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Multisensory Motor Coordination in Children and Adults

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A thesis submitted for the award of
Doctor of Philosophy

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ID No.: ______________

Date: __________

For Leah-Ann and Leo

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ABSTRACT

Multisensory Motor Coordination in Children and Adults

David Gaul

Motor skills are the basis for any bodily movement. They allow individuals to walk, write, interact with the environment, and participate in physical activity. These motor skills play a central role in lives of children and adults and specifically allow them to be physically active and healthy. As such, the ability to coordination movement is vital to our everyday lives and can influence the quality of life we experience. This thesis sought to examine the motor coordination processes in children and adults, and investigate how the factors of age and obesity influence these processes. Firstly, this thesis found that children's fine motor skill proficiency fell below normative levels (Study 1) and that children's sensory-motor integration was still developing at age 12 (Study 2). Further to this, given the extensive research showing that obese individuals demonstrate less proficient fine and gross motor skill competence than their normal-weight peers, this thesis also examined the effect of obesity on the motor coordination of adults. Results from studies 3 and 4 demonstrated that obese individuals were less able to accurately control and coordinate movements compared to their normal-weighted peers. Traditionally, these differences have been attributed to the mechanical implications of excess mass. However, given the limited influence of mass in fine motor skill tasks used in this series of studies, these findings further support the hypothesis that obese individuals experience sensory integration difficulties. If this is the case, the decreased perceptual-motor function might impede the performance of everyday life activities as well as their willingness to participate in physical activity. This offers new insight into the potential for decreased motor coordination to be a contributing factor to the increasing prevalence of obesity in children and adults.

Chapter 1: Introduction to the Thesis

Introduction

The ability to coordinate movement is an inherent component of human life. From birth, we engage in coordinated movement in order to interact with the environment around us. Examples include the successful completion of reaching and grasping actions, which require the ability to appropriately coordinate the speed and accuracy of movements (Haywood and Getchell, 2009). Motor development is required for typical development in children and can be considered a facilitator of efficient cognitive development. As we move, we are exposed to greater sensory and perceptual experiences through interaction with the environment. As motor development progresses, we become more efficient in the integration of sensory information available and coordination of the motor outputs required which results in more effective and less variability in movement (Gallahue, Ozmun and Goodway, 2012). Manual coordination, in the form of reaching and grasping, is one of the first voluntary motor patterns that we develop in childhood, prior to sitting up or crawling. It is a vital part of everyday life and supports successful engagement of many activities of daily living. Fine motor skills are the use of small muscles involved in movements that require the functioning of the extremities to manipulate objects (Gallahue & Ozmun, 2006). Fine motor skill proficiency is the core of many of these everyday tasks and involved in activities requiring manual coordination of movement such as dressing oneself, using cutlery to eat, brushing your hair or handwriting in school. Overall, fine motor skill competence plays an important role in typical childhood development. However, at present, little is known about the impact of changes occurring in the modern environment (i.e., reduced physical activity, increased sedentary behaviours and the prevalence of obesity) and the maturation process influences the development of fine motor skill in children. Children now spend less time engaged in physical activity pursuits and varied movement experiences such as organized team sports, climbing trees or playing board games than in the past (Fjørtoft, 2001; Sandseter and Kennair, 2011; Hansen-Sandseter and Sando, 2016). This is primarily as a result of the increased prevalence of forms of leisure time activities that are sedentary (Tremblay *et al.*, 2011). Children now spend increasing amounts of time watching television, playing games consoles or using digital tablets or phones, often replacing time that was often spent being physical active (Roberts and Foehr, 2005; Rideout, Foehr and Roberts, 2010; Bucksch *et al.*, 2014).

Evidence, since the turn of the century, has shown that children's levels of physical activity and motor skill proficiency have decreased significantly (Morgan *et al.*, 2013; Robinson *et al.*, 2015). As motor competence, particularly in Fundamental Movement Skill (FMS), which Gallahue and Donnelly (2003) define as "an organized series of basic movements that involve the combination of movement patterns of two or more body segments" (p. 52), are a predictor of engagement in physical activity both in childhood and through adolescence, motor skill proficiency could be a key contributor to tackling this problem. These falling levels of physical activity have given rise to the increased prevalence of obesity. Obesity has become a major public health concern and is now the second leading avoidable cause of death in the world. Obesity is associated with decreased motor competence, physical activity and perceived competence. As such, this can give rise to a vicious cycle of physical inactivity and weight gain. If you are less well able to move you are less likely to move (often).

In more recent times, there have been links made between obesity and impairments in cognitive function. This has lead to evidence suggesting lower academic achievement and poorer executive function, attention and visual motor coordination in obese individuals. Further to this, research has begun to expand on the potential presence of 'perceptual motor coordination' or 'sensory motor integration' difficulties as a result of obesity (Petrolini et al. 1995; Bernard et al. 2003; D'Hondt et al. 2008; Osika and Montgomery 2008; D'Hondt et al. 2009; D'Hondt et al. 2011; Gentier et al. 2013). As such, difficulties in the integration and performance of motor coordination tasks could impair the effective performance of many activities of daily living. These motor coordination difficulties have been previously observed in a number of other special populations including those suffering from Parkinson's disease (Rand *et al.*, 2014), Autism Spectrum Disorders (Green *et al.*, 2009), Cerebral Palsy (Himmelmann *et al.*, 2006) and Developmental Coordination Disorder (DCD) (Summers, Larkin and Dewey, 2008a; Bart *et al.*, 2011) among others. Obesity is already known to negatively influence individual's quality of life and impair many activities of daily living mainly due to the mechanical constraints of excess mass. Therefore, the presence of motor coordination problems could further the difficulties already being experienced.

The sensory integration process relies on the complex interaction between the individual, the task being carried out, and the environment in which it takes place. This relationship between the sensory integration process and motor behaviour has been extensively studied in typically developing adults and, more recently, to gain a greater understanding of how this process is altered in individuals with Autism Spectrum Disorders (Fitzpatrick *et al.*, 2016) and Schizophrenia (Varlet, Marin, Raffard, *et al.*, 2012). However, we know little about these processes in children and even less about how these processes change as a result of obesity.

The dynamical systems theory offers a framework to help explain the interaction between all factors involved in these changes by suggesting that the development of motor skill relies on the ever-changing relationship between all components of a system (e.g. the individual, the task and the environment – Newell, 1986). According to this model, motor development can be seen as the ‘‘continuous change in motor behaviour throughout the life cycle, brought about by the interaction between the requirements of the movement task, the biology of the individual and the conditions of the environment” (Gallahue & Ozmun 2006, p.25). As such, we can view motor development as a constantly evolving process depending on all genetic and environmental influences acting on an individual. Therefore, it is believed that motor coordination emerges from the interaction between all the factors leading to the observable motor patterns. This thesis applies a dynamics systems approach to examine the effect of age and obesity on the coordination of movement in children and adults.

Aim of the thesis

The aim of this thesis was to investigate motor coordination levels in children and adults and evaluate the influence age and obesity on the motor control process.

Objectives of the thesis

Study 1 sought to determine the current state of fine motor skill proficiency in a sample of Irish primary school children. In addition to this, we sought to investigate whether levels of fine motor skill proficiency were demonstrating trends also seen in gross motor skill, with children falling below normative levels.

The objective of study 2 was to establish a baseline for children's manual coordination ability and an understanding of the sensory integration in children. At present little is known about how it develops with age and how it compares to adult levels in a rhythmic pendulum task. This study sought to build upon study 1 by investigating with a finer grain of analysis, the processes underlying coordination in children.

The primary objective of study 3 was to determine the influence of obesity on the sensory integration process and examine if it affects the coordination process in adults. This study was carried out to strengthen the argument for the presence of a link between sensory integration difficulties and obesity. As the sensory integration structures are fully developed in adulthood, this study aimed to examine the influence of obesity on visual motor coordination in adults. This facilitates greater understanding of this relationship, free from changes as a result of the maturation process in children.

Finally, study 4 sought to build upon the findings of study 3 by analysing how obesity affects adult's ability to control the speed and accuracy of manual aiming task and its effect on performance and movement kinematics. This study aimed to further examine the relationship between obesity and motor coordination in a more ecological setting. This could provide a greater indication as to the consequence of sensory integration problems in obese individuals in a scenario similar to those encountered in daily life. As children are also frequently required to perform actions quickly and accurately in many sporting or academic activities, the findings of this study may highlight a relationship between obesity and motor coordination in children and adults.

Publications

- **D. Gaul** & J. Issartel. Fine motor skill proficiency in typically developing children: On or off the maturation track?, *Human Movement Science*, 2016, 46, 78-85. DOI:10.1016/j.humov.2015.12.011

- **D. Gaul**, A. Mat, D. O'Shea & J. Issartel. Impaired Visual Motor Coordination in Obese Adults, *Journal of Obesity*, 2016, 1-8. DOI: 10.1155/2016/6178575

- **D. Gaul**, L. Fernandez and J. Issartel. "Its not what you do it's the way that you do it" The influence of obesity on the speed and accuaracy of a discrete aiming task, *Experimental Brain Research*, 2017. (Under Review).

- **D. Gaul** & J. Issartel. Getting into the swing of things: An investigation into rhythmic unimanual coordination in typically developing children, *Neuroscience Letters*, 2018. (Accepted for Publication).

Poster AND Scientific Talks

Poster Presentations:

- **D. Gaul** & J. Issartel. Fine motor skill proficiency in typically developing children: On or off the maturation track?, *Association for the Study of Obesity on the island of Ireland Annual Conference*, 2017, Dublin, Ireland.

- **D. Gaul**, A. Mat, D. O'Shea & J. Issartel. The effect of Obesity on Motor Control, *Neural Control of Movement*, 2017, Dublin, Ireland.

- **D. Gaul**, and J. Issartel. A Fine Line between Skilled and Unskilled: A longitudinal analysis of fine motor skill proficiency in Irish Primary School Children, *All Ireland Postgraduate Conference in Sport Sciences, Physical Activity and Physical Education*, 2017. Carlow, Ireland.

- **D. Gaul** & J. Issartel. Fine motor skill proficiency in Obese Children, Endocrine Abstracts, 2015, 37, EP588. European Congress of Endocrinology. Dublin. Ireland.

- J. Issartel, A. Mat, D. O'Shea & **D. Gaul**. Altered sensory motor integration in Obese Adults, Endocrine Abstracts, 2015, 37, EP600. European Congress of Endocrinology. Dublin. Ireland.

- **D. Gaul,** D. Cody & J. Issartel. The Effect of Obesity on Coordination ability of Children. *European Conference on Obesity*, 2014, Sofia, Bulgaria

Scientific Talks:

- J. Issartel & **D. Gaul**. A longitudinal analysis of fine motor skill proficiency in Primary School Children, *North American Society for the Psychology of Sport and Physical Activity (NASPSPA)*, 2017, San Diego, USA.

- **D. Gaul**, A. Mat, D. O'Shea & J. Issartel. Altered Visual Motor Coordination in Obese Adults, *14th European Workshop on Ecological Psychology*, 2016, Groningen, and Holland.

- **D. Gaul**, A. Mat, D. O'Shea & J. Issartel. From Children to Obese Adults: An unfrotunate trend. *PsychHike*, 2015, Down, Ireland.

- **D. Gaul**, & J. Issartel. The Lost Lego Blocks, PEPAYS Research Forum 2015, Limerick, Ireland

- **D. Gaul,** D. Cody & J. Issartel. Perception Action Deficit in Obese Children, *13th European Workshop on Ecological Psychology*, 2014, Fermanagh, Ireland.

Awards

- Irish Research Council Government of Ireland Postgraduate Scholar GOIPG/2014/1516.
- Dublin City University Faculty of Science and Health Distinguished Scholar 2012
- Dublin City University Tell It Straight Competition 2017 - Winner

Contribution to Peer-Reviewed Publications

This thesis contains four original papers (2 published, 1 accepted for publication and 1 under review) conducted in collaboration with my supervisor and through collaborations with other institutions. My contribution to each paper presented in this thesis is outlined in the table below:

TABLE 1.1: CANDIDATE CONTRIBUTION TO PEER-REVIEWED PUBLICATIONS.

<table>
<tr><th colspan="2">Chapter 3:</th></tr>
<tr><td colspan="2">Fine motor skill proficiency in typically developing children: On or off the maturation track?</td></tr>
<tr><td colspan="2">Published in Human Movement Science, 2016, 46, 28. 10.1016/j.humov.2015.12.011</td></tr>
<tr><td>Authors
David Gaul & Johann Issartel</td><td>Affiliation
School of Health and Human Performance, Dublin City University</td></tr>
<tr><td colspan="2">Candidate Contribution:
The candidate was responsible for all aspects of study design including formulation of the research question in collaboration with supervisor Dr. Johann Issartel. The candidate also carried out all data collection and statistical analysis as part of the study. The candidate is the first author on the paper and wrote all sections of the paper with assistance from Dr. Johann Issartel.</td></tr>
</table>

<table>
<tr><th colspan="2">Chapter 4:</th></tr>
<tr><td colspan="2">Getting into the swing of things: An investigation into rhythmic unimanual coordination in typically developing children.</td></tr>
<tr><td colspan="2">Accepted for publication in Neuroscience Letters, 2018.</td></tr>
<tr><td>Authors
David Gaul & Johann Issartel</td><td>Affiliation
School of Health and Human Performance, Dublin City University</td></tr>
<tr><td colspan="2">Candidate Contribution:
The candidate's contribution to study design was the formulation of the research question which utilized the application of an existing experimental methodology to a previously unexamined subject group (children). The candidate carried out all subject recruitment, data collection, and statistical analysis as part of the study. The candidate is the first author on the paper and wrote all sections of the paper with assistance from Dr. Johann Issartel.</td></tr>
</table>

Chapter 5:	
Impaired Visual Motor Coordination in Obese Adults	
This paper was published in *Journal of Obesity,* 2016, Article ID 6178575, 1-8.	
Authors	**Affiliation**
David Gaul[1], Arimin Mat[2], Donal O'Shea[2,3] and Johann Issartel[1].	[1]School of Health and Human Performance, Dublin City University, Dublin, Ireland. [2]Weight Management Service, St Columcille's Hospital, Loughlinstown, Ireland.[3]Department of Endocrinology, St Vincent's University Hospital, Dublin 4, Ireland.
Candidate Contribution: The candidate's contribution to study design was the formulation of the research question which utilized the application of an existing experimental methodology to examine the sensory integration process in obese adults in collaboration with Dr. Johann Issartel. The candidate carried out all subject recruitment and data collection in collaboration with Dr. Arimin Mat and Prof Donal O'Shea. The candidate carried our all data and statistical analysis as part of the study. The candidate is the first author on the paper and wrote all sections of the paper in collaboration with Dr. Johann Issartel, Dr. Arimin Mat, and Prof. Donal O'Shea.	

Chapter 6:	
"Its not what you do it's the way that you do it": The influence of obesity on the speed and accuaracy of a discrete aiming task	
This paper is under review in *Experimental Brain Research*, 2017.	
Authors David Gaul[1], Laure Fernandez[2]and Johann Issartel[1].	**Affiliation** School of Health and Human Performance, Dublin City University
Candidate Contribution: The candidate formulated the research question in collaboration with Dr. Johann Issartel and Dr. Laure Fernandez. The candidate wrote the code for analysing the data in collaboration with Dr Laure Fernandez. The candidate supervised data collection and carried out all statistical analysis as part of the study. The candidate is the first author on the paper and wrote all sections of the paper in collaboration with Dr. Johann Issartel, Dr. Laure Fernandez.	

Chapter 2: Review of the Literature

2.1 Obesity

2.1.1 The Obesity Problem

Obesity is the greatest public health concern of the 21st century with the worldwide prevalence of obesity doubling since 1980 (WHO, 2014). Obesity results from an energy imbalance between calorific intake and energy expenditure and subsequent accumulation of fat (Ceschia *et al.*, 2015). Obesity is second only to smoking as the cause of premature death in the world (The Global BMI Mortality Collaboration, 2016). According to World Health Organization (WHO) figures from 2014, 39% of adults (1.9billion people) were overweight, with more than 13% of these being found to be obese. The obesity problem also seems to continue with 42 million children under the age of 5 being found to be either overweight or obese in 2013 (World Health Organization, 2014). Perhaps more alarmingly, despite concerted efforts to combat childhood obesity, one in three adolescents are obese in Europe according to a recent WHO report (World Health Organization, 2017).

