INTRODUCTION

The main aim of this thesis was i) to determine which aspects of dynamic balance control differ between children with and without DCD, ii) to investigate whether motor learning differs between children with and without DCD in a task that requires dynamic balance control and iii) to determine whether children with DCD show transfer of the training to other skills. In all our studies, the Wii Fit ski slalom test (criterion test) was used as a dynamic balance task to study performance and change of performance. Intervention consisted of variable practice of Wii Fit balance games or repetitive practice of the ski slalom game. Performance was tested at baseline (T0), after six weeks (T1) and after intervention (T2) or at baseline (T1) and after intervention (T2). In this final chapter, the main findings of this thesis are summarized and discussed. Additionally, study limitations and implications for further research and clinical implications are presented.

Main findings per research question

1. What are the differences in dynamic balance control in a Wii Fit ski slalom test between children with and without DCD?

Dynamic balance control was studied using a virtual reality (VR) task (ski slalom) of the Wii Fit system in which children controlled an avatar by shifting their weight on a balance board. We have investigated the performance of children with and without DCD in this VR task. We compared the groups on accuracy achieved and time needed, to study the differences in dynamic balance control in the means of 10 repetitions. The validity of the task was confirmed by the relatively high correlation between the rate of learning (accuracy) over the initial ten repeated trials and the MABC2 component balance (chapter 4) \( r = 0.55 \).

The main finding reported in chapter 2 and 3 is that initial motor performance in this task is less accurate in children with DCD compared to their peers according to the outcome measures of the Wii Fit. Moreover, from the kinetics of the shifts of weight (chapter 3) it appears that children with DCD and TD children also show differences in the way they manoeuver the avatar through the gates. The TD group initially used a longer trajectory to navigate through the gates and a trend of more variation of CoP displacements in lateral direction and trends towards fewer reversals in antero-posterior (AP) and lateral directions. These data suggest that a shorter path length of the CoP and more erratic weight shifts of children with DCD underlie the lower task performance as compared to their TD peers.

Differences between TD children and children with DCD were also found in the South African study, indicating that the initial poorer motor performance in the dynamic balance task can be attributed to a distinct motor coordination deficit independent of culture and previous play-, sports- and gaming-experience (chapter 4, 5, 6 and 7). Children with DCD anticipated less and responded slower to correct, confirming the findings of other studies (Gomez et al., 2015; Wilmut et al., 2006; De Oliveira & Wann, 2010; Hyde & Wilson 2011; Jover et al., 2010; Jucaite et al., 2013). Based on these
results, it can be concluded that children with DCD have more difficulties in tasks requiring dynamic balance control.

2. Is motor learning different between children with and without DCD?

The process of direct motor learning was studied in different ways and tested by changes in the performance on the criterion test, which gave us the opportunity to study short-term motor learning (chapter 4). For intervention, we used different practice schedules. In chapter 2 and 3, we used a variable practice schedule in which participants practiced balance games other than the ski slalom game (Table A1, chapter 6). In chapter 5, we used a task-specific repetitive schedule, in which only an easy and advanced version of the ski slalom game were practiced. In chapter 6 and 7, we studied motor learning by comparing the variable and repetitive practice schedules directly.

The short-term motor learning rate (changes during the first 10 repetitions in one session) was less steep in children with DCD compared to their peers, but showed good retention over a 6 weeks period (chapter 4). When learning was measured over a longer period of training, the rate of change in performance was similar between the groups (TD versus DCD), and again the learned skills were retained over several days. The groups did, however, perform on a different level (chapter 5, 6 and 7). Different practice schedules -repetitive and variable practice- led to similar improvement in the mean standardized game scores on the games played during the training period and retention over sessions was comparable. These results imply that children with DCD may initially need more time to acquire motor skills, but during a longer period of training they show a similar rate of motor learning as TD children with retention of the learned level over time.

The results of motor learning showed to be task specific. In our first study (chapter 2), children with DCD improved their performance both on accuracy and speed after variable practice, but when this effect was compared to the effect of spontaneous learning, only speed was approaching significance, while accuracy was not. The results in chapter 6 show that learning curves during the training sessions were independent of type of practice schedule between DCD and TD groups. There were, however, specific differences in effect of the two training schedules. After the repetitive schedule both TD and DCD groups scored more accurately and seemed to have reached their ceiling in contrast with the groups that followed the variable practice schedule. After variable training, the rate of learning was larger at posttest than pretest in both children with DCD and TD children. These results suggest that children with and without DCD are sensitive towards task specificity and repetition.

