example, an interesting study is currently performed in Groningen, the Netherlands (UMCG/RUG, trial number ODB10015), where it is investigated whether exercising (e.g. jumping) during execution of mathematics or spelling tasks benefits academic achievement in preadolescent children.

Third, as the studies in Part A of this thesis only included boys, results may not generalize to girls. Future research and interventions may therefore focus on sedentary girls, which is highly relevant because it has been shown that girls are less active during childhood in terms of daily MVPA and are less likely to be member of sport clubs as compared to boys (Eime et al., 2013; Silva et al., 2013). In addition, many studies showed that girls become increasingly less active during adolescence, which in turn has negative effects on health (Kimm et al., 2002; Treuth et al., 2004).

A fourth interesting research theme concerns the possible importance of lapses of attention (tau) as has been shown in Chapter 3 of this thesis. Replication of these findings would be necessary to examine whether lapses of attention indeed mediate performance on tasks aiming to measure for instance working memory.

Concerning talented athletes, there is a growing body of evidence on enhanced neurocognitive in elite athletes of all ages. However, it is not yet known whether these athletes have an innate capacity do develop these functions better than less talented peers, whether these functions are a prerequisite to perform at the highest level in a specific sport, or whether neurocognitive functions are enhanced as a result of more experience (training) in a sport that requires excellent neurocognitive functions. Nevertheless, neurocognitive functioning might be an important aspect of the overall functioning of an athlete, next to the better-known predictors of performance at elite levels, such as endurance capacity and fitness. Therefore, several directions for future research are suggested.

First, since it is suggested that even the slightest improvement on these factors might be important for performance at the highest level, it should be investigated whether important neurocognitive functions such as attention and motor inhibition can be trained.

Second, future research on neurocognitive functions in talented athletes should not only focus on trainability of these functions, but also on predictability of neurocognitive functions (by collecting longitudinal data) for later success and the relationship with performance. A first attempt was done by Vestberg et al. (2012), who related executive functioning to goals and assists in soccer players. However, especially for youth soccer teams in the Netherlands, scoring goals is not the main output of performance in talented children. Therefore, it may be useful to try to objectively assess other aspects of athlete performance such as correct passes, to obtain a complete profile of a talented athlete on all aspects (i.e. technical, physical, anthropometrical, tactical and neurocognitive) of athletic capacities.

Third, as in this chapter was suggested, especially complex neurocognitive functions with a motor component may discriminate between highly talented and less talented young athletes, but further research is necessary to replicate and extend our findings, for example by comparing highly talented open sports athletes (e.g. soccer players) to highly talented closed sports athletes (e.g. swimmers).

Fourth, a recent study showed that team sport athletes are better able to maintain attention during physical exercise especially under high exercise intensity as compared to non-athletes (Hutterman & Memmert, 2014). Future research may also focus on performance of other functions such as visuomotor adaptation and inhibition under high exercise intensity or high-pressure situations, because in sports such as soccer, the intensity of the game is high and many important match situations (e.g. goals) happen during the end of a game (Abt, Dickson, & Mummery, 1999; D'Ottavio & Castagna, 2001), illustrating the necessity of maintaining high levels of neurocognitive functioning also during fatigue and vigorous exercise.

CONCLUDING REMARKS

The key findings of this thesis are:

PART A

- A moderate effect size of acute physical exercise on executive functions was found (d=.52), which indicates that a short bout (e.g. 30 minutes) of exercise may enhance executive functioning in youth and young adults.
- In line with previous studies, it was found that physical activity and sedentary behavior in preadolescent children are unrelated,
- Children who are not involved in any sport activities (e.g. not a member of a sports club) show poorer motor inhibition and impaired functioning on several working memory components as compared to youth elite soccer players.
- Children who are not involved in any sport activities show more lapses of attention and poorer central executive component of verbal memory as compared to elite and amateur soccer players of the same age.
- Total time spent in physical activity (i.e. active transport, playing outdoors, physical education and sports) is positively associated with the central executive components of verbal and visuospatial working memory.
- Total time spent in sedentary behavior (i.e. TV watching and gaming) is negatively associated with motor inhibition and the central executive component of visuospatial working memory.

PART B

- Youth elite soccer players outperform amateur soccer players and children who are not involved in organized sports on highly unpredictable conditions of visuomotor coordination where high adaptation of the visuomotor system is required.

- Youth elite soccer players show better motor inhibition and are better able to attain and maintain an alert state as compared to amateur soccer players.
- Youth elite soccer players outperform amateur soccer players on implicit motor learning, resulting in earlier stability in terms of mean reaction times on an implicitly learned motor sequence as compared to the amateur soccer players.

Taken together, although more research is warranted on causality, the studies in part A of the current thesis show that participation in organized sports might play a specific role in the relationship between physical activity and neurocognitive functioning. The findings suggest that, in addition to other well-described effects on physical health and social development, children should be encouraged to participate in organized sports activities, because it may positively affect neurocognitive functioning as well.

Results of the studies in part B of this thesis provide promising results on superior performance on several neurocognitive functions in young highly talented athletes, which has paved the way to investigate the necessity of these functions for later success in sports at the highest level.

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