The consequences of being obese are well documented with increased risk of cardiovascular disease, cancer, non-insulin-dependent (type II) diabetes mellitus, stroke, hypertension, obstructive sleep apnoea and depression being highlighted in the literature (Lee *et al.*, 2012). Further to this, obesity has also been found to decrease individuals quality of life (Rosmond and Bjorntorp, 2000; Fontaine and Barofsky, 2001; Ford *et al.*, 2001; Swallen, 2005; Tsiros *et al.*, 2009). A review by Fontaine and colleagues (2001) found obesity was associated with reduced quality of life in a variety of aspects including physical functioning, self-esteem, social interaction, work capacity and sexual activity. Interestingly, in studies where weight reduction was achieved, patients frequently reported increased quality of life (Fontaine and Barofsky, 2001). However, Ford et al. (2001) found higher Body Mass Index (BMI), a measure of body fat calculated by dividing your weight (kg) by your height (m^2), was more strongly associated with reduced physical functioning compared to mental or affective functioning. This is not surprising then given that individuals with high BMI are at higher risk of suffering falls or stumbling as a result of altered centre of mass and impaired postural control (Corbeil *et al.*, 2001; Fjeldstad *et al.*, 2008; Singh *et al.*, 2009; Handrigan *et al.*, 2010; Mitchell *et al.*, 2015). Singh, Park, Levy and Jung (2009) investigated balance in a sample of 10 morbidly (BMI > $40kg/m^2$) and 10 lean weight

(18.5 kg/m^2 < BMI< 24.9 kg/m^2) controls. They found that obese individuals demonstrated significantly shorter functional reach and increased postural sway during quiet stance, making them of greater risk of falls. This increased risk of fall is of particular concern in older populations. Mitchell, Lord, Harvey and Close (2015) found that being obese was associated with a 25% higher risk of experiencing a fall in the previous 12 months in a sample of 5681 adults over the age of 65 years.

In addition to increased risk of falls, obesity also influences the mobility of individuals, effecting their gait and movement. Lai, Leung, Li and Zhang (2008) found that obese adults walked significantly slower, had shorter stride length and demonstrated differences in terms of the spatial temporal aspects of gait and joint motion compared to their normal weight counterparts. The authors concluded that these differences were a consequence of their greater mass and in an effort to reduce energy expenditure and movement of the knee (Lai *et al.*, 2008). These difficulties manifest themselves in terms of reduction in physical activity levels and the associated reduction in cardiorespiratory fitness levels (Duvigneaud *et al.*, 2008; Kuk and Lee, 2010). A reduction in time engaged in physically active pursuits and increased time engaged in sedentary behaviour results in a reduction in cardiorespiratory fitness in addition to an accumulation of excess body mass (Cantell, Crawford and Tish Doyle-Baker, 2008). Duvigneaud, Matton, Wijndaele, Deriemaeker, Lefevre, Philippaerts, Thomis, Delecluse and Duquet (2008) found that obese adults, particularly those with higher waist circumferences, demonstrated significantly reduced levels of cardiorespiratory fitness (CRF) levels compared to lean controls. These changes as a result of obesity can have far reaching consequences including increased difficulty to engage in many activities of daily life, reduced physical activity and poorer social and emotion health which can drastically impact on individuals quality of life.

2.1.2 The Obesogenic Environment

The human genome has not changed substantially in the past 3 decades, therefore the drastic rise in obesity is likely to be a consequence of changes in human behaviour and the environment that we live in (Wiklund, 2016). Children now grow up in an increasingly obesogenic environment. These changes are important as the environment that our children develop in helps predict the physical activity patterns they engage in

(Ferreira *et al.*, 2007). Children now spend considerable amounts of time interacting with digital devices such as tablets, games consoles or television (Biddle *et al.*, 2010; Lauricella, Wartella and Rideout, 2015). Rideout (2013) found that 75% of American children had access to some type of 'smart' device (smartphone, tablets) at home, a 23% increase since 2011. In addition to this, children aged 8 and younger who use mobile devices on a daily basis were found to spend 1hour and 7minutes engaging with them on average (Rideout, 2013). Parental influence also is an important factor in children's engagement in screen time activities. Lauricella, Wartella and Rideout (2015) found that children mirrored their parent's screen time behaviours. Parents across all age groups who spent the greatest amount of time with TV, tablets and smartphones had children who also spent greater amount of time with these devices than their peers (Lauricella, Wartella and Rideout, 2015).

These increased opportunities to engage in sedentary behaviours often replace those traditionally involving physical activity or sport participation (Maitland *et al.*, 2013). Research by Swinburn and Egger (2002) has shown that increased time engaged in playing video games or watching television is associated with increased prevalence of obesity whilst involvement in physically active leisure time activities may provide protection from obesity in children. The effects of these behaviours tend to have long-term consequences on children's physical activity and sedentary activity engagement as they track into later childhood and adolescence. A study by Biddle et al. (2010) suggests that sedentary behaviours, particularly TV viewing, track from childhood into adolescence. In addition to this, the authors suggested that tracking for sedentary behaviours may be stronger than the levels observed in the literature for physical activity (Telama, 2009). This is a worrying trend particularly with the increase in the range of sedentary leisure activities available to children. As such, we can see the reduction in physical activity and increase in sedentary behaviours as two side of the same coin. Pietilainen and colleagues (2008) suggested that this relationship between physical activity, sedentary behaviour and obesity can lead to a self-perpetuating vicious cycle of inactivity and increasing adiposity from childhood into adolescents. Further to this, evidence has shown that childhood obesity is associated with greater risk of becoming obese in adulthood (Freedman *et al.*, 2005).

A possible explanation in this physical activity deficit in obesity may lie in the relationship between obesity and motor skill development. A study by Ceschia et al. (2015) found that increased BMI was associated with decreased performance capabilities, which limited proper motor skill development that directly affects children's ability to engage in physical activity and sporting activities. As motor skill proficiency is positively associated with higher physical activity, motor skill interventions may have a prominent role in tackling this obesity epidemic (Wrotniak *et al.*, 2006; Cliff *et al.*, 2009, 2011; Lopes *et al.*, 2012). However, the relationship between obesity and motor coordination can be difficult to disentangle in childhood given the rapid biological changes that take place and environment experiences children are exposed to.

2.2 Motor Skill

2.2.1 Motor Development

Motor development can be defined as the change in movement behaviour and the factors underlying those changes (Haywood and Getchell, 2009). This is a continuous process. However, the amount of change is more noticeable at certain points over an individual's lifespan (Haywood and Getchell, 2009). Although not directly linked, motor skill development follows a similar advancement as physical growth and chronological age. As children mature, they develop greater physical capabilities. However, this progress can be faster or slower at different points and can vary between individuals. Further to this, development is also a sequential process with the reaching of one stage before the next stage in an orderly and irreversible pattern. This has lead to the formation of well-established patterns or stages of development that occur from birth into adulthood. Gallahue and Ozmun (2006) developed the Hourglass model for stages of development, which documents the key stages and when they should be attained.

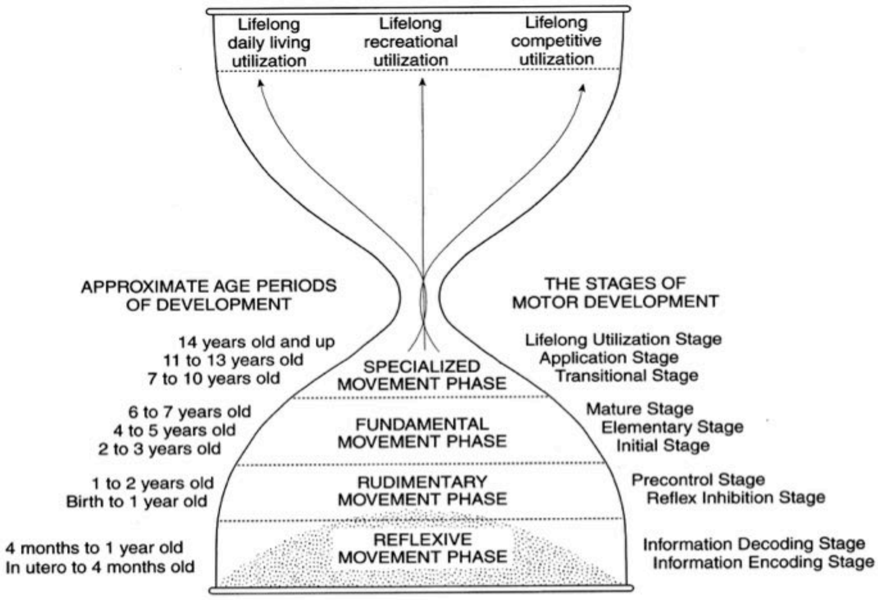

FIGURE 2.1: HOURGLASS MODEL OF THE STAGES OF DEVELOPMENT (GALLAHUE & OZMUN 2006, REPRODUCED WITH PERMISSION FROM MCGRAW HILL)

During the first year of life, infants experience the reflexsive movement phase which consists of predominantly involetary movements. Examples of these movements include the Palmar grasp, Babinski, Moro and Suckle (Piek, 2006). As infants mature and are exposed to greater information from the environment, they replace these involuntary movements with the more voluntary movements of the rudimentary movement stage. These movements are primarily related to survival and involve postural stability, locomotion and maniuplation of objects (Gallahue and Ozmun, 2006). Development of these skills enable infants to further interact and control their environment through skills such as sitting, crawling, walking and grasping. The fundamental movement stage of development begins between the ages of 2 and 7 years, and plays a crucial role for motor skill development in children as it lays the foundations for motor skill ability in the future (Haibach, Reid and Collier, 2011). It is after this stage that children and adolescents enter the specialised movement phase and develop motor skills for lifelong utisilastion in activities of daily living, physical activity and sport participation. At each of these phases, infants, children, adolescents and adults develop motor skills. Motor skills are the basis of any bodily movement. They involve the coordination of limbs and muscles to achieve an end goal (Haywood and Getchell, 2009). We frequently classify motor skills into two taxonomies: gross motor skills and fine motor skills.

2.2.2 Gross Motor Skill

Gross motor skills involve movement of the large musculature and consist of activities such as running, and jumping. A study by Lima, Bugge, Pfeiffer and Anderson (2017) found that children with proficient gross motor skills in childhood demonstrated good gross motor skill in adolescence. Lima et al. (2017) also found that heavier children had a higher chance of falling into the lowest motor quotient group at older ages in a selection of FMS. FMS are a subclassification of gross motor skill which have been defined as the basic observable patterns of movement (Gallahue and Ozmun, 2006; Gallahue, Ozmun and Goodway, 2012). These are the basic patterns which underpin sport specific movements and they can be broken into object control, locomotion and balance skills (Gallahue, Ozmun and Goodway, 2012). Children with poor FMS frequently demonstrate lower levels of health related fitness and participate in less physical activity compared with children who have proficient motor skills (Okely and Booth, 2004).

Recent evidence suggest that children's FMS proficiency levels are falling below the expected levels (Okely and Booth, 2004; Hardy *et al.*, 2010, 2013; O' Brien, Belton and Issartel, 2016). Hardy, King, Farrell, Macniven and Howlett (2010) carried an investigation into the FMS proficiency in a sample of 330 Austrailian 4 year old pre school children. The results of the study showed approximately 70% of children had mastered the run however the level of mastery for the other skills ranged between 9% and 44%. Interestingly, the study also identified gender differences, with girls showing higher levels of locomotor skills while boys demonstrated higher object control skills. Another Austrailian study by Okely and Booth's (2004) of older Australian children between the ages of 6-9 years found that none of the 6 FMS assessed had more than 35% of sample meet mastery level. O'Brien, Belton and Issartel (2016) used the TGMD-2 to evaluate a sample of 12 and 13 year old Irish adolescents performance in a selection of 9 fundamental movement skills. Alarmingly, only 11% of the sample were at or near mastery level for 9 FMS, a milestone which should be reached by age 11. Importantly, motor skill proficiency has been found to be associated with higher participation in physical activity while lower levels of motor skill ability have been associated with lower levels of physical activity (Wrotniak *et al.*, 2006; Cliff *et al.*, 2009, 2011; Lopes *et al.*, 2012) A longitudinal study by Lopes et al. (2012) found that children with the greatest motor skill proficiency maintained physical activity levels over a 3 year period while children in the lower and middle tertile for motor skill proficiency showed significant decreases in physical activity (Lopes *et al.*, 2012). Williams, Pfeiffer, O'Neill, Dowda, McIver, Brown and Pate (2008) suggested that children with the highest and lowest levels of motor skill proficiency are likely to experience long-term consequences in terms of physical activity levels. As such, children with low levels of motor skill could experience lower levels of physical activity throughout childhood and into adolescence.

2.2.3 Fine Motor Skills

Fine motor skills are the use of small muscles involved in movements that require the functioning of the extremities to manipulate objects (Gallahue and Ozmun, 2006). As such, they are less influenced by mechanical constraints such as excess mass or muscle strength. Fine motor skills are a prominent feature of everyday life as they are involved in many activities of daily living such as brushing your teeth, using utensils to eat and putting on clothes (Marr *et al.*, 2003; Van der Linde *et al.*, 2013). Fine motor skill proficiency has been extensively touted as an indicator of school readiness (Grissmer *et al.*, 2010). Grissmer, Grimm, Aiyer, Murrah and Steele (2010) carried out an analysis on motor skills assessment from 3 data sets examining school readiness of kindergarten children. They found that general knowledge, attention and fine motor skill were stronger predictors of later science, reading and math ability than were early science, reading and math scores alone.

Studies from the early nineties found that primary school children spend between 30% and 60% of their school day performing fine motor tasks (McHale and Cermak, 1992). This time is spent carrying out a combination of both academic (writing) and non-academic activities (zipping up coat). A later study by Marr et al (2003) found that almost 85% of time spent engaged in fine motor tasks involved paper and pencil based activities. As such, fine motor skill proficiency has been found to be strongly linked to higher academic achievement and earlier development of reading (Luo *et al.*, 2007; Cameron *et al.*, 2012). Further to this, children with strong fine motor skills have also been found to exhibit higher mathematical achievement (Son and Meisels, 2006; Luo *et al.*, 2007). Son and Meisels (2006) carried out a longitudinal study of 12,583 kindergarten children. Results showed that children with higher level of fine motor skill proficiency demonstrated greater mathematical ability at school entry and showed greater improvements over the school year. Luo, Jose, Huntsinger and Pigott (2007) also found that fine motor skill predicted mathematical achievement over time in a sample of kindergartners. Carlson, Rowe and Curby (2013) suggested that the link between academic achievement and fine motor skill proficiency was a result of visual spatial integration component of fine motor skill. Visual spatial integration involves the processing of visual information from the environment and integrating it into fine motor movements (Sortor and Kulp, 2003). On the other hand, visual motor coordination involves the coordination of small muscle movements of the hand, may be linked to cognitive and perceptual development (Bushnell and Boudreau, 1993; Diamond, 2000; Adolph, 2005). Diamond (2000) suggested that motor and cognitive development were fundamentally interrelated, with perturbation in cognitive domain resulting in adverse motor development, as seen in neurological disorders, and vice versa. These motor difficulties can have a profound impact upon the quality of life experienced by children.

Qualitative investigations by Summers Larkin and Dewey (2008a, 2008b) examined the perception of parents of children with movement difficulties from Australia and Canada. Findings indicated that children with coordination difficulties required significantly greater structure and support from parents in order to complete daily routine. The time pressure experienced during the morning routine on school days was a common cause of concern and period where the consequence of children's motor difficulties were particularly evident. Beyond childhood, fine motor skill proficiency is also an important component of other activities in adulthood such as using a computer mouse or even surgical skill in surgeons (Rosser *et al.*, 2007; Badurdeen *et al.*, 2010; Adams, Margaron and Kaplan, 2012). Adams, Margaron and Kaplan (2012) investigated the potential benefit of playing video games as a means to improve the laparoscopic skills of surgeons. Interestingly, it was found that a 6-week training programme of video game play resulted in greater laparoscopic skill improvements than the use of laparoscopic simulators.

Overall, fine motor skill acquisition plays an important role in children's development as they enable children to interact with their environment, carry out activities of daily living and participate in valued behaviours of childhood like play, education and social interaction (Summers, Larkin and Dewey, 2008a, 2008b; Cools *et al.*, 2009). However, motor coordination difficulties are not something that children just grow out of and can have significant influences on adolescence and even adulthood (Losse *et al.*, 1991; Knight *et al.*, 1992; Geuze and Börger, 1993; Fitzpatrick and Watkinson, 2003).

2.2.4.1 Motor Skill Tests

In order to adequately evaluate motor skill proficiency a variety of motor skill assessments have been developed including the *Körperkoordinationtest für Kinder* (KTK) (Kiphard and Shilling, 1974, 2007), *Test of Gross Motor Development-2 (TGMD2)* (Ulrich, 2000)*, Movement Assessment Battery for Children 2nd Edition (MABC-2)* (Henderson and Sugden, 1992; Henderson, Sugden and Barnett, 2007) *and the Bruininks Oseretsky Test of Motor Proficicency 2nd Edition (BOT-2)*(Bruininks, 1978; Bruininks and Bruininks, 2005) to name a few. These tests assess various aspects of motor skill proficiency including gross motor skills, FMS and fine motor skills and vary in terms of age suitability, sensitivity and reliability (Cools *et al.*, 2009). They have been designed and validated for a variety of age groups. Ultimately, the test selected should be based on the hypothesis being tested.