Six weeks of variable practice had minor impact on kinetic measures in children with DCD since no distinct differences in trajectory of the CoP or the amplitude of the lateral weight shift were found after training (chapter 3). Only a decrease in the number of reversals in AP and lateral directions was found, a sign of better control, which was already initiated in the second criterion test that followed after a period of no training. Apparently, change in kinetics does not synchronize with change in performance.
In sum, children with DCD showed no learning deficit but acquired skills and retained the learned, which was independent of practice schedule.

3. Does training with Wii Fit balance games show transfer to other skills?
Improving motor skills in children with DCD through training or intervention should result in transfer to tasks other than the ones trained, in order to meet the complete definition of motor learning (Magill, 2011; Sattelmayer, Elsig, Hilfiker & Baer, 2016). To show that active motion gaming can support clinical intervention in children with DCD, it is essential to know if improvements in performance on game scores translate into skills needed in daily life. Our studies proved with strong effect sizes that Wii Fit training has an impact on motor tasks that require dynamic balance control as used in daily life of children, such as standing on one leg, balancing on a beam, agility tasks like hopping or jumping sideways and slalom running. Based on these results, the Wii Fit training schedules fulfilled the criteria of motor learning with the extension of transfer to tasks that require different movements or adapting behavior. Both variable and repetitive training protocols yielded positive transfer effects to tasks that require balance skills with similar movement elements like the static yoga balance task, but also with less common movement elements like hopping or slalom running. This outcome was equally strong and independent of the social and cultural backgrounds of the children with DCD from the Netherlands and South Africa (chapter 2, 5, 6 and 7). To tasks with fewer common elements such as manual dexterity, the intervention in the Dutch sample described in chapter 2 showed no transfer, while the South African sample of children with and without DCD did (chapter 5, 6 and 7). Concluding, children with and without DCD showed positive transfer effects after either variable or repetitive training protocols to tasks that required balance skills.

Discussion of the main findings
The ski slalom game requires task-related lateral shifting of weight to control the avatar on the screen, while keeping postural balance. The combination of these two aspects – online control of the avatar and balance control of the standing body - is called dynamic balance control in this thesis. Balance control is the basis for all voluntary motor skills. It provides stability of the body during motor tasks by control of body posture against gravity in static or dynamic conditions and by adapting to destabilizing forces that may act upon the body (Huxham, Goldie & Patla, 2001; Shumway-Cook & Woollacott, 2014). The present study offers no possibilities to disentangle control of the avatar and balance control during the motor tasks. In our studies, we found a consistent lower performance in VR gaming in children with DCD compared to their typically developing peers. This finding points at either a deficit or a developmental motor delay. In the following we will discuss our findings in order to find explanations in the light of current theories for DCD.

A deficit in the internal model or a developmental delay
The ski slalom game requires dynamic interaction between the child and the avatar on the screen
using on-line visual and auditory feedback. In order to present a smooth control of action, the nervous system should realize rapid shifts of weight resulting in changes in trajectory tuned to the change of the virtual environment and correcting for error in trajectory. This mechanism can only be used if the nervous system identifies the current and can predict the future location of the body or of body parts, the so-called forward internal model (Desmurget & Grafton, 2003; Wolpert, 1997). A deficit in the predictive part of the internal model is associated with inadequate motor planning resulting in inaccuracies in shifting body weight to control the position of the avatar position over time, thus missing gates. Such a deficit in children with DCD is supported by other studies (Jover et al., 2010; Jucaite et al., 2013). The ski slalom game challenges the link between action and perception. Poor anticipatory postural adjustments (APAs), or difficulties with forward modeling of postural adjustments point to a dysfunction of cerebellum or posterior parietal cortex (Massion, 1992; Kawato, 1999). However, this is a theoretical interpretation, as we did not directly manipulate or study the internal model or the neural networks that might dysfunction. A deficit of predictive control in the children with DCD would explain the slower and different postural corrections in VR gaming.