2.2.4.2 Test of Gross Motor Development-2

The Test of Gross Motor Development, Second Edition (TGMD-2) is a qualitative assessment of gross motor skill proficiency (Ulrich, 2000). This test is divided into locomotor and object control categories and evaluates 12 FMS including run, skip, kick, throw and catch (Ulrich, 2000). The test is validated for use in children between the ages of 3-10 years, a period of dramatic changes in a child's gross movement skill development takes place (Ulrich, 2000). Hardy, King, Farrell, Macniven, and Howlett (2010) found the presence of gender differences in an assessment of FMS using the TGMD-2 in a sample of 425 children. Girls were found to demonstrate higher level of mastery for locomotor skills while boys demostrate higher mastery in object control skills. This finding outlines the presence of gender sterotype differences in the acquisition of FMS (Hardy *et al.*, 2010). These gender differences in FMS proficiency were also found by Cliff, Okely, Smith and McKeen (2009) and were seen to be related to physical activity levels in preschool children. The TGDM-2 offers a criterion approach and provides norms which makes it an excellent tool in the identification of children who are behind their peers in gross motor development (Cools *et al.*, 2009).

2.2.4.3 Körperkoordinationtest für Kinder

The Körperkoordinationtest für Kinder (KTK) is a gross body control and dynamic balance assessment (Kiphard and Shilling, 2007). The KTK is a shortened 4 item version of the original Hamm-Manburger Körperkoordination Test für Kinder developed by Kiphard and Schilling (1974). It is a relatively simple test to set up and takes approximately 20 minutes to carry out. The KTK has been described as being thoroughly standardized and considered highly reliable (Cools *et al.*, 2009). Despite these positives, the KTK is limited to one aspect of gross movement skill assessment and does not cater for locomotion functioning and object control. It also is a product oriented form of assessment which does not give the full picture of technique and motor control (Kiphard and Shilling, 2007; Cools *et al.*, 2009). Laukkanen, Pesola, Sääkslahti and Finni (2014) measured the relationship between habitual physical activity levels and gross motor skill in 5-8 year olds using the KTK. They found that gross motor skill was positively associated with physical activity and negatively associated with sedentary time (Laukkanen *et al.*, 2014). This finding was suppported by Lima and colleagues (2017) who found the positive reciprocal relationship between physical activity levels and motor competence in a longitudinal study using the KTK in a sample (N=696) of 5-7 year olds. The study also highlighted that children with higher BMI were more likely to demonstrate lower motor coordination in childhood and adolescence.

Ré and colleagues (2017) also assessed motor competence in a sample (N=424) of 5-10 year old children using both the KTK and the TGMD2. They found a low to moderate correlation (r range = 0.34-0.52) between tests. Interestingly, they found that the TGMD2 classified 39.4% of the sample as demonstrating low motor competence (<5%) compared to only 18.4% in the KTK. They concluded that the TGMD2 may be more susceptible to socio-cultural differences in addition to measuring slightly different aspects of motor competence compared to the KTK (Ré *et al.*, 2017). Rudd et al. (2016) also examined the relationship between KTK and TGMD-2 and concluded that both measures were valid measure of overall motor competence. However, they both measure discrete aspects of motor competence. Rudd et al. (2016) concluded that in order to gain a holistic measure of children's motor competence, the use of multiple test batteries or motor skill assessments would be beneficial.

2.2.4.4 The Movement Assessment Battery for Children

The initial, Movement Assessment Battery for Children test (MABC) (Henderson and Sugden, 1992) and the revised form Movement-ABC-2 (MABC-2) (Henderson, Sugden and Barnett, 2007) are commonly used motor skills assessments. This test has been used extensively to detect the presence of delays or difficulties in a child's motor development (Henderson, Sugden and Barnett, 2007; Cools *et al.*, 2009). Pitcher, Piek and Hay (2003) used the MABC to examine fine and gross motor skill in a sample of children with Attention Deficit Deficit Disorder (ADHD). There was a significant differences between motor skill ability of ADHD and control children. The MABC has also been used to investigate motor skill problems in children with Autism spectrum disorders (Green *et al.*, 2009). Green et al (2009) found 79% of children with Autism spectrum disorders had movement impairments as classified by the MABC. The test focuses on how a child manages everyday tasks encountered in school and at home (Henderson, Sugden and Barnett, 2007). The test itself takes 20-30 minutes to complete and measures movement skills in three categories: manual dexterity skills, ball skills and balance skills (Henderson, Sugden and Barnett, 2007). As such, the MABC-2 is considered suitable for assessment of motor abilities, early milestones, FMS and specialized movement skills (Burton and Miller, 1998).

In their study, Fisher and colleagues (2005) measured habitual physical activity using acceleromotery in a sample of 394 children and found weak associations with fundamental movement skill as measured by the MABC. Logan, Robinson, Rudisill, Wadsworth and Morera (2014) compared motor skill performance on TGMD-2 and MABC-2 in a sample of 64 children. Findings illustrated that both assessments demonstrated 81.8% agreement in identifying 9 out of 11 children at risk of Developmental Coordination Disorder (DCD) and 27 out of 29 (93.1% agreement) children demonstrating motor delays. However, like Rudd et al. (2016) comparison of the KTK and TGMD, Logan et al. (2014) concluded that the TGMD-2 and the MABC-2 measured different components of motor competence and can't be used interchangably. A limitation of the test is the presence of different activities for different age bands. As such, specific motor skills cannot be directly compared across age brackets (Cools *et al.*, 2009).

2.2.4.5 Bruininks-Oseretsky Test of Motor Proficiency 2nd Edition

The Bruininks-Oseretsky Test of Motor Proficiency 2nd Edition (BOT-2) is based on the original test designed by Oseretsky in Russia in 1903 which was translated into English in 1946 (Doll, 1946). Initially, the Oseretsky Test was used by researchers and was often adapted for use with mentally ill children and adults, children with neuromuscular impairments in addition to normally developing children between the ages of 6-14 (Ziviani, Poulsen and O'Brien, 1982). In 1978, Bruininks developed the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP). The Bruininks-Oseretsky Test of Motor Proficiency, Second Edition (BOT-2) is the most recent version of the BOTMP (Bruininks and Bruininks, 2005). It's design enables it to measure the important components of children's motor behaviour such as gross and fine motor skills (Lam, 2011). A study by Pitchford, Papini, Outhwaite and Guilliford (2016) investigated the relationship between fine motor skill and early development of math and reading ability in young children. To do this, they used the Fine Motor Precision and Fine Motor Integration subtests of the BOT-2. Fine motor skill competence, particularly Fine Motor Integration, was a better predictor of later math ability compared to reading ability.

The BOTMP and BOT-2 have been proven reliable and sensitive when used to assess the fine and gross motor skills of a number of different disorders and neurological impairments which have both major and minor effects on the motor control of patients such as; ADHD (Kooistra *et al.*, 2005; Cho *et al.*, 2014), Autism and Aspergers (Ghaziuddin and Butler, 1998; Sahlander, Mattsson and Bejerot, 2008), Cerebral palsy (Chen *et al.*, 2011, 2013), Dyslexia (Kooistra *et al.*, 2005) and other intellectual and physical disabilities (Van Pelt and Kalish, 1983; Aken *et al.*, 2007; Wuang and Su, 2009; Johnson *et al.*, 2010; Lucas *et al.*, 2013). The depth of detail provided in the BOT-2 and BOTMP make them useful for investigating unexplored aspects of motor development (Düger *et al.*, 1999). Cho, Ji, Chung, Kim and Joung (2014) found that children with ADHD had significantly worse performance on all subtests of BOT-2 except upperlimb coordination compared to control children. This trend was also observed in adults with Aspergers disorder by Sahlander, Mattsson and Bejerot (2008) in 6 (running speed & agility, balance, bilateral coordination, strength, dexterity) of the 8 subtests of the BOTMP. The large number of test activities in addition to the separate composites and subtests make the BOT-2 very useful in terms of the scope in which it can be used by various health care and educational professionals. A study by Ziviani, Poulsen and O'Brien (1982) examined the correlation between the BOTMP and the Southern California Sensory Integration Test (SCSIT) in 49 children between the ages of 4-12. These children had been referred to occupational therapists following identification of learning difficulties by their teachers using intelligence testing (Ziviani, Poulsen and O'Brien, 1982). The children were tested pre and post a 12 month Sensory Integration treatment with the SCSIT and BOTMP long form. Ziviani and colleagues (1982) found that both tests correlated significantly with each other. As such the authors noted how the fine motor skill composite of the BOTMP may be useful for screening children with sensory integrative difficulties in addition to being able to identify improvements in fine motor skills following the intervention (Ziviani, Poulsen and O'Brien, 1982). Given its validity, reliability and widespread use, in addition to the presence of a distinct fine motor skill composite, the BOT-2 was deemed the most suitable assessment tool to specifically examine fine motor skill proficiency of children in Study 1.

2.3 Motor Coordination

2.3.1 Manual Coordination

Motor coordination is the ability to integrate separate motor systems with varying sensory modalities into efficient patterns of movement (Gallahue & Ozmun 2006, p254). Rhythmic manual coordination has been the subject of extensive research in the field of motor control and can be understood in terms of entrainment dynamics of coupled oscillators (Kugler and Turvey, 1984; J. Kelso, 1995). This has led to the development of well-established patterns of movement. Many of these studies have implemented simple experimental paradigms such as pendulum swinging (Schmidt *et al.*, 1991, 2007; Hajnal *et al.*, 2009; Varlet, Marin, Issartel, *et al.*, 2012; Armstrong *et al.*, 2013; Armstrong and Issartel, 2014) or tapping (Repp, 2005a; Repp and Su, 2013) to answer research questions in relation to the effect of stimulus modality, frequency, or continuity on coordination ability.

Auditory stimuli have generally been found to be associated with greater synchronization in the temporal domain (Ernst and Bülthoff, 2004) while visual stimuli are more salient in the spatial domain (Alais and Burr, 2004). A study by Varlet et al. (2012) using discrete stimuli found participants demonstrated better synchronization with short beeps (auditory) compared to a short flashes (visual) during a pendulum swinging task. Conversely, when the stimulus was continuous, Armstrong et al. (2014) found that adults demonstrated higher levels of coordination for visual conditions compared to auditory conditions. Other research by Hajnal, Richardson, Harrison and Schmidt (2009) investigated the influence of position and amount of information available on stability of visuomotor coordination. Participants aimed to coordinate their movements with a oscillatory dot while the stimulus was occulated at different locations and for different amounts. Results showed participants coordination was less stable when the end points were occluded compared to other occlusion locations. This finding emphasised the importance information of end/reversal points of visual stimuli to preserve stability of coordination.

The presence of information in the environment around an individual can also result in the emergence of unintentional coordination. Therefore the strength of coordination often depends on the availability of information and how much attention is paid to the stimuli. A study by Schmidt et al. (2007) found that the magnitude of unintentional coordination and the stability of intentional coordination during a pendulum task was influenced by visual tracking of the stimulus. This finding highlights that if we are attentive to the movement of a visual stimulus it results in a tighter coupling with the sensory information available and better performance. When taken together, these results highlight the important role played by the information within a system in the establishment and preservation stability of coordination. As such, it is this information that is responsible for constraining the system and producing the observed behaviour. These studies enable researchers to gain a better understanding of how humans use various stimuli, including visual, auditory and tactile information available, to interact with the environment around them. These findings enable us to gain a better understanding of the individual characteristics of visual and auditory stimuli, and how we best utilise them. As individuals use the sensory information available to plan, initiate and control our actions, a better understanding of this process facilitates the development of more effective interventions or applications that use sensory integration process.

2.3.2 Multisensory Integration

As we live in a multisensory environment, we rarely encounter stimuli in isolation. As such, we are often required to prioritize information or pay attention to particular sources of information. For example, as a speeding car approaches and begins to brake, we gain visual information as it advances toward us in addition to the auditory information of the squealing brakes. These sources of information contribute to the course of action we decide on and the motor behaviour we adopt (e.g. which direction to jump). As such, there has been extensive research examining how we integrate a combination of stimuli (Varlet, Marin, Issartel, *et al.*, 2012; Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). Often the combination of multiple sources of information can be beneficial (Ernst and Bülthoff, 2004). Armstrong et al. (2014) found slight improvements in coordination when multisensory information was available compared to unisensory, particularly in the most difficult frequency conditions. However, there is little known about these processes in children and if the way children integrate unisensory or multisensory information varies as a result of the maturation process. The majority of information available in children is focused around the presences of sensory integration problems in children with neurological or developmental disorders.

2.3.3 Sensory Integration problems

At present, much of what we know about the sensory integration process is based around atypical sensory integration in special populations, for example in Autism spectrum disorders (Dawson and Watling, 2000; Baranek, 2002; Piek and Dyck, 2004), Cerebral Palsy (Kayihan, 2001; Bleyenheuft and Gordon, 2013), Dyslexia (Viana *et al.*, 2013) and Developmental Coordination Disorder (Piek and Dyck, 2004). Ayres (1985) used the term " developmental dyspraxia" to describe the presence of difficulties in the planning and initiation of movements. Dawson and Watling (2002) emphasised that sensory sensitivity and motor difficulties affect all aspects of cognitive, social and academic function in addition to physical function. In this review, the authors highlighted that problems with motor skill, motor planning and/or motor praxis seem to be a prominent feature of Autism spectum disorders (Dawson and Watling, 2000). Motor praxis is the neurological process by which motor commands are conceived, organized and carred out (Ayres, 1985). Viana et al. (2013) investigated the effect of altered sensory conditions on the postural control capabilities of dyslexic and non-dyslexic control children. They found that dyslexic children demonstrated poorer performance, characterized by higher body sway variability compared to controls, even when visual and somatosensory information was available. The authors concluded that dyslexic children might suffer from sensory integration difficulties, particularly when required to integrate sensory information from different sources. A review by Bleyenheuft and Gordon (2013) also found that the sensory integration difficulties associated with Cerebral Palsy has a significant influence on the ability of sufferers to control precision grip movements and as such has a marked influence on individuals ability to successfully carry out many activities of daily living. Despite the abundance of sensory integration problems in a variety of developmental and neurological disorders, there is a current lack of concensus and evidence on the effectiveness of interventions designed to address these sensory integration difficulties (Dawson and Watling, 2000; Baranek, 2002). At present, there is little known about how these processes develop in children as a consequence of the maturation process. In addition, there is less known about how these processes are impacted upon by conditions such as DCD or obesity. Therefore, there is a need for further research to gain a better understanding of the development of the sensory integration process in both healthy and unhealthy children.

2.3.4 Sensory Integration and Obesity

More recently, evidence has begun to emerge suggesting the presence of sensory integration difficulties in obese individuals. A number of studies in other fields have highlighted the influence of being overweight/obese on the sensory integration process. Wan, Spence Mu Zhou and Ho (2013) examined if overweight individuals demonstrated impaired detection and/or discrimination of auditory, vibrotactile and audio tactile stimuli and how it may influence driver safety. Their results showed overweight individuals benefited less from multisensory stimuli in the detection task. In addition, overweight participants were found to benefit from multisensory stimuli in the discrimination task when the stimulus was directed to their hands rather than to their abdomen via a seatbelt. This finding suggests that the excess adiposity in overweight and obese may reduce individuals' sensitivity to tactile information. Scarpina, Migliorati, Marzullo, Mauro, Scacchi and Costantini (2016) investigated the temporal binding window in obese adults using a simultaneity judgment task (SJ) and the temporal order judgment task (TOJ). In these tasks, participants were presented with visual and auditory stimuli at different stimulus offsets and required to determine if they appeared simultaneously or successively (SJ) or required to judge which was first and which was second (TOJ). Results found that obese individuals demonstrated a wider temporal binding window compared to normal weight controls. As the temporal binding window can be considered a measure of the effectiveness of multisensory integration process, obese individuals demonstrated less efficient ability to successfully integrate the sensory information available.

This sensory integration process has a vital role in the effective coordination of motor behaviour. Goulding Jones, Taylor, Piggot and Taylor (2003) found that overweight and obese children demonstrated significantly impaired balance as measured by the balance subtest of the BOTMP compared to their normal weighted peers. Frequently, these balance differences are attributed to the effect of excess mass on centre of gravity. However, D'Hondt, Deforche, De Bourdeaudhuij and Lenoir (2008) investigated balance and postural sway between obese and normal weight children in a number of postural conditions. The task required children to complete a traditional 9-hole peg task activity while standing on a balance beam or while being seated. Not surprisingly, obese children performed worse for the balance beam activity due to the increased postural demands as a result of their excess mass. Interestingly, obese children were also found to score significantly worse while in the seated position. This led to the suggestion of obese children experiencing '*perceptual motor coordination difficulties'* which interfere with their ability to plan and control their movements. Gentier, D'Hondt, Shultz, Deforche, Augustijn, Hoorne, Verlaecke, De Bourdeaudhuij, Lenoir (2013) also alluded to the presence of sensory integration difficulties as a result of obesity. Gentier and colleagues (2013) found that obese children demonstrated poorer fine motor skills in addition to gross motor skills compared to their normal weight peers. As fine motor skills are not directly affected by excess mass, this highlights the potential influence of a neuromuscular factor that impedes obese individual's motor control.

Hue, Simoneau, Marcotte, Berrigan, Doré, Marceau, Marceau, Tremblay and Teasdale (2007) suggested that the structural and mechanical changes to the feet as a result of obesity are likely to reduce the quality and/or quality of the sensory information which individuals experience. As such, this could be seen as a source of integration difficulties and result in impaired motor behaviour. D'Hondt, Segers, Deforche, Shultz, Tanghe, Gentier, De Bourdeaudhuij, De Clercq and Lenoir (2011) examined normal weight and obese childrens gait kinematics as they walked barefoot in normal light and reduced light conditions. They found that obese children demonstrated greater dependence on visual information compared to their normal weight counterparts during a walking task under different sensory conditions (D'Hondt, Segers, *et al.*, 2011). This resulted in longer periods spent in stance and double support phases in addition to different temporal phasing of gait (D'Hondt, Segers, *et al.*, 2011). These patterns have been previously found in children with Developmental Coordination Disorder, with results suggesting that children with movement difficutlies are more relient on visual information than typically developing children in order to maintain balance during walking (Deconinck *et al.*, 2006).

Despite the evidence to support the presence of these difficulties, we are still unclear whether these problems exist before becoming obese or are a consequence of obesity – the classic chicken or egg problem. Early research by Petrolini, Iughetti and Bernasconi (1995) suggested that visual motor coordination difficulties could be a potential cause of sedentary behaviours in obese children. A birth cohort study of 11042 children by Osika and Montgomery (2008) also provided evidence for the prior. They found that poorer physical control and motor coordination in childhood at ages 7 and 11 was associated with obesity in adulthood. Alternatively, these difficulties could be a consequence of the various physiological changes that occur as a result of obesity. Cairney, Hay, Faught and Hawes (2005) suggested that children with DCD were at greater risk of being overweight or obese as a result of reduced participation in physical activities due to their motor coordination difficulties. The etiology of these difficulties remains to be determined although a number of potential causes have been suggested in literature such as brain inflammation, neurotransmitter function and hormonal imbalances (Liang *et al.*, 2014b; Scarpina *et al.*, 2016). Therefore, we are still not in a position to determine whether sensory integration difficulties are a cause or an effect of obesity. However, it is likely that this relationship is influenced by the complex interaction between all the components of the system thus having both a nature and nurture element.

2.4 Dynamic Systems Theory

2.4.1 Newell's Model

The dynamical systems theory provides us with a framework to explain how all behaviours emerge based on the ever-changing relationship between all components of a system (e.g. the individual, the task and the environment - Newell, 1986). We can thus see motor development as the "continuous change in motor behavior throughout the life cycle, brought about by the interaction between the requirements of the movement task, the biology of the individual and the conditions of the environment" (Gallahue and Ozmun 2006, p.25).

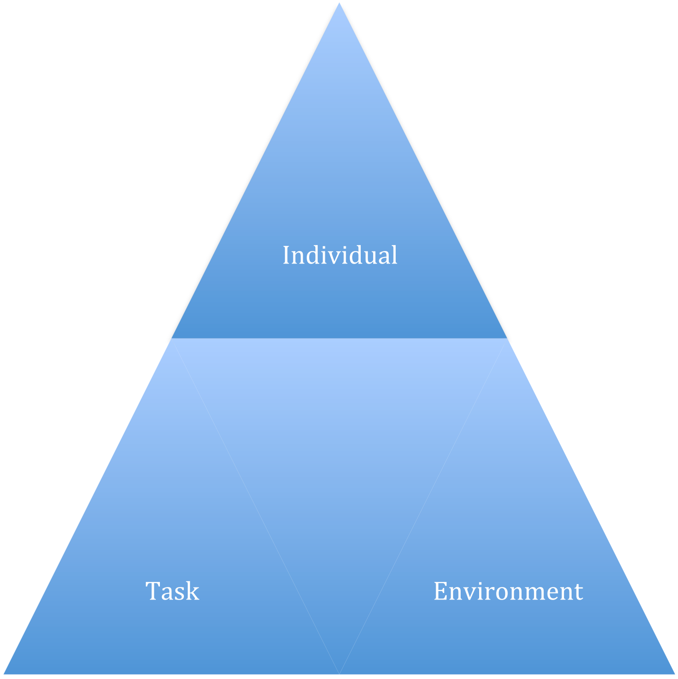

FIGURE 2.2: NEWELL'S MODEL OF CONSTRAINTS (ADAPTED FROM HAYWOOD AND GETCHELL (2009) P6.)

Thelen and Smith (1994) suggested that motor development is a function of the interaction between genetically determined processes and input from the environment. Due to modern technological and economical advances, children are now presented with increased opportunities to engage in technology-based leisure time activities (Vandewater *et al.*, 2007; Biddle *et al.*, 2010; Lauricella, Wartella and Rideout, 2015). Vandewater, Rideout, Wartella, Huang, Lee and Shim (2007) found parents of 0-6 year olds reported that 75% of children watched television on a typical day. This replaces time that was traditionally spent being physically active and so children are exposed less to the varied movement experiences that are needed for normal motor development (Maitland *et al.*, 2013). It is unlikely that any single factor is responsible for atypical motor development in children, but rather that motor development differences are a consequence of the accumulation of a number of different factors over a period of years. As such, dynamic systems theory offers us a holistic framework with which to view the consequence of the effects of decreased physical activity levels, increased sedentary behaviours and increased prevalance of obesity influence motor skill development and motor behaviour. It is likely that all these factors, in addition to others such as lack of practice, nutrition, fitness, age, gender and socioeconomic status, play a role in the organisation of motor behaviour.

2.4.2 The Haken-Kelso-Bunz (HKB) Model

A key feature of the dynamic systems perspective is that a system is self organising, being capable of spontaneously organising itself without implicit instruction from a specific agent – the brain in humans (Kelso, 1995). Therefore, this theory is not concerned with explaining the cause or source of all the components involved in the coordination of movement but rather sees coordination as a temporary formation of muscles and joints to achieve a speific task according to the various contraints within the system (Kelso, 1995). Work by Haken, Kelso and Bunz (1985) on the application of dynamic systems theory to human movement, which led to the HKB model, paved the way for experimentation examining how movement was organized and controlled (Haken, Kelso and Bunz, 1985). This model resulted in a variety of simple experimental paradigms such as tapping, wrist oscillations and swinging of pendulums to investigate how manipulation of frequency, type or amount of stimulus effected the coordination of movement (Schmidt, Carello and Turvey, 1990; Peper and Beek, 1998; Repp, 2005b; Richardson *et al.*, 2007). These simple experiments showed how human movement is drawn to organise itself in the most stable state (Haken, Kelso and Bunz, 1985). Dynamical systems perspectives have been extensively used to explain coordination dynamics during rhythmic coordination in pendulum based tasks (Schmidt *et al.*, 1991, 1998; Lopresti-Goodman *et al.*, 2008; Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). Lopresti-Goodman, Richardson, Silva and Schmidt (2008) expanded on earlier work on unintentional coordination and investigated the effect frequency on unintentional entrainment. Results showed that when the frequency of an environmental stimulus is changed to above ±10% or ±15% of an individuals preferred tempo, the emergence of unintentional entrainment is reduced and thus indiivudals must intentionally coordinate their movements in order to synchronise with the stimulus.

Other work based on dynamical systems theory has examined how coordination emerges unintentionally from exposure to environmental stimuli (Schmidt *et al.*, 2007), when swinging your legs together (Schmidt, Carello and Turvey, 1990) or through verbal or visual interaction (Richardson, Marsh and Schmidt, 2005). The consistancy with which rhythmic manual coordination tasks have been modelled make them an ideal methodology to investigate the consequence of external factors, such as obesity or age, on the motor coordination process. The work of Jirsa and Kelso (2004) and Schoner (1990) has suggested that discrete and rhythmic actions adhere to the same non linear oscilliator dynamics. As such, motor control during the classically used Fitts' task (Fitts, 1954; Fitts and Peterson, 1964) experimental paradigm can be seen through the lense of the dynamical interaction between task, environment and the organism .

2.4.3 Fitts' Task

Fitt's Law, which describes the linear relationship between speed and accuracy, has been extensively studied in the research (Fitts, 1954; Meyer *et al.*, 1988; Plamondon and Alimi, 1997; Elliott, Helsen and Chua, 2001). A study by Elliot, Carson, Goodman and Chua (1991) examined the influence of visual information availability and instructional provision on the movement kinematics and end point variability during an aiming task. The authors found that instructing participants to move as fast as possible or as accurately as possible had distinct influences on the movement kinematics and endpoint variability of participant's performance. Not surprisingly, instructing participants to move as fast as possible lead to increased endpoint error whilst instructing participants to move as accurately as possible lead to increased movement times. Further to this, the availability and quality of visual information (full vision, partial occlusion or full occlusion) also altered aiming performance. It was found that the reduction of visual information led to increased likelihood of undershooting the target.

Fitts' Law has been shown to be robust and hold true for investigations of motor control in special populations such as those with congenital spastic hemiplegia (CSH) and Parkinson's disease. Smits-Engelsman, Rameckers and Duysens (2007) examined motor control in individuals with CSH using a Fitts' tapping task. They found, despite the obvious limitations in fine motor control, participants with CSH performance obeyed Fitts' Law with results showing movement time increased as task difficulty increased. Bienkiewicz and Craig (2015) demonstrated altered temporal accuracy using a Fitts' tapping task in a sample of patients with Parkinson's disease. Results showed Parkinson's patients made greater errors than healthy controls, with those with the most severe forms of Parkinson's demonstrating the most errors. The success of many reaching or aiming tasks requires individuals to control the speed and accuracy of their movements (Zoia *et al.*, 2005). As such, difficulties in the integration and performance of goal directed reaching tasks could impair the effective performance of many activities of daily living such as brushing ones hair, feeding oneself or picking up items

(Kirby, Edwards and Sugden, 2011). For example Parkinson's sufferers frequently experience difficulties in the performance of everyday actions such as walking, dressing oneself, handwriting or using a computer mouse as a result of their motor control problems (Stoffers *et al.*, 2002). Berrigan, Simoneau, Tremblay, Hue and Teasdale (2005) investigated the influence of obesity, particularly the increased balance demands, on the control of speed and accuracy of a goal directed aiming task. In this study, 9 obese and 8 healthy controls were asked to move as fast and as accurately as possible to a target of varying widths. Results showed that obese participants moved slower, particularly for the smallest targets, and demonstrated greater centre of pressure displacement than normal weight controls. These results suggest that the increased balance demands of obesity act as a constraint to the speed and accuracy of upperlimb movements while in a standing position. It is without doubt that the dynamic interplay between the various components of a system can impair the quality of sensory integration and thus result in coordination difficulties.

2.4.4 Coordination Difficulties

As mentioned earlier, coordination difficulties are frequently found in neurological or developmental disorders such as cerebral palsy (Bleyenheuft and Gordon, 2013), ADHD (Piek and Dyck, 2004), PD (Bienkiewicz and Craig, 2015) or Autism spectrum disorders (Baranek, 2002). However, coordination difficulties have also been found in otherwise typically developing children free from intellectual or neurological impairments (Losse *et al.*, 1991; Knight *et al.*, 1992; Smyth, 1992; Sigmundsson, 2003, 2005). Henderson (1987) emphasized that clumsy children are a heterogeneous group and that the range of difficulties experienced varies between children. Geuze and Börger (1993) carried out a follow up study of 12 clumsy children and 14 controls. Results showed 50% of clumsy children still demonstrated significantly impaired motor competence 5 years after initial assessment. Sigmundsson (2005) suggested that the source of these difficulties could be attributed to visual motor, perceptual motor and proprioceptive deficits. Children who experience these coordination difficulties have been traditionally referred to as 'clumsy' children. However, more recently, there has been a move toward the establishment of a standardized diagnosis of children who experience these coordination difficulties, frequently identified by falling into the lowest 10th percentile of motor skill assessments. These children are often classified as having developmental coordination disorder.

2.4.5 Developmental co-ordination disorder DCD

Developmental co-ordination disorder (DCD) is a developmental disorder that affects an individuals ability to effectively co-ordinate their movements (Dewey and Wilson, 2001). It is estimated that between 5-9% of children experience DCD (Maeland, 1992; Missiuna and Polatajko, 1994; Kadesjo and Gillberg, 1999; Gillberg and Kadesjö, 2003; American Psychiatric Association, 2013). Historically, DCD has been known by other terms such as developmental dyspraxia or more commonly clumsy child syndrome (Gubbay, 1978; Missiuna and Polatajko, 1994; Sigmundsson and Hopkins, 2005). More recently, a move has been made toward a more standardized description of DCD according to the Diagnostic and Statistical Manual of Mental Disorders: DSM-5. (American Psychiatric Association, 2013).

A. Performance in daily activities that require motor coordination is substantially below that expected given the person's chronological age and measured intelligence. This may be manifested by marked delays in achieving motor milestones (e.g., walking, crawling, and sitting), dropping things, clumsiness", poor performance in sports, or poor handwriting"
B. The disturbance in Criterion A significantly interferes with academic achievement or activities of daily living
C. The disturbance is not due to a general medical condition (e.g., cerebral palsy, hemiplegia, or muscular dystrophy) and does not meet criteria for a Pervasive Developmental Disorder
D. If Mental Retardation is present, the motor difficulties are in excess of those usually associated with it

FIGURE 2.3: DIAGNOSTIC CRITERIA FOR DCD (ADAPTED FROM DSM-5, AMERICAN PSYCHIATRIC ASSOCIATION 2013).

Children with DCD commonly experience delays in reaching developmental milestones, experience physical awkwardness, poor balance and handwriting and have difficulty engaging in physical activities (Dewey and Wilson, 2001; Cermak and Larkin, 2002; Kaplan, Sadock and Sadock, 2007; Cairney *et al.*, 2016). This leads to difficulties in children's academic achievement, social interaction and physical activity participation in addition to problems in the completion of many activities of daily living (Piek, Baynam and Barrett, 2006; Faught *et al.*, 2008; Magalhães, Cardoso and Missiuna, 2011; Zwicker *et al.*, 2012). Summers and colleagues (2008b) found that parents of children with motor problems frequently reported that their children were unable to cut certain foods, took longer to eat and were often messy eaters regularly spilling food on the table or themselves. These difficulties are also regularly found in self care activities such as brushing their teeth, brushing their hair and flossing their teeth (Missiuna, 1999; Missiuna *et al.*, 2007). Missiuna, Moll, King, King and Law (2007) found that parents of children with DCD concerns varied according to childrens' age. Results showed parents of younger children were primarily worried about implications of their child's coordination difficulties on their motor development and ability to engage in play. Parents of slightly older children tended to be more concerned with difficulties in self care activites, academic achievement and interaction with peers while the parents of the oldest children tended to be most worried about their child's self-esteem and emotional wellbeing later in childhood. The effects of motor coordination difficulties can have consequences on childrens' social and emotional wellbeing in addition to the physical difficulties. A study by Fitzpatrick and Watkinson (2002) interviewed 16 adults who had previously experienced physical awkwardness as children. The participants all recalled withdrawing from activities which highlighted their coordination difficulties or intentionally failed or "clowned" as a coping mechanism to avoid embarrassment and ridicule in physical education class or sporting activities (Fitzpatrick and Watkinson, 2003).