Predictive control uses visual perception, tactile perception and proprioception in order to plan and adapt goal directed movements (Royeen & Lane, 1991). The study of Hyde & Wilson (2011) showed impairments of the early online correction of trajectory, when the arm movement had to switch to a sudden different location. This early online correction relies on the internal feedback signals (Archambault, Caminiti & Battaglia-Mayer, 2009; Shadmehr & Krakauer, 2008). Comparison of the planned and the actual movement yield an error signal that is used to elicit corrective motor commands to the moving limbs. It is known that the time between visual detection of error and the correction is longer in children with DCD (Dubrowski, Bock, Carnahan & Jüngling, 2002; van Braeckel et al., 2007) and combined with poor forward modeling will result in delay and thus less proficient performance in VR gaming. The study of Schoemaker et al. (2001) points at a deficit in visual-proprioceptive perception in goal-directed or fast motor tasks in children with DCD. However the motor and not the perceptual component seemed to contribute most to poor performance in that study. Differences between TD and DCD might also be explained by a lack of sensitivity in detecting proprioceptive input, as is known in young children below the age of three years (Foudrariat, Di Fabio & Anderson, 1993; Forssberg & Nasner, 1982) and older people (Benjuya et al. 2004). Information from proprioceptors supplies position sense which needs to match with visual information of the position of the body. In a standing task with eyes closed, young adults increase postural sway to generate more proprioceptive input from the lower limb muscles, whereas older people do not use this strategy because of fear of falling (Benjuya et al., 2004). Likewise, fear of losing balance might restrict children with DCD in amplitude of shifting weight to increase their sensory input. In sum, in children with DCD reduced sensitivity to visual and sensory input and fear of falling restricting the proprioceptive input may explain lesser adaptations to the task demands and result in poor task performance.
Besides input deficits, also prolonged movement time is associated with DCD due to alteration of antagonist timing, opposing the aimed movement (Johnston et al. 2002). The initially more rigid strategy of children with DCD described in chapter 3 resembles movement strategies seen in older people, who show reduced amplitude of CoP excursions during quiet stance (Horak, Nutt & Nashner, 1992) and more rigid co-activation strategies between ankle, trunk and head movements in voluntary movement and compensatory postural responses (Tucker et al. 2008). These muscle co-contractions are considered to impede adaptive responses, altering the response time during rapid changes in direction and limit the degrees of freedom available, all considered risk factors for falling (Ho & Bendrups, 2002; Allum, Carpenter, Honegger, Adkin, & Bloem, 2002). Smaller lateral displacements of the CoP of the children with DCD may be the result of a higher level of muscle co-activation that is usually associated with the early acquisition phase (Bernstein, 1967).

Inefficient timing may result in more reversals (chapter 3). In the children with DCD repetition, of the task resulted in a more steady movement pattern in the goal-directed weight shifts with fewer reversals. This suggests that children with DCD are better able to predict the consequences of lateral shifts related to the position of the CoP and the location of avatar relative to the gates.

It has been common opinion that children with DCD will grow out of their motor problems, but this opinion has changed. If children really grow out of their age related problems, this can only be studied by longitudinal research, which is scarce. The longitudinal study of Visser et al. (1998) in boys during puberty showed that performance on the MABC improves spontaneously during puberty in about half of the children. This was interpreted as evidence that the hormonal changes induced a speeding up of the maturation/myelination of the CNS, reducing structural constraints on motor skill development. Follow-up studies (Losse et al., 1993; Geuze & Börger, 1994; Cantell et al, 2003) showed that DCD is persistent and extends into puberty in a considerable proportion of children. In a considerable percentage of children diagnosed with DCD symptoms continue into adulthood presenting complications in various (new) areas of functioning and participation, such as driving, writing, tidying desks or folding clothes (Kirby et al. 2011; Gagnon-Roy et al 2016). There is evidence that this has a negative impact on quality of life and level of participation compared to peers (Hill et al. 2011; Tal-Saban et al. 2014). Intervention aimed at improving motor proficiency, thereby enhancing movement experience and motivation which will improve participation and by this help to avoid the persistence of negative experiences in adolescence.

Studies are needed to understand whether type of training or the severity of the deficit influences the point where improvements level off. It is known that children with DCD form a heterogeneous group and individual differences in skill acquisition will be present. The fact that after extensive training, only a few children were able to play the ski slalom game as successful as their TD peers does not refute or support the internal model deficit or developmental delay hypothesis as an explanation for the poor performance of the children with DCD. Given this heterogeneity, it may be that some of the children have a deficit, whereas others have a developmental delay. The present study did not aim to differentiate this. In short, there is a need for investigating how the changes
in motor performance relate to type of intervention and support of environment. Studies that monitor performance over a longer period of time are needed in order to gain better insight into the predictors of the (catching up) potential of children with DCD.

**Motor learning in children with DCD**

Motor learning is only established after a multilevel improvement is observed (Biotteau, Peran, Vayssiere, Tallet, Albaret & Chaix, 2016), which was the case in both children with and without DCD in our studies. Consistent improvements over the training period were found in Wii performance, i.e. speed and accuracy, with retention being present over time and transfer to both similar tasks and ecologically more valid tasks. A large part of the children showed better dynamic balance control as they hopped faster, and walked more accurately over a line after training on the Wii Fit. Bernstein (1967) theorized that the body could only solve the problem of controlling the degrees of freedom when muscles work together in synergies. The finding that after intervention the CoP trajectory approaches the optimal trajectory more often may reflect this. An important question is, however, why children with DCD showed normal motor learning during the practice schedules we offered, but insufficient acquisition during their earlier development. Longitudinal studies are needed to address this important question.