Children with DCD also experience difficulties engaging in physical activitiy. Kwan and colleagues (2013) found children with DCD demonstrated significant lower levels of Moderate to Vigorous Physical Activity (MVPA) compared to typically developing children. This study also highlighted the influence of psychosocial factors such as perceived competence, poorer physical activity motivation and lower enjoyment of physical activity on the physical activity levels of children with motor difficulties. As such, these factors are likely to mediate children with motor problems engagement in physical activity. This avoidance in particpation in physical activity can lead to a negative cycle physical activity engagement and increased sedentary behaviour. As a consequence, children with DCD are at a higher risk of obesity (Cairney, Hay, Faught and Hawes, 2005; Cairney *et al.*, 2010; Hay, Faught and Cairney, 2010; Wagner *et al.*, 2011; Hendrix, Prins and Dekkers, 2014; Lifshitz *et al.*, 2014; Zhu *et al.*, 2014), coronary vascular disease (Faught *et al.*, 2005) and reduced fitness levels such as strength, flexibility, cardiovascular fitness and body composition (Hands and Larkin, 2002; Schott *et al.*, 2007; Rivilis *et al.*, 2011; Cairney *et al.*, 2016). Schott Alof, Hultsch and Meermann (2007) found that children with DCD performance significantly worse on a 20m sprint, jump and reach test and medicine ball throw compared to typically developing peers. It was also found that these differences in fitness widened with age between DCD and typically developing children. Cairney, Hay, Faught and Hawes (2005) found a higher prevalence of overweight and obesity in children with DCD compared to those with DCD in a sample of 578 children between 9 and 13 years. The authors suggested that this was as a result of reduced participation in physical activities due to their motor coordination difficulties. The findings of Cairney, Hay, Veldhuizen, Missiuna and Faught (2010a) supported this hypothesis by identifying an activity deficit between in children with possible DCD (referred to as "pDCD") (identified by low motor competence but without diagnonsis). Interestingly, physical activity levels were found to be significantly lower in girls with pDCD than in boys and seemed not to increase with time while boys levels did increase. As such, DCD may be a previously discounted risk factor for being overweight or obese in adolescence. Cairney, Hay, Veldhuizen, Missiuna, Mahlberg and Faught (2010b) also found that children with pDCD had higher BMI values at baseline than their typically developing peers. Further to this, Cairney et al. (2010) found that children with pDCD were at significantly greater risk of becoming overweight and obese over time compared to control children.

In a review of the relationship between obesity and DCD, Hendrix et al. (2014) emphasised the lack of clear evidence to provide an answer to the question of casuality. A number of longitudinal studies all found body composition to increase over time in children with pDCD while control childrens scores remained relatively constant (Cairney *et al.*, 2010; Li *et al.*, 2011; Chirico *et al.*, 2012). Chirico and colleagues (2012) found pDCD BMI and FM increased at a greater rate than their typically developing counterparts over a 3 year period in a sample of 12 to 15 year olds. Li, Wu, Cairney and Hsieh (2011) also found increased BMI in the pDCD over a 3-year period. In addition, results demonstrated pDCD children to have significantly lower physical fitness than typically developing counterparts with motor coordination ability being found to be a significant correlate of physical fitness (Li *et al.*, 2011). As such, it is generally considered that coordination problems exist prior to any physical signs of being overweight or obese (Zhu *et al.*, 2014). However, Wagner et al. (2011) suggested that obesity may play a role in the etiopathology motor coordination difficulties. Results found that obese adolescents showed a higher risk of having severe DCD (MABC2 score <5th Percentile) in comparison to normal weight adolecents (Wagner *et al.*, 2011).

As such, obesity may cause an activity deficit which led to reduced motor competence and in turn contribute to DCD. At present, there is a lack of definitive evidence to determine causality between this complex relationship between obesity and coordination difficulties leads us to the classic chicken or egg paradox.

2.5 Neurocognitive Function

2.5.1 Motor skill and cognition

There is an array of literature showing the link between various aspects of motor skill and cognition. Piaget's (1966) theories of cognitive development maintain a close relationship between cognitive and motor development. These two processes can be seen to be intertwined (Boudreau and Bushnell, 2000). A study by Soska, Adolph and Johnson (2010) found that infants who mastered sitting early in life exhibited better object manipulation skills and three dimensional shape recognition. This relationship was also examined by Diamond (2000) in his examination of brain structure and function. Results found that the same cortical areas of the brain were activated during both motor coordination and executive function tasks (Diamond, 2000). Executive function is generally defined as the "higher level or "meta-cognitive" function that manages other more basic cognitive functions in relation to goal directed behaviour (Etnier and Chang, 2009). As such, executive function is frequently considered as consisting of activities such as the planning, coordination, initiation and stopping of behaviours and the processing of information related to them (Kramer *et al.*, 1994; Alvarez and Emory, 2006), problems with executive function are likely to have knock on effects on the motor control processes (Corti *et al.*, 2017). Oberer et al. (201) suggested that this relationship may be a consequence of executive function, motor skill and fitness all sharing proportions of the same higher order cognitive processes – such as orientation, planning abilities and strategy use. The relationship between gross motor skills, fine motor skills and executive function may been explained by the maturation of brain structures such as the cerebellum, prefrontal cortex and basal ganglia among others (Oberer, Gashaj and Roebers, 2017). As mentioned earlier, motor skill proficiency has been strongly linked to academic achievement (Grissmer *et al.*, 2010). This relationship has been found to persist through the school years with children who had good motor skills in preschool demonstrating higher reading levels in third grade (McPhillips and Jordan-Black, 2007). A potential explanation for the motor cognition link is the fact that the majority of activities related to displaying cognitive skill require fine motor skill to complete (Grissmer *et al.*, 2010). Grissmer et al. (2010) outlined how writing requires fine motor skills of hand and fingers; reading requires fine motor control of eye movement and tracking, while speaking requires fine motor skills involved in the production of sound. However, at present, there is little research examining fine motor skill ability in typically developing school age children despite its importance in many school activities (McHale and Cermak, 1992; Marr *et al.*, 2003).

2.5.2 Obesity and Cognition

Recent research has begun to find association between cognitive performance and obesity (Huizinga *et al.*, 2008; Fedor and Gunstad, 2013). A number of studies have found links between neurodegenerative diseases such as Alzheimer's Disease (AD) and Dementia and obesity (Kivipelto *et al.*, 2005; Whitmer *et al.*, 2005; Beydoun, Beydoun and Wang, 2008; Crichton *et al.*, 2012). Beydoun, Beydoun and Wang (2008) and Crichton, Elias, Buckley, Murphy and Bryan (2012) both conducted reviews and found that being overweight and obese led to an increased risk of developing AD and Dementia. A longitudinal study by Whitmer et al. (2005) indicated that the risk of dementia was increased by 35% for overweight participants and 74% among obese participants. A review investigating the relationship between obesity and cognitive function have found negative relationships between elevated BMI and almost all cognitive domains including attention, memory, numeracy, executive function and motor control (Prickett, Brennan and Stolwyk, 2014). A study by Huizinga, Beech, Cavanaugh, Elasy and Rothman (2008) found a significant association between low numeracy skill and higher BMI in adults. Fedor and Gunstad (2013) examined the cognitive function in high level collegiate athletes with high BMI. Results found that higher BMI was associated with reduced cognitive function, in particular verbal memory, visual memory and visual motor speed, in the sample expected to have good cardiovascular fitness levels. Another study found adverse effects on cognitive function in obese participants and suggested that earlier onset and long term obesity could adversely effect later cognitive performance (Elias *et al.*, 2003).

A number of studies have employed neuroimaging techniques to assess the relationship between obesity and cognitive function. Volkow, Wang, Telang, Fowler, Rita, Alia-klein, Logan, Wong and Thanos (2009) also found an association between higher BMI and lower prefrontal metabolism of the brain. A second neuroimaging study by Taki, Kinomura, Sato, Inoue, Goto, Okada, Uchida, Kawashima and Fukuda (2008) also found a negative association between BMI and brain activity and structure suggesting decline in cognitive performance. As the prefrontal regions of the brain are involved with executive function, this relationship could explain the reduced cognitive function in obese adults reported in the literature. The influence of obesity on cognitive function is perhaps more important in childhood as it can influence children's academic achievement and thus later life prospects (Taki *et al.*, 2008). A longitudinal study by Chandola, Deary, Blane and Batty (2006) found that lower IQ scores in childhood were associated with obesity and weight gain in adulthood. A review by Liang Matheson, Kaye, Boutelle (2014) examined the neurocognitive correlates of obesity and obesity related behaviours in children and adolescents. As with the review by Prickett et al. (2014) investigating this relationship in adults, Liang and colleagues (2014) found a negative relationship between obesity and aspects of cognitive function such as executive function, attention, visuospatial performance and motor skill. Lokken, Boeka, Austin, Gunstad, Harmon (2009) found exteremly obese adolescents demonstrated significant deficts in attention and executive function when compared to normative data for a computerized cognitive test battery. Smith, Campbell, Hay and Troller (2011) proposed that an increase in weight can be seen in some part to be a consequence of neurological predisposition characterized by reduced executive function. Further to this, the authors suggested obesity also has a compounding negative impact on the brain.

The mechanisms behind this relationship are yet to be fully understood but potential causes include brain inflammation, hormone deregulation, structural changes of the brain or oxidative stress (Smith *et al.*, 2011). However, the mechanisms responsible are beyond the scope of this series of studies. Instead, greater research is required to ascertain what influence does obesity have on the motor coordination process. The link between cognitive performance and obesity in the literature strengthens further the rationale of the presence of sensory integration difficulties in obesity (Gunstad *et al.*, 2010; Miller and Spencer, 2014; Martin *et al.*, 2016; Wang *et al.*, 2016). This thesis seeks to further investigate this relationship using an extensively used methodology that limits the mechanical constraints of excess mass and facilitates the greater examination of the effect of obesity on the motor control process. The consequences of which could have significant consequences upon quality of life and overall health across the lifespan (Wang *et al.*, 2016).

2.6 Conclusion

It is without doubt that the ability to effectively coordinate movement is a vital component of human life and is essential in order to complete many activities of daily living or participate in physical activity. Evidence seems to demonstrate reduced physical activity levels and reduced motor skill proficiency in addition to increased sedentary behaviours in children. The increased prevalence of obesity is also likely to impact on typical motor development and motor skill proficiency (Robinson *et al.*, 2015). In addition, obesity also seems to interfere with cognitive function in children and adults. However, it remains to be seen whether these cognitive difficulties exist prior to or are a consequence of the various physiological consequences of becoming obese. In general, the studies discussed above indicate the complex interaction between the task, organism and the environment, and how this can influence motor behaviour. As such, environmental and organism constraints such as reduced motor skill proficiency, increased sedentary behaviour and/or prevalence of obesity among others, are likely to have significant effects on how individuals coordinate and control their movements. In addition, these changes are likely to impact on the development of motor skill proficiency in childhood and adolescence and perhaps into adulthood. The initial purpose of this thesis will be to examine the current level of fine motor skill proficiency and manual coordination in children.

Chapter 3: Fine motor skill proficiency in typically developing children: On or off the maturation track?

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Abstract

Fine motor skill proficiency is an essential component of numerous daily living activities such as dressing, feeding or playing. Poor fine motor skills can lead to difficulties in academic achievement, increased anxiety and poor self-esteem. Recent findings have shown that children's gross motor skill proficiency tends to fall below established developmental norms. A question remains: do fine motor skill proficiency levels also fall below developmental norms? The aim of this study was to examine the current level of fine motor skill in Irish children. Children (N=253) from 2nd, 4th and 6th grades (Mean Age = 7.12, 9.11 and 11.02 respectively) completed the Fine Motor Composite of the Bruininks Oseretsky Test of Motor Proficiency 2nd Edition (BOT-2). Analysis revealed that only 2nd grade children met the expected level of fine motor skill proficiency. It was also found that despite children's raw scores improving with age, children's fine motor skill proficiency was not progressing at the expected rate given by normative data. This leads us to question the role and impact of modern society on fine motor skills development over the past number of decades.

Keywords: Fine Motor Skill; Developmental Trajectory; Children; Motor Learning

3.1 Introduction

Fine motor skills are the use of small muscles involved in movements that require the functioning of the extremities to manipulate objects (Gallahue and Ozmun, 2006)**.** Fine motor skills play a key role in many activities of daily living such as self-care, feeding and dressing (Marr *et al.*, 2003; Van der Linde *et al.*, 2013). A study by McHale and Cermak (1992) found that children spend between 30-60% of their school day performing fine motor tasks. Those activities involving manipulation of writing implements, such as pencils, are perhaps the most important skill regarding academic achievement, with paper and pencil based activities making up as much as 85% of the time spent engaged in fine motor tasks (Marr *et al.*, 2003). Children with strong fine motor skills have been found to demonstrate higher academic achievement, mathematical achievement and earlier development of reading (Luo *et al.*, 2007; Cameron *et al.*, 2012). Overall, fine motor skill acquisition plays an important role in children's development as they enable participation in valued occupations of daily living, play, education and social interaction (Summers, Larkin and Dewey, 2008a; Cools *et al.*, 2009). However at present, little is known about the impact of changes occurring in the modern environment (i.e., technological and technical innovations) influence the development of fine motor skill in children.

The dynamical systems theory offers a framework to help explain the interaction between all factors involved in these changes by postulating that the development of fine motor skill relies on the ever-changing relationship between all components of a system (e.g. the individual, the task and the environment - Newell, 1986). According to this model, motor development can be seen as the "continuous change in motor behavior throughout the life cycle, brought about by the interaction between the requirements of the movement task, the biology of the individual and the conditions of the environment" (Gallahue and Ozmun 2006, p.25). According to Thelen (1994), development is contingent and constantly evolving based on the environment in which it takes place. Children now grow up in an environment where they are exposed to more time engaging with digital devices such as television, tablets and video game consoles (Biddle *et al.*, 2010; Lauricella, Wartella and Rideout, 2015). These changes seem to be progressing at an alarming rate with young people consuming an average of seven hours and thirty-eight minutes of media daily, an increase of one hour and seventeen minutes since the previous measure five years previously (Roberts and Foehr, 2005; Rideout, Foehr and Roberts, 2010). As such, the environment in which children now grow up in can be quite passive with increased opportunity for engagement in sedentary behaviors that limit the varied movement experiences required for typical motor development (Maitland et al. 2013).

Thelen and Smith (1994) argue that development is a function of the interaction between genetically determined processes and input from the environment. As motor development is a result of the interaction between the task, the individual and the environment, changes in any of these constraints have consequences on the acquisition of motor skills (Newell, 1986). There is evidence that demonstrates how these environmental changes have negatively influenced the levels of gross motor skill development and, in particular, FMS proficiency (Hardy *et al.*, 2013). A study by O Brien et al. (2015) found that only 11% of Irish 11-14 year-olds reached mastery level of 9 FMS tested. This is particularly alarming considering all skills should be mastered by ten years of age (Gallahue and Ozmun, 2006). As gross motor skill proficiency has decreased in recent times as a result of environmental factors, it is, therefore, plausible to assume that fine motor skills have also been affected. A question remains, do these environmental changes positively or negatively affect the fine motor skill development of children? As many screen-based activities such as playing video games or using tablets require fine motor skills, one could expect that these changes could potentially increase children fine motor skill proficiency levels. This has been suggested in the laparoscopic training of surgeons (Rosser *et al.*, 2007; Badurdeen *et al.*, 2010; Adams, Margaron and Kaplan, 2012). On the other hand, certain fine motor skills could be at risk of being 'lost in the sea of instant messaging and other technologies' causing children's fine motor skill acquisition to pursue a different trajectory and fall below the expected levels for children's age and gender in the past (Coll, 2015).

When considering the motor skill level of children, it is crucial to take into account the full range of motor skill proficiency. On the lower end of the spectrum, children with motor skill impairments such as those with Developmental Coordination Disorder (DCD) are frequently reported as having difficulty when tying shoelaces, buttoning shirts, doing up zippers, brushing their teeth and using cutlery (Missiuna, 1994; Cairney, Hay and Flouris, 2005; Summers, Larkin and Dewey, 2008b; Wang *et al.*, 2009; Magalhães, Cardoso and Missiuna, 2011). These children frequently suffer from a range of physical, social and emotional consequences (Fitzpatrick and Watkinson, 2003; Henderson and Henderson, 2003). In general, children with motor skill impairments are often subject to ridicule and embarrassment, reduced self-efficacy and lower self-esteem as a result of their motor coordination problems (Fitzpatrick and Watkinson, 2003; Mandich, Polatajko and Rodger, 2003; Cairney, Hay, Faught, Wade, *et al.*, 2005). Some studies have shown that this leads to avoidance of participation in activities that highlight their impairments such as play and social interaction (Fitzpatrick and Watkinson, 2003; Bart *et al.*, 2011; Fong *et al.*, 2011). Unfortunately, these motor coordination problems frequently persist into adolescence and adulthood (Losse *et al.*, 1991; Geuze and Börger, 1993; Cousins and Smyth, 2003). This is contrary to the belief that fine motor skill difficulties are just a stage that children "grow out of" (Losse *et al.*, 1991). However, not all children with fine motor skill difficulties have DCD. This raises the following question: what happens to children who experience mild fine motor skill problems that cause them to fall behind the expected rate of development? With time, do these children manage to catch up and reach a mature level of fine motor skill proficiency? On the contrary, these difficulties may persist throughout life and ultimately affect their quality of life. In both cases, it is important to find out if and how the current generation of children's fine motor skill proficiency has been affected and whether the fine motor skills necessary to succeed in modern society have been influenced by environmental factors.

In the present study, we aimed to examine the current level of fine motor skill proficiency in typically developing (TD) children and assess whether children are developing their fine motor skills at the expected rate, or whether their development has been affected by recent changes in the environment. Due to the complex level of interaction between environmental factors, it was anticipated that these changes have led to some components of fine motor skill to improve and other components to deteriorate.