Proficiency of typical motor performance depends on motor learning, amount of experience and social contextual factors. Difference in amount of experience was controlled by exposing the TD and DCD groups to similar intensity of training and by studying cultural differences. The rate of learning during the same amount of training (100 trials) in repetitive and variable conditions for both TD and DCD children was not different between groups. So for this stage of learning, despite the poorer coordination pattern, no deficit in motor learning in this context was found in children with DCD.

Our studies showed that children with DCD were able to learn as well as TD children, but remained performing at a poorer level. It is likely that with more or longer training the performance differences will persist. The performance differences were not explained by environment or cultural context. The initial performance of the Wii score was different between Dutch TD children and children with DCD. Even though the specific task used was novel, Dutch children have been previously exposed to computer games which are part of their daily life. Importantly, the children with DCD from South Africa were similarly different from their TD peers, although neither of them had any previous experience with computer games. These results imply that lack of practice opportunity alone does not explain the poor performance of children with DCD compared to TD children in these tasks.

Does that mean that psychological factors play an additional role? Low motor competence reduces motivation to participate in physical activity. This may lead to reduced contact with peers, less amount of time practicing motor skills and not keeping up a reasonable level of physical fitness (Causgrove, Dunn & Watkinson, 1994; Bouffard, Watkinson, Thompson, Causgrove, Dun & Romanov, 1996; Fitzpatrick & Watkinson, 2003; Kirby, Davies & Poynor, 2005; Cantell & Kooistra 2002; Cairney et
al. 2005; Hands, 2008; Cantell, Crawford & Doyle-Baker, 2008). In our study it was remarkable that all children were enthusiastic about the task and remained motivated over the five or six week period of intervention and in the task with 100 repetitions. We can only speculate which game factors keep the motivation and fun factor so high in active computer games and why this is perceived differently in recreational and sport activity in children with DCD. It is important that children with DCD are offered enjoyable and efficient training and therefore parents and teachers should be advised on how to support children with DCD to prevent multiple negative experiences and physical activity avoidance.

The role of instruction, feedback and knowledge of results
The ski slalom task is largely an implicit learning task. The only explicit instruction is given when the task is first introduced to the child: the computer console presents a standardized instruction how to shift the body weight sideways by an avatar moving the upper body to the right and left side. Additional explicit instructions were given between the fourth and fifth run during which a demonstration was given of the lower limb balance strategy described by Michalski et al. (2012). The learning curves of chapter 3 showed no additional effect of the explicit instruction.

It is known that the type of feedback during motor learning can play a distinct role in its effect. During active video gaming on-line, visual information is available as knowledge of performance during the task and passing or failing a gate is signaled auditory. Knowledge of results is presented after completion of each run. Apparently, the children benefited from the augmented implicit feedback of the VR game to improve their dynamic balance control. The immediate reaction of the avatar responding to each weight shift of the child is also a form of feedback, specific to these kinds of computer games. This could have been a stronger mediator in learning, and seemed to work better than observing and imitating peers, or learning from their own mistakes, which has been reported to be deficient in children with DCD (Goodgold-Edwards & Cermak, 1990). This implies that changes in direction by the avatar on the screen in immediate response to movements by the child on the balance board has had a positive effect on motor learning in children with DCD, most probably through strengthening action-perception coupling.

Transfer of motor learning to real life dynamic balance tasks
Transfer from acquired motor skills to another or a new task usually occurs when the skills or underlying abilities required to perform the tasks are similar in some way (Seidler & Noll, 2008; Smethurst & Carson, 2001). Having already mastered one of the skills makes learning the second skill easier. This positive transfer occurs when the modifications of the action based on the procedural knowledge can generalize to other related movements (Maxwell, Masters & Eves 2003; Kelso, 1995). To study transfer, we used standardized motor test items that approach daily life activities of children, specifically the Movement ABC, 2nd edition (MABC-2) and subtests of the Bruininks Oseretsky Test, 2nd edition (BOT-2) Balance, Running Speed & Agility and Bilateral Coordination.
After transfer effects of motor skills to these tasks became apparent, we decided to include also motor tasks that tap strength and endurance which may be considered factors that underlie many of the common daily life activities of children. We included functional strength of lower extremities of the FSM and the sprint tests (see Fig 8.1). It is a remarkable finding that children improve in strength items and anaerobic fitness after Wii Fit training. The children with DCD even approached or reached the pretest scores of the TD children for the subtest Balance (BOT2), the lateral step-up, sit to stand, stairs and the sprint slalom. The question arises whether this improvement is caused by common elements needed in the trained dynamic balance and in running up and down the stairs or sprinting with many turns, or whether the children become generally more active by participating in the study and thereby increasing fitness. The latter seems less likely.