3.2 Methods

3.2.1 Participants

A total of 253 children (139 males and 114 females aged 6-12 years) took part in this study. The children (71% Irish Caucasian) were randomly selected from 5 different primary schools in the Dublin area (Ireland) between January 2013 and May 2014. Children's socioeconomic status (SES) was determined by using postcode as a proxy measure accordingly to census data. The children who participated were predominantly of lower to middle social class. The children were divided into 3 age groups, 2^{nd} grade (51M 39F, M_{age} =7.12), 4^{th} grade (47M 33F, M_{age} =9.11) and 6^{th} grade (41M 42F, M_{age} =11.02) based on their year of study in primary education. Ethical approval was received from the University Research Ethics Committee. Prior to the study, the parents/guardians of each child provided informed consent for their child to participate. Three children with intellectual (Autistic spectrum disorder) or physical disabilities (Wheelchair user with Muscular Dystrophy) were excluded from the analysis, as they could not complete the testing protocol.

3.2.2 Procedures

Children's fine motor skill proficiency was assessed using the Fine Motor Composite of the BOT-2 (Bruininks and Bruininks, 2005). The fine motor composite is made up of two composite areas: fine manual control and manual coordination. Fine manual control composite is divided into two subtests, fine motor precision (FMP) (7 items, score range = 0–41) and fine motor integration (FMI) (8 items, score range = 0–40) including activities such as writing, cutting and folding which require precise control of finger and hand movements. The manual coordination composite, which measures children's throwing, catching, and object manipulation, with an emphasis on speed and dexterity, is split into manual dexterity (MD) (5 items, score range = 0–45 points) and upper-limb coordination (ULC) (7 items, score range = 0–39 points). The point scores are summed to give total point scores, which in turn are converted to scale scores (M=15; SD=5) for each subtest. The scores for the total fine motor composite are reported as total scale scores; standard scores (M=50; SD=10); or percentile ranks that are age and gender adjusted. In addition, findings can be reported as Descriptive Categories ranging from "Well-Below-Average" to "Well-Above-Average."

3.2.3 Statistical Analysis

Data was analysed using IBM SPSS 21for Mac OS. Descriptive statistics were calculated for anthropometric and motor skill variables. One sample t-tests were carried out on the Total Fine Motor Composite score for each grade to compare against the expected norms. Point Scores for each subtest were used to analyse the effect of grade and gender using two-way between groups ANOVA's. A repeated measure's ANOVA was carried out on the standard scores for FMC and MC composites to investigate the effect of age and gender when necessary. Post-Hoc tests using the Bonferroni correction were carried out on significant effects.

3.3 Results

According to the descriptive scoring categories for standard scores provided by the BOT-2, 36% of the 6th grade cohort fell into the below average category compared to 13% and 12.5% for the 2nd and 4th grade respectively. A series of one sample t-test's were carried out on Total Fine Motor Composite scores to compare each grade to the normative score of 50. There was a significant difference in scores for 6th Grade (M=44.55, SD=7.90; t(82)=6.28, p<.01 and 4th Grade (M=47.50, SD=7.02; t(79)=3.187, p<.01) compared to the population norm.

TABLE 3.1: PERCENTAGE OF EACH AGE GROUP THAT FELL INTO BOT-2 DESCRIPTIVE CATEGORIES

Grade	Well above average (%)	Above average (%)	Average (%)	Below average (%)	Well below average (%)
2nd grade	0	6.66	80	13.33	0
4th grade	0	1.25	85	12.5	1.25
6th grade	0	5	59	36	0
Overall	0	8	69	22	0.8

A two-way between groups (Gender x Grade) ANOVA was carried out on the Standard Score for the Fine Motor Composite Score to assess the effect of gender and grade. There was no interaction effect found between grade and gender F(2,247)=1.30 p<.05. There was a main effect found for grade, F(2,247)=10.03 p<.01, η_ρ^2=.08. Post Hoc test using the Bonferroni correction revealed that mean score for 2nd grade children (M=50.02, SD=8.46) differed significantly from that of 6th grade children (M=44.55, SD=7.90). There was no significant main effect found for Gender F(1,247)=1.64, p>.05.

A 2 (Composite) x 2 (Gender) x 3 (Grade) repeated measures ANOVA was carried out on the standard scores for FMC and MC composites. There was a significant interaction effect between Grade and Composite, Wilks' Lambda = 0.95, $F(2,247)=5.93$, $p<.01$, $\eta_p^2=.05$. Post Hoc tests using the Bonferroni correction revealed that 6th grade children (M=44.80, SD=7.57) scored significantly lower than 4th grade (M=49.35, SD=7.48) and 2nd grade (M=51.74, SD=7.64) peers for the FMC composite but there were no significant differences between grades in MC scores with 2nd, 4th and 6th grade children scoring 47.63, 46.70 and 45.43 points respectively.

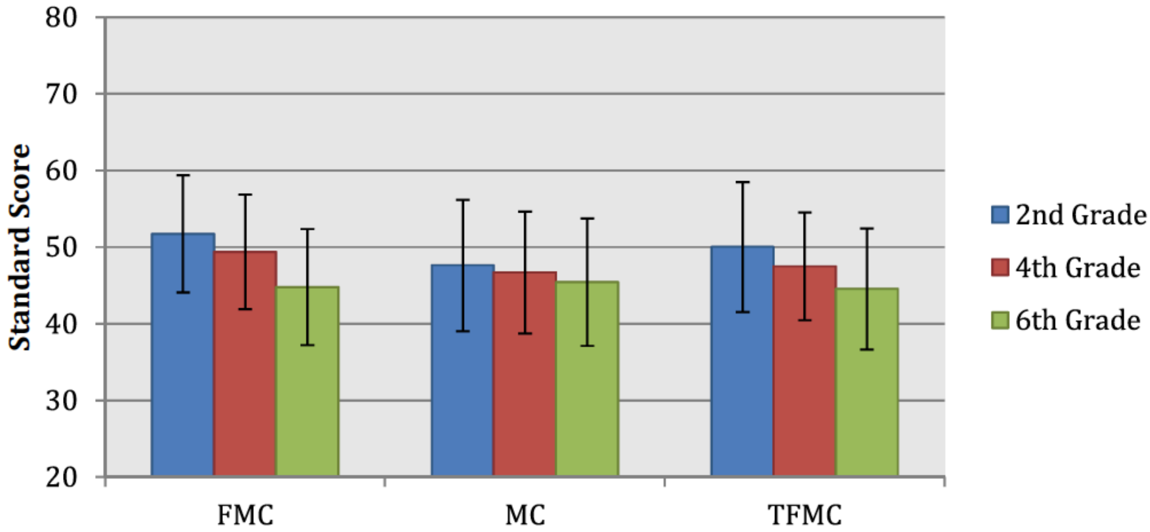

FIGURE 3.1: STANDARD SCORES FOR FINE MANUAL CONTROL (FMC) AND MANUAL COORDINATION (MC) UNITS AND TOTAL FINE MOTOR COMPOSITE (TFMC).

A 4 (Subtest) x 2 (Gender) x 3 (Grade) repeated measures ANOVA was carried out the point scores for each of the 4 subtests. A main effect was found for grade, $F(2,250)=43.44$, $p<.01$ on the point scores for FMP subtest, with a large effect size, $\eta_p^2=.26$. Post hoc tests using the Bonferroni correction found that 2nd grade children (M=29.19, SD=5.54) scored significantly ($p<.01$) lower compared to their 4th (M=33.65, SD=4.29) and 6th (M=35.63, SD=3.92) grade peers in addition to a significant difference being found between 4th and 6th grade ($p<.05$). There was also significant main effect for grade for the FMI subtest, $F(2,250)=16.42$, $p<.01$, $\eta_p^2=0.12$. Post hoc tests using the Bonferroni correction showed that 2nd grade (M=33.97, SD=4.40) scored significantly lower compared to 4th (M=36.23, SD=3.48) and 6th (M=36.92, SD=2.41) grade children ($p<.01$). Significant main effects were also for grade on the point scores for the MD (F(2,250)=113.82, p<.01) and ULC (F(2,250)=91.60, p<.01) subtests both with large effect sizes (η_ρ^2=.48 and η_ρ^2=.42 respectively). Post Hoc tests with Bonferroni correction found that all 3 grades groups performance differed significantly on MD scores (p<.01) with 2nd grade (M=21.11, SD=3.79) once more scoring lower than their 4th (M=25.45, SD=3.86) and 6th (M=30.11, SD=4.11) grade peers. Post hoc tests found that all grade groups differed significantly (p<.01) for ULC with 6th grade (M=34.17, SD=2.90) scoring higher than their 4th (M=31.08, SD 5.72) and 1st (M= 22.09, SD 8.27) grade peers. Main effects for gender were found for FMP and ULC subtests (p<.01). Males were found to score significantly lower (M=31.99, SD=5.86) for FMP and significantly higher for ULC (M=29.56, SD=8.21) than females (M=33.92, SD=4.5 and M=28.08, SD=7.74 respectively).

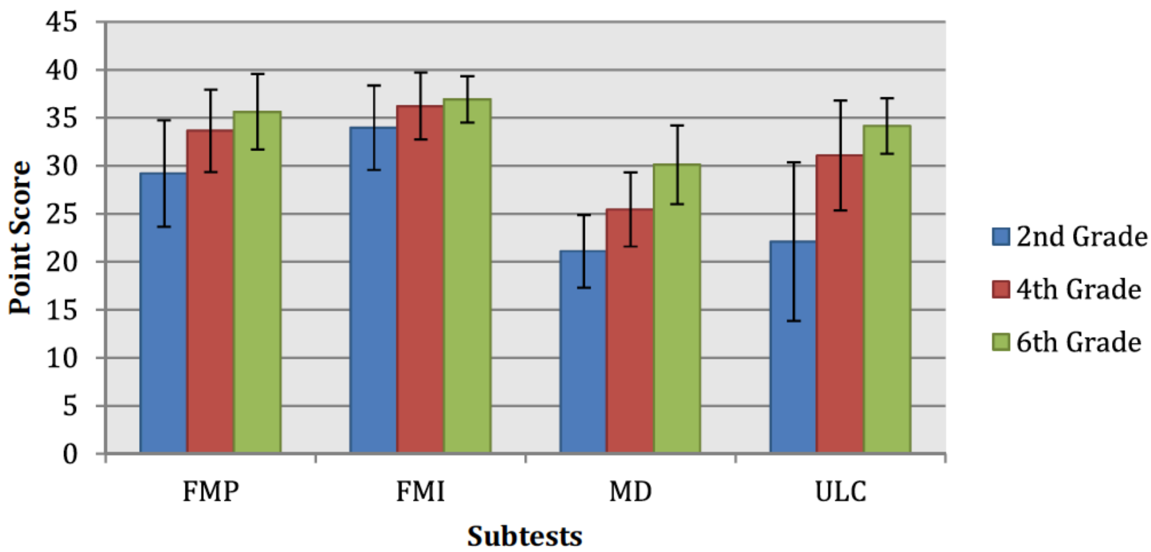

FIGURE 3.2: POINT SCORES FOR FINE MOTOR PRECISION (FMP), FINE MOTOR INTEGRATION (FMI), MANUAL DEXTERITY (MD) AND UPPER LIMB COORDINATION (ULC) SUBTESTS.

3.4 Discussion

This study investigated the current level of fine motor skill proficiency of children aged 6-12 years. Overall, the main findings highlight that children's subtest point scores (performance before gender and age correction) do improve with age (Figure 3.2). These age-related differences mirrors those found by D'Hondt et al. (2011) in a study examining gross motor skill proficiency. Similarly, Bardid and colleagues (2015) found that older children perform better than their younger peers on gross motor coordination activities. However, our results revealed that children fall below the expected levels (standard score of 50) given by normative data (Figure 3.1). These results seem to be in contradiction with the typical theory of development, with the youngest children appearing to demonstrate the best scores. These differences demonstrate that children's fine motor skill proficiency does not regress with age, rather that children's fine motor development does not occur at the expected rate. This finding emphasizes the downward trend observed in the literature on children's motor skill proficiency falling below expected levels (Okely, Booth and Chey, 2004; Hardy *et al.*, 2013; Bardid *et al.*, 2015). As a result of the standardized nature of motor skill assessments, the task constraint can be seen as remaining constant, and any biological changes in children in the past decade are likely to have had negligible effect on motor skill proficiency. Therefore, it is reasonable to assume that any differences found are likely the result of changes in the environmental constraint.

One of the potential reasons that could explain changes in the well-established norms of motor development is the increasingly prominent role that technology plays in modern society. A number of studies have shown how children now grow up in media-saturated environments with technology playing a central role in their daily life (Vandewater *et al.*, 2007; Rideout, Foehr and Roberts, 2010; Lauricella, Wartella and Rideout, 2015). These relatively new leisure time activities have taken the place of traditional activities such as playing with blocks, Lego©, board games or jigsaws with a potentially detrimental effect on the rate of development of fine motor skills. To better understand and link all these elements together, it seems important to refer to Thelen and Smith (1994) who suggested that there is an intimate relationship between an individual and the physical and informational properties of the environment around them. As motor skill development emerges from this dynamic relationship between the organismic and environmental components, any changes in these properties influence motor skill acquisition. In this instance, the lack of practice of the skills that compose the various activities of each subtest such as catching, throwing or manipulation of objects such as pencils, scissors, cards or block. The FMP and FMI subtests are mainly composed of activities that rely on the grip and manipulation of a pencil. The development of pencil grip used for writing is a complex skill which has been found to improve with age as a result of practice (Schwellnus *et al.*, 2012). Surprisingly, only 2nd grade children were found to reach the expected level for the FMC composite, which includes both FMP and FMI subtests. In the past, pencil and paper activities were found to be a core component of school tasks making up 85% of the timing carrying out fine motor skills (Marr *et al.*, 2003). However, changes in the teaching methodologies used in school and leisure time activities that children now engage in may have reduced the time spent engaging in drawing activities in favour of more technology based activities (Flewitt, Messer and Kucirkova, 2014).

Additionally, the MD subtest showed the lowest scores of all the subtests. This subtest is also composed of activities involving the manipulation of objects with an added component: a time-pressured environment (e.g. placing as many pegs in a board as possible in 15 seconds). It is likely that any difficulties that children have in control and manipulation of objects would be magnified by tests where the level of success is constraint by time in comparison with the FMP and FMI subtests that are completed without a time constraint. The ULC subtest relies heavily on hand-eye coordination of a child. Traditionally, most children would participate in throwing and catching activities from a young age that would help develop hand-eye coordination. Therefore, it is not surprising to see children falling below expected proficiency levels for the ULC subtest, given the reduction in physical activity and motor skill competence in recent years (Okely, Booth and Chey, 2004; Woods *et al.*, 2010; Hardy *et al.*, 2013; Bardid *et al.*, 2015). The finding that standard scores for the MC composite do not differ significantly between grades suggests that component of fine motor skill is progressing steadily for all ages while still falling below normative levels.

Previous research has shown that cultural differences influence the motor skill proficiency of children (Chow, Henderson and Barnett, 2001; Lam and Schiller, 2001; Chui *et al.*, 2007; Luo *et al.*, 2007; Lam, 2008; Saraiva *et al.*, 2013; Bardid *et al.*, 2015).

Studies by Chow et al. (2001) and Chui et al. (2007) both found differences in components of fine motor skill between children from Hong Kong and their American counterparts. Children from Hong Kong were found to score higher for manual dexterity units while American children scored better for upper limb coordination subtests that require projection and interception of objects (Chow, Henderson and Barnett, 2001; Chui *et al.*, 2007). Bardid and colleagues (2015) have also found cultural differences between Belgium and Australian children on some of the subtests of the Körperkoordinationstest für Kinder (KTK). These findings emphasis the need for caution when using norms developed in one country as a direct comparison to the performance by children of another country (Lam, 2008). Additionally over the last decade, lifestyles across the world have changed significantly due to advances in technology and increased standards of living, which has altered children's leisure time activities and physical activity patterns (Dollman, 2005; Bardid *et al.*, 2015). Consequently, one can question whether the current level of children's motor competence would reach the level previously observed in the past[1]. It is reasonable to assume that lack of motor skill proficiency observed in this article and the studies mentioned above can be attributed to a combination of both cultural and societal changes.