Besides tasks with common motor elements, our results showed improvement in aiming and catching but for manual skills the results differed between the Dutch and the South African samples. As discussed in chapter 7, improved postural control, faster postural changes and shorter response time may have helped improving the aiming and catching tasks. It is harder to give an explanation for the improvement of the manual skills. It is known that in implicit learning as a relative subconscious process, the dorsolateral prefrontal cortex is involved which is also related with working memory processes, selective attention and visuo-spatial and visuo-motor processing (Bo, Jennet & Seidler,

**Fig 8.1.** The four items challenging daily life activities of the FSM and the two sprint tests developed for this project.
Both the manual skills and our games require visuo-spatial and visuo-motor processing and selective attention. Together with the implicit training of extracting goal relevant information, we can only cautiously suggest that this might have resulted in small improvements in non-practiced fine motor skills.

Clinical implications
The fact that children with DCD perform at a lower level while showing motor learning at an equal rate, retention of the acquired skills and similar transfer compared to TD children implies that intervention is likely to be successful. Our studies legitimize the use of variable or repetitive training protocols for intervention in children with DCD. Given the positive effects of the Wii-Fit training on motivation and fitness, therapists, when planning intervention programs for children with DCD, should consider including active video gaming as an important additional and enjoyable tool to support the regular dynamic balance intervention. It is preferable to offer the VR training in a structured manner, according to protocol and time on task. As a training protocol, we used ten games, or twenty minutes play time, twice or three times a week for at least five weeks. This schedule was effective but may be further optimized. The sessions were supervised, which is apparently a positive factor since lack of structure, guidance and supervision in home based programs failed to establish improved motor skills or physical activity (Howie et al., 2017). Training in small groups as in our studies, and participation of parents as tested by others (Ashkenazi et al., 2013) proved to be manageable and successful.

Many physiotherapists aim their intervention to improve the smoothness and coordination of the motion, but our results indicate that the kinetic adaptations are not necessarily linearly related to improved proficiency. It therefore seems more important that children with DCD get plenty of practice in motion games than that their movements are corrected. It may be the case that children with DCD need more time to explore and find their optimal strategy for performing the task. It could also be that they keep using a less optimal strategy but still get better outcomes over time.

Strengths and limitations and recommendations for future studies
This project used VR active video gaming to study dynamic balance control and motor learning. So far, most studies concentrated on static balance posture and in the case of motor learning on serial reaction time tasks. The inclusion of a replication study in this series of learning studies, finding similar results in a different population of children, makes the evidence that children with DCD do not have a motor learning deficit even stronger. The design of our first study would have been stronger if it had been a cross-over design, but we compensated for this by testing the change over time without intervention against change due to intervention.

Another limitation of this study is our focus on the short term to medium term learning phase. Although transfer was established, the full automatization phase of the learning stages was not reached yet (Fitts & Posner, 1967; Bernstein, 1967) and requires further study. We observed learning
taking place from the first fast learning phase, in which the learning curve of the children with DCD was less steep, towards the second slower phase, in which the learning curve was not different between groups, leading to consolidating and automating the performance, in which transfer of the skill to a new task was possible (Seidler, 2010; Fitts, 1954; Doyon & Benali, 2005). To study the process of automatization, we recommend a study on children with DCD, in which the length of training period extends until the learning curve levels off to an insignificant amount of change. The amount of automatization may also be studied by combining the task with another task, and even continue the training until no interference of the dual task occurs.

Neuroimaging studies of changes in connectivity in the brain through motor learning in VR tasks will give more insight in the amount of functional and structural connections that are influenced by dynamic balance training in both children with and without DCD. Moreover, it would show how these training induced changes are related to performance.

**Conclusion**

The studies presented in this thesis show that a distinct dynamic balance control deficit is present in children with DCD, as they anticipate less and respond slower to correct in a dynamic balance task. Importantly, the rate of motor learning on a short to medium time scale of children with DCD is similar to that of TD children. We therefore may conclude that children with DCD do not have a motor learning deficit in the tasks and conditions studied. Moreover, the skills acquired through VR training showed positive transfer effects to ecologically valid motor tasks in children with and without DCD. The improvements seen after Wii Fit training shows the potential benefit of virtual reality based motor training and augmented feedback in children with DCD.

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