In this study, males were found to score higher than females for throwing and catching activities in the point scores ULC subtest whereas females scored significantly higher for drawing and cutting activities of the FMP subtest. Research has shown that gender differences are likely as a result of environmental influences such as lack of opportunities to practice, encouragement and reinforcements that female motor proficiency is lower rather than genetic differences (Okely and Booth, 2004; Hume *et al.*, 2008; Haywood and Getchell, 2009). The ULC subtest contains object control skills such as throwing, catching and bouncing, which boys have been found to be more proficient in compared to girls (Barnett *et al.*, 2009; Blakemore, Berenbaum and Liben, 2009). The Manual Dexterity Subtest not only contains some object control skills (sorting cards and moving pegs) but also is measured in a time-pressured environment. Subjectively, boys tended to demonstrate greater motivation to improve score between trials during test compared to girls. This is in keeping with research which shows boys to display more competitive and egocentric nature compared to girls more cooperative and calmer demeanor (Garcia, 1994). The FMP subtest involves less competitive fine motor skill tasks (no time pressure) and encourage precision and accuracy such as; tracing lines and drawing shapes, which often have a female gender bias associated with them (Garcia, 1994; Hardy *et al.*, 2010). However, as gender differences are frequently observed in motor skill proficiency in children (Barnett *et al.*, 2010; Breslin *et al.*, 2012), the BOT-2 provides gender adjusted norms which control for gender bias. As a result, these gender differences were not present when analyzing the standard scores. These low level's of motor skill proficiency can have multiple repercussions for teachers, parents, and children themselves. Children with fine motor skill impairments have problems with everyday activities such as using utensils to eat or dressing themselves (Zwicker *et al.*, 2012) in addition to decreased levels of social interaction with peers (Mandich, Polatajko and Rodger, 2003). In relation to academic achievement, children with fine motor skill difficulties frequently take longer to complete tasks as a consequence of problems with the manipulation of the pencil. They tend to be exposed to fewer learning experiences, with less practice time to develop their skills in the classroom in comparison with their peers (Cameron *et al.*, 2012). Consequently, these children's fine motor skill proficiency will fall behind their more skilled peers. The finding that children's motor skill is not progressing at the expected rate could lead to the creation of a new sub-group with a lower level than TD children while being above the level of children with impairments that are of clinical implications (e.g. DCD).

However, it is also important to mention that there is some evidence that video gaming can lead to improvement in manual dexterity and hand-eye coordination in laparoscopic surgery training in surgeons (Rosser *et al.*, 2007; Badurdeen *et al.*, 2010; Adams, Margaron and Kaplan, 2012). Touch screen devices require several actions such as swiping, dragging and dropping, pushing or tapping which all require fine motor skill to perform (Price, Jewitt and Crescenzi, 2015). As such, it might be possible that children are now developing a new set of fine motor skills that meet the demands of the environment that they are now faced with. These new skills allow for the proficient use of touch screen technologies or games consoles.

3.5 Conclusions

As these "new fine motor skills" are not measured by traditional tests like the BOT-2, this may require the adjustment of the tasks currently used to assess fine motor skill or the creation of additional tests to accurately measure fine motor skill proficiency while ensuring the influence of the current environment is taken into account. It is unlikely that there is a unique root cause of these motor development delays. According to the dynamical systems approach, these differences are likely the result of an accumulation of many small changes in the environment leading to significant differences between children's current level of fine motor proficiency and what has been considered typical development in the past (Thelen and Smith, 1994). However, further longitudinal studies are required to ascertain whether children eventually catch up with their expected rate of development or whether these differences continue to exist into adulthood. In addition, there is a need to assess how engagement in physical activity, sedentary behaviour, and screen time activities could influence children's fine motor skill proficiency levels.

3.6 Acknowledgements

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3.7 Link between Chapter 3 and Chapter 4

The ability to carry out many activities in daily living requires fine motor skill. As such, failing to develop fine motor skill proficiency could have severe consequences on individual's quality of life. The purpose of Chapter 3 was to examine the current state of Irish children's fine motor skill proficiency and determine where it lies in relation to normative levels. The results indicated that children's performance level below expected levels as outlined by normative data for the Bruininks-Oseretsky Test of Motor Proficiency 2nd Edition (BOT-2). This finding showed us that despite children's performance improved (raw scores) with age, it failed to progress at the expected rate as given by standard scores. This causes us to question the influence of the environment which children now grow up in plays on fine motor skill acquisition. Specifically, we are prompted to question whether these shortfalls are a result of lack of development of the coordinative structures which underpin fine motor skill or whether they are at the expenses of the development of other fine motor skills which are more applicable to the demands of todays environment.

Chapter 4 seeks to build upon the findings of Chapter 3 by investigating children's ability to coordinate their movements in a rhythmic coordination pendulum task. The ability to co-ordinate movements underpins fine motor skill. As such, children's reduced levels of fine motor skill proficiency found in Chapter 3 could be a result of problems in children's ability to co-ordinate their movements. Further to this, this study sought to examine children's performance compared to the one observed in adults. Finally, this study also investigated how children's coordinative processes differed between older and younger children.

Chapter 4: Getting into the swing of things: An investigation into rhythmic unimanual coordination in typically developing children.

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Abstract

Unimanual coordination is a vital component of everyday life and underpins successful engagement of many activities of daily living and physical activity participation. The ability to coordinate with environmental stimuli has been extensively studied in adults in a variety of situations. However, we know little about these processes in children and even less about how these processes change as age increases. This paper examines children's performance in a rhythmic unimanual coordination task using a handheld pendulum. Participants (aged 6, 9 and 11 years) manipulated the pendulum at 3 frequencies (preferred frequency, +20% of preferred and -20% of preferred frequency) in coordination with 3 stimuli (Visual, Auditory and Visual-Auditory combined). Results showed that children's coordination levels and movement variability improved with age, however still fell below those observed in adults. In addition children demonstrated preferences for visual stimuli or multisensory stimuli compared to auditory stimuli on their own Interestingly, children were found to demonstrate different movement amplitudes for -20%, preferred and +20% frequency conditions. In conclusion, children's unimanual coordination levels were found to follow the typical maturation process and improve with age. Further to this, findings suggest the potential benefit of multisensory information for unimanual coordination in children.

Keywords: Motor Coordination; Multisensory; Synchronization; Amplitude; Maturation; Unimanual

4.1 Introduction

The ability to accurately coordinate our movements in response to environmental stimuli is an essential component of everyday life. Many biological and physical properties are influenced by this constant exposure to environmental information. The environment, in combination with the genetic characteristics of an individual, play a central role in children's development (Thelen and Smith, 1994). The ability to move is one of the essential components of typical child development (Gallahue and Ozmun, 2006). Early work by Piaget (1953) suggested a link between a child's cognitive development and motor development. A more recent study suggests that these two processes are fundamentally intertwined and considered that motor development is a prerequisite for the development of certain perceptual functions (Bushnell and Boudreau, 1993). The ability to coordinate our actions with the environment can be seen as a natural process and an inherent part of typical development and essential for everyday life. This natural entrainment by which humans use information to guide their motor behaviour has been observed in a number of visual-motor coordination tasks using handheld pendulums (Schmidt *et al.*, 2007; Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). The type and frequency of stimuli are often the constraints manipulated to analyse individual's coordination mode and stability (Lopresti-Goodman *et al.*, 2008; Varlet, Marin, Issartel, *et al.*, 2012; Armstrong and Issartel, 2014). Studies investigating how the brain integrates different sensory information have become a focus of neuroscience research in recent times. Sensory integration is the process of extracting information from the external environment, processing and initiating an action to meet the task requirements (Blakemore, Wolpert and Frith, 2002). The ability to appropriately select the best modality (ies) of information depends on how reliable and precise the information is (Lalanne and Lorenceau, 2004). Auditory stimuli have generally found to be associated with greater synchronization in the temporal domain (Ernst and Bülthoff, 2004) while visual stimuli are more important for coordination in spatial tasks (Alais and Burr, 2004). A study by Varlet and colleagues (2012) found that participants were better coordinated for continuous visual stimuli compared to continuous auditory stimuli. The authors attributed this finding to visual information being frequently experienced in a continuous form in our daily environment while audio stimuli can be either discrete or continuous. Armstrong and Issartel (Armstrong and

Issartel, 2014) found adults demonstrated better coordination for visual conditions compared to auditory conditions.

As we live in a multisensory environment, we rarely encounter stimuli in isolation but rather are exposed to multiple sources of information that are required to be perceived, integrated and acted upon. As such, we are often required to prioritize information or pay attention to particular sources of information. For example, as a speeding car approaches and begins to brake, we gain visual information as it advances toward us in addition to the auditory information of the squealing brakes. These sources of information contribute to the course of action we decide on and the motor behaviour we adopt (e.g. which direction to jump). Previous research has shown that the combination of both visual and auditory stimuli has led to improved performance (Sinnett, Soto-Faraco and Spence, 2008). Multisensory integration has been extensively studied in terms of the importance of congruency of spatial and temporal information to be beneficial or detrimental to coordination (Carson and Kelso, 2004; Ernst and Bülthoff, 2004; Elliott, Wing and Welchman, 2010). The combination of auditory and tactile information has been shown to improve synchronization in tapping tasks (Elliott, Wing and Welchman, 2010; Wing, Doumas and Welchman, 2010; Repp and Su, 2013). The potential benefit of multisensory information in motor coordination has also been studied in pendulum based tasks (Varlet, Marin, Issartel, *et al.*, 2012; Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). Armstrong et al. (2014) found slight improvements in coordination when multisensory information was available compared to unisensory in adults, particularly in the most difficult frequency conditions. However, there is little known about these processes in children and if the way children integration unisensory or multisensory information progress with age. The majority of information available in children is focused around the presences of sensory integration problems in children with neurological or developmental disorders

In more recent times, research examining motor coordination has been expanded to investigate the coordinative process in special populations such as individuals with Autism Spectrum Disorder (Fitzpatrick *et al.*, 2016) Schizophrenia (Varlet, Marin, Raffard, *et al.*, 2012), Social Anxiety Disorder (Varlet *et al.*, 2014), and even obese individuals (Gaul *et al.*, 2016). Varlet and colleagues (2012) found lower stability of coordination in pairs with a Schizophrenic patient present during social motor coordination pendulum swinging task. This pattern of coordination difficulties has also been found in individuals suffering from Social Anxiety Disorder in a similar pendulum task (Varlet *et al.*, 2014). Interestingly, Gaul, Mat, O'Shea and Issartel (2016) found significantly poorer levels of coordination and movement variability in obese adults compared to normal weight controls in a visual motor coordination task. These difficulties in basic visuomotor coordination will likely persist in activities that require more complex forms of coordination such as in the completion of everyday tasks, physical activity or sports participation. Difficulties in motor coordination are a feature of a number of neurological, psychiatric and developmental disorders such as Cerebral Palsy, Autism Spectrum Disorder or Developmental Coordination Disorder (DCD). These kinds of motoric difficulties in motor coordination are a key feature of Autism Spectrum Disorders. Fitzpatrick and colleagues (Fitzpatrick *et al.*, 2016) found children with ASD demonstrated impaired social motor coordination compared to typically developing (TD) children in rhythmic coordination task. This novel finding raises interesting questions as to the etiology of coordination difficulties in individuals free from neurological or developmental disorders.

This breath of research examining rhythmic coordination has led to strong evidence on how adults utilize sensory information. However, there is at present limited research investigating how children can perform those coordination tasks and how they develop with age. The research that does exist tends to focus on social coordination in children and adolescents with ASD (Fitzpatrick *et al.*, 2013, 2016). One such study by Fitzpatrick et al (2013) investigated intentional and unintentional coordination in adolescents with ASD. Results showed adolescents with ASD demonstrated weaker levels of coordination compared to controls in both intentional and unintentional social entrainment.

This study sought to examine children's sensory-motor integration through their performance in a rhythmic coordination task using a handheld pendulum. This study aimed to evaluate the different ability levels in children and how they compared to adult levels on a pendulum-swinging task in terms of accuracy and stability of coordination. Secondly, this study sought to investigate how children's patterns of coordination differed between children of different ages. We hypothesized that children's coordination would improve with age with the oldest children demonstrating the highest level of coordination. We also hypothesized that manipulation of frequency to above and below preferred frequency would increase task difficulty. Finally, we also aimed to examine whether children demonstrated similar patterns of behaviour in terms of movement amplitude and stimulus preference as those seen in adults.

4.2 Material and Methods

4.2.1 Participants

A sample of children (N=71) carried out a unimanual coordination task using a handheld pendulum. This task involved coordination of the participant's movement with a number of computer generated stimuli. All participants were right handed, had normal or corrected vision and no known neuromuscular deficit that would affect their performance based on their school records. The Laterality Quotient, i.e., the degree of handedness, was assessed by asking subjects to complete the 10-item version of the Edinburgh Handedness Inventory (M=85.1, SD=14.2). Colour blindness was assessed using the Ishihara Test of Colour Blindness short form. Prior to inclusion in the study, informed consent was obtained from the parents of all children. The study was approved by Dublin City University Research Ethics Committee (DCUREC/2011/038) and conducted in accordance with the Helsinki Declaration.

4.2.2 Stimuli

There were a total of 3 stimuli in the experiment. There were 2 unimodal stimuli (visual and auditory individually) and 1 bimodal stimulus (visual and auditory together). The visual stimuli, created in Matlab using Psychophysics Toolbox (Brainard, 1997), were presented on a screen (Dell Trinitron Ultrascan 1600HS Series CRT Monitor, Model D1626HT) placed approximately 1meter from the participant at eye level. The visual stimuli consisted of a square (5.2cm x 5.2cm) that faded from red to yellow while oscillating (Visual Panning (VP)) horizontally across the screen on a grey background in a sinusoidal manner with an amplitude of 28cm. The auditory stimuli were presented through noise cancelling headphones and consisted of a continuous tone that modulated from a low pitch (400 Hz) to a high pitch (800 Hz) in a sinusoidal fashion panning (Audio Panning (AP)) from one ear to the other. The high pitch sound was always heard in the left ear and the low pitch heard in the right ear. The bimodal (MP) condition's consisted of the presentation of both auditory and visual stimuli at the same time.

For the VP condition, participants had to swing to the left as the square moved left and to the right as the square moved right on the screen synchronizing the endpoint of the movements with the square's endpoints. For the AP condition, participants were required to swing the pendulum to the left as the sound panned to the left ear with a high pitch and to the right as the sound panned to the right ear with a low pitch through the headphones, synchronizing the endpoint of the movements with the sounds endpoints. The MP condition required participants to swing to the left as the square and sound moved left and to the right as the square and sound moved right. This presentation ensured both visual and auditory stimuli had both spatial and temporal information thus making them comparable. Participants were asked to swing the pendulum to an angle of 45° each side. Participants view of the pendulum was occluded by a wooden panel.

All data was recorded at 100Hz using a Measurement Computing Data Acquisition Device (Measurement Computing USB-1608FS) for analysis. The experiment was controlled and run through Matlab using a Graphical User Interface as part of a Psychophysics Toolbox Extension (Brainard, 1997).

4.2.3 Procedure

The experimental procedure was the same as that outlined in Armstrong and Issartel (Armstrong and Issartel, 2014) with greater attention given to provide clearer and more age appropriate instructions to cater to age and understanding of children. The participants were then given an outline of each of the three stages 1) preferred frequency calculation 2) Familiarisation and 3) Experimentation. Participants gripped a handheld pendulum with their right hand securely so that they were in full control of the pendulums movements. The screen was positioned to the participant's right hand side at eye level and as such participants were required to turn their head to look at the screen. The pendulum was 49 cm long with a weight of 53 g attached at the end of the rod. Its eigenfrequency was 0.75 Hz (Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). Participants were prevented from viewing the pendulum's movements and their forearm by a wooden cover and a cloth curtain. Participants swung the pendulum in a darkened room, through the sagittal plane by flexing and extending their wrist and were told to move the pendulum within an amplitude which they felt comfortable with. For the preferred frequency calculation participants were asked to swing the pendulum in a dark room for two minutes at a pace that was 'most comfortable' for them which they "could swing at all day" (Schmidt *et al.*, 2007). The preferred frequency of each participant was used to create two additional frequencies: +20% of preferred and -20% of preferred.

During the familiarisation stage, participants were required to coordinate the movements of the handheld pendulum with each of the three conditions (VP, AP and MP). The instructions for the task were the same as in the experimentation stage and are described above. The participants were given one trial of each of the visual, auditory and multisensory condition at preferred frequency. The participants received additional presentations of the stimuli if required to ensure understanding of the different experimental conditions. One block of the experiment consisted of three frequencies (preferred frequency, +20% and -20%) and the three stimuli (AP, VP and MP), resulting in a total of 9 conditions. Participants completed one trial of each of the 9 randomised conditions for each of the two blocks. There was a 30 second break after each 40 second trial and a two minute break between blocks to eliminate fatigue.

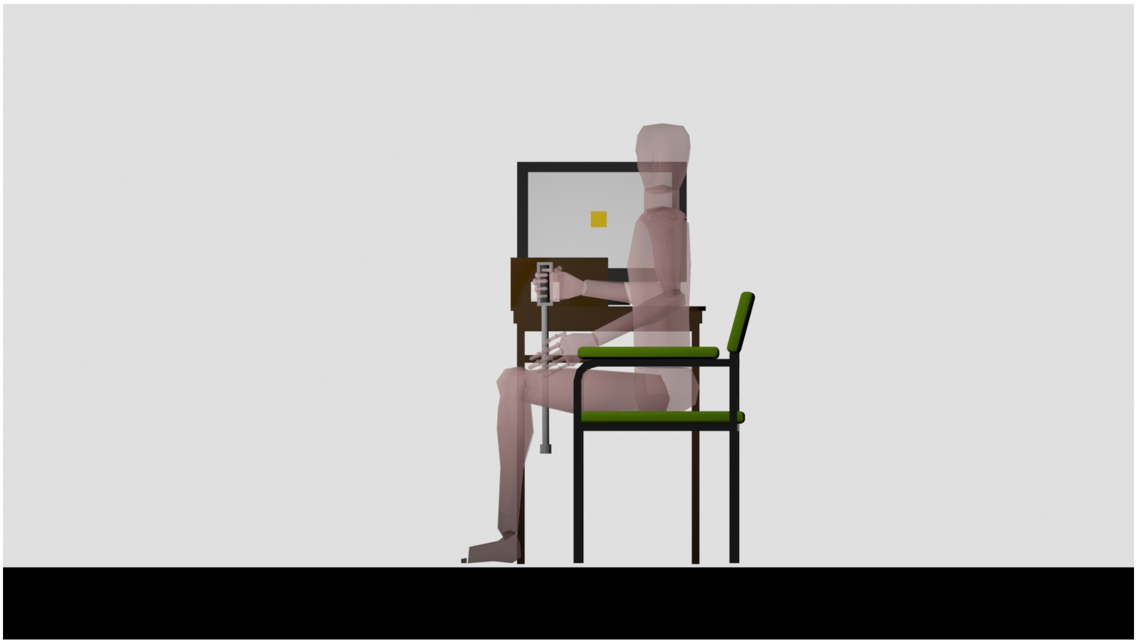

FIGURE 4.1: EXPERIMENTAL SET UP FOR PARTICIPANT

4.2.4 Data Reduction

We assessed participant's coordination using continuous relative phase (CRP) and the standard deviation of CRP (SD CRP), to determine the level of coordination between the participant's movements and that of the stimuli in addition to the variability of this coordination. Prior to analysis, the first 10 seconds of data were removed and the remaining 30 seconds were filtered using a low pass 10 Hz Butterworth filter. The sample rate was 100Hz. This process resulted in 3000 data points (30sec x 100 data points). The average PF was 0.91Hz resulting in a average period of 1.09sec. The first and last cycles were also trimmed to ensure full cycles were analysed which led to the removal of 218 data points (2.18 sec x 100Hz) which left on average 2782 data points. Data was then normalised between ±1 using min max scaling. For each of the 9 experimental conditions, dependant variables were calculated all trials and averaged between both trials for the same condition. In a small number of cases, some trials were removed when a participant CRP value was above 90°. This resulted in 7% of trials being removed.

To assess the degree of coordination between the participant and the stimulus the CRP was calculated using a Hilbert Transform and scaled between ±180° . In order to limit distortions caused by Hilbert Transform during the computation of relative phase, the first and last cycles of each trial were removed (Pikovsky, Rosenblum and Kurtz, 2003). Low values for CRP indicate better coordination with 0° representing perfect coordination and 180° would have indicated opposite coordination mode. The variability of coordination was assessed using the SD CRP calculated from the CRP values. Participants movement amplitude was calculated using their mean movement amplitude to each side in degrees and suming values for left and right.

4.2.5 Statistical Analysis

All statistical analysis was performed using SPSS (IBM SPSS Statistics 19). A 3(Condition) × 3(Frequency) × 3(Class) repeated measures Analysis of Variance (ANOVA) was carried out CRP, Standard Deviation of CRP, Amplitude and Standard Deviation of amplitude to assess the accuracy and stability of the motor coordination. Sphericity was assessed and the Greenhouse and Geisser's correction for degrees of freedom were applied when sphericity was not met. Post hoc analysis using the Bonferroni correction was carried out. For clarity, only statistically significant differences are reported in the results section ($p<0.01$ and $p<0.05$).

4.3 Results

TABLE 4.1: DESCRIPTIVE STATISTICS OF SAMPLE DIVIDED BY CLASS GROUP

	1st Class	**3rd Class**	**5th Class**
N (Male/Female)	21(11M/10F)	25(13M/12F)	25(11M/14F)
Mean Age ± SD (years)	6.97 ± .40	9.18 ± .55	11.18 ± .50
Preferred Frequency ± SD (Hz)	0.86 ± .086	0.89 ± .077	0.99 ± .129

4.3.1 Continuous Relative Phase

There was a significant interaction effect found between Condition and Frequency (F(3.4, 233.8)=2.7, $p<0.05$, $\eta_p^2 =$ 0.04). For VP and MP conditions, post hoc comparisons using the Bonferroni correction ($p<0.01$) revealed that participants demonstrated significantly lower levels of coordination for +20% (M=55.52, SE=3.14 and M=54.07, SE=3.28) and -20% Conditions (M=55.58, SE=2.61 and M=55.82, SE=2.6) compared to preferred frequency (M=42.19, SE=2.69 and M=38.96, SE=2.75) respectively. For AP conditions, the +20% condition (M=74.15, SE=3.47) was found to differ significanlty ($p<0.05$) than preferred frequency (M=63.77, SE=3.53).The was also a significant main effect found for class, F(2,68)=12.13, $p<0.01$, η_p^2= 0.26. Post hoc analysis revealed that 5th Class children (M=43.30, SE=3.49) performed significantly better than their 1st (M=68.44, SE=3.8) and 3rd (M=57.95, SE=3.49) Class counterparts.

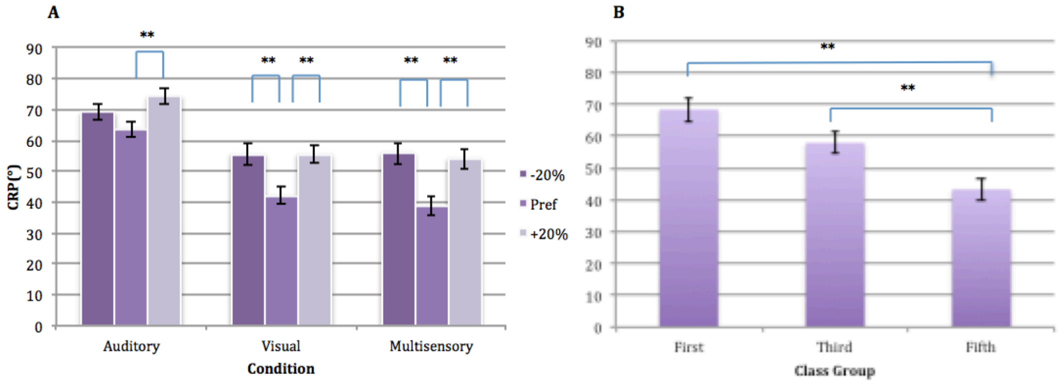

FIGURE 4.2: CONTINUOUS RELATIVE PHASE (CRP) VALUES DIVIDED BY A) CONDITION X FREQUENCY AND B) CLASS. LOW VALUES FOR CRP INDICATE BETTER COORDINATION WITH 0° REPRESENTING PERFECT COORDINATION AND 180° WOULD HAVE INDICATED OPPOSITE COORDINATION MODE (*P<0.05, **P<0.01).

4.3.2 Standard Deviation of Continuous Relative Phase

There was a significant interaction effect between Class and Frequency F(4,136)=2.76, *p<0.01*, η_p^2 =0.08. Post hoc test using the Bonferoni correction yielded significant differences between 5th Class (M=23.55, SE=1.91) and 3rd Class (M=33.22, SE=1.91) (*p<0.01*), 5th and 1st Class (M=41.06, SE=2.09) (p<0.01), and 1st and 3rd Class (*p<0.05*). For +20% frequency, there was a significant difference between 5th Class (M=29.04, SE=2.19) and 3rd Class (M=37.13, SE=2.19) (*p<0.05*), 5th and 1st Class (M=41.63, SE=2.39) (*p<0.01*). There was also a signifcant difference found between 5th Class (M=24.84, SE=2.20) and 1st Class (M=35.94, SE=2.39) (*p<0.01*) for preferred frequency. There was also a significant main effect for Condition, F(1.74, 118.45) = 37.53, *p<0.01*, η_p^2 = 0.36. A post hoc comparison showed significantly higher variability between AP Conditions (M=36.95, SE=1.17) and VP Conditions (M=31.88, SE=1.27), AP (M=36.95, SE=1.17) and MP (M=29.46, SE=1.22) (*p<0.01*) and VP and MP (*p<0.01*).

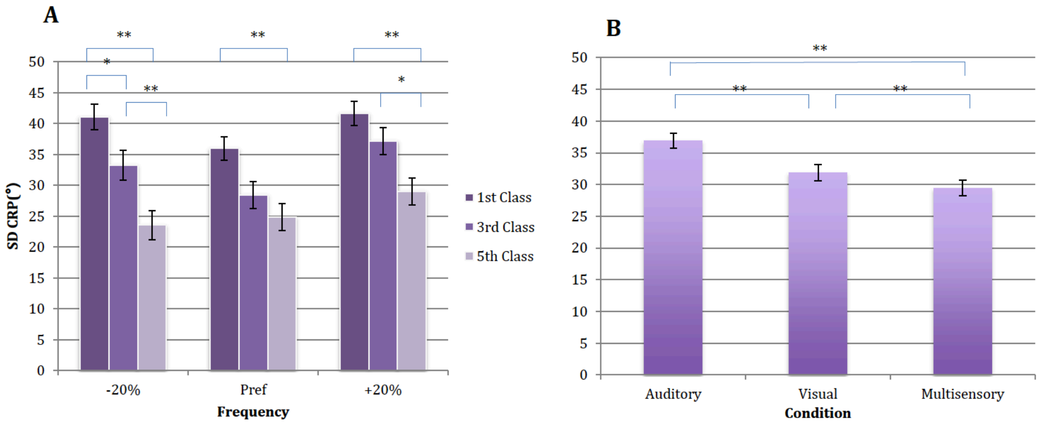

FIGURE 4.3: STANDARD DEVIATION OF CONTINUOUS RELATIVE PHASE (SD CRP) VALUES DIVIDED BY A) CLASS X FREQUENCY INTERACTION AND B) CONDITION. (* P<0.05, **P<0.01).

4.3.3 Amplitude

There was a significant effect found between Condition and Frequency, F(3.41,231.85) =3.68, $p<0.01$, $\eta_p^2 = 0.051$. A Post hoc analysis found that participants swung the pendulum over a greater amplitude for +20% (M=75.1, SE=1.93) compared to -20% (M=68.62, SE=1.97) and preferred frequency (M=71.23, SE=2.09) in AP conditions compared to VP and MP conditions. For VP and MP conditions, children moved over a significantly smaller amplitude for -20% (M=63.41, SE=1.56 and M=65.61, SE=1.79) compared to preferred frequency (M=70.83, SE=1.80 and M=72.62, SE=1.8) and +20% (M=71.40, SE=1.7 and M=73.22, SE=1.66) frequencies respectively. There was also a significant main effect for Class, F(2,68)=3.16, $p<0.05$, $\eta_p^2 = 0.09$. A post hoc analysis found that 5th Class (M=74.47, SE=2.72) children moved over significantly greater amplitude compared to their 1st Class counterparts (M=64.56, SE=2.97) ($p<0.05$).

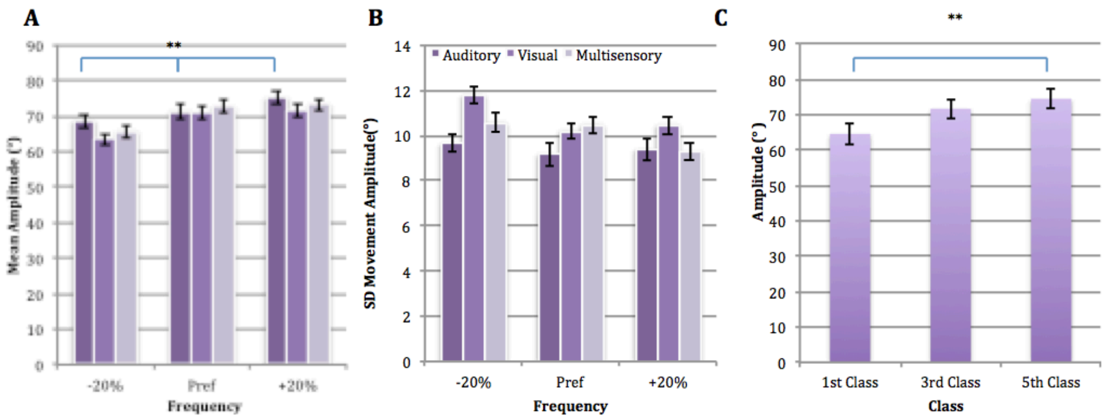

FIGURE 4.4: PARTICIPANTS A) MOVEMENT AMPLITUDE AND B) STANDARD DEVIATION OF MOVEMENT AMPLITUDE FOR CONDITION X FREQUENCY AND C) MOVEMENT AMPLITUDE FOR CLASS GROUP.

4.3.4 Standard Deviation of Amplitude

There was significant interaction effect found between Condition and Frequency F(3.59,243.95)=3.53, $p<0.01$, $\eta_p^2 = 0.02$. Post hoc tests found that children demonstrated significantly more variable movement amplitudes in VP conditions for -20% (M=11.78, SE=.51) conditions compared to preferred frequency (M=10.19, SE=.37) and +20% (M=10.45, SE=.37) conditions ($p<0.05$). For MP conditions, +20% conditions (M=9.27, SE=.36) had lower variability of movement amplitude compared to preferred frequency conditions (M=10.46, SE=.4, $p<0.01$) and -20% conditions (M=10.56, SE=.5, $p<0.05$). There was also a main effect found for Class group, F(2,68)11.73, $p<0.01$, $\eta_p^2 = .26$. Post hoc testing revealed 5th Class (M=8.24, SE=.49) children demonstrated significantly less variability in movement amplitude compared to their 1st (M=11.73, SE=.54) and 3rd Class (M=10.31, SE=.49) peers ($p<0.01$).

4.4 Discussion

This study sought to establish a baseline level of data for typically developing children in terms of accuracy and stability of coordination. Children's coordination levels fell significantly below that of adult levels reported in the literature for similar tasks (Varlet, Marin, Issartel, *et al.*, 2012; Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). However despite these high values for CRP, children were capable of carrying out the task to better levels to what has been observed in Obese adults (Gaul *et al.*, 2016). In addition, we also found that older children demonstrated superior levels of coordination and greater stability of coordination compared to their younger peers. These results are in line with the hypotheses outlined by the authors. This is the first study of our knowledge that has used a pendulum-based task with TD children. The finding of stronger levels of coordination for visual conditions in comparison to auditory conditions has been frequently reported in the literature (Varlet, Marin, Issartel, *et al.*, 2012; Armstrong and Issartel, 2014). This could perhaps be due to the continuity of stimulus presentation (Varlet, Marin, Issartel, *et al.*, 2012). The stimuli were also presented with a spatial element with both visual and auditory stimuli panning. The intention was to choose stimuli that would lead to stable levels of coordination as has previously been demonstrated (Schmidt *et al.*, 2007). There was little evidence to suggest children could have used multisensory information to improve their overall coordination (Figure 1A) however Figure 2B suggests multisensory information may reduce the variability coordination. The potential benefit from multisensory information to aid coordination has been the subject of mixed results to date (Varlet, Marin, Issartel, *et al.*, 2012; Armstrong and Issartel, 2014). Children demonstrated similar patterns of results for visual and multisensory conditions in comparison to audio only conditions. This suggests that the presence of visual information provides the most reliable information for children to coordinate their movements. It also highlights that, in such tasks, children are not yet able to benefit from the multisensory information available. In the case of adult study, with a similar paradigm, the ceiling effect observed in terms of high level of coordination could explain the difficulty to use another sensory modality to further improve coordination. In the current scenario, children can improve their coordination. One could expect that they would have benefited from the auditory information as supplementary information leading to an improved level of coordination. The ability to integrate multiple sensory inputs with the aim to produce more accurate levels of coordination may be an element of development that only reaches maturity during adolescence.

Overall, children's coordination levels were shown to improve with age, with 11-year-old children demonstrating significantly higher levels of coordination than their younger 9 and 6 year old peers. This pattern falls in line with the traditional theory of maturation with improvements in performance with increases in age (Gallahue and Ozmun, 2006). Not surprisingly, children demonstrated greater variability in their coordination compared to previously reported adult values (Varlet, Marin, Issartel, *et al.*, 2012; Armstrong and Issartel, 2014). This pattern has been reported in a variety of other studies, with children demonstrating less stable performance in a number of contexts (Wolff, Kotwica and Obregon, 1998; Getchell and Whitall, 2003). Getchell and Whitall (Getchell and Whitall, 2003) found that children demonstrated a reduction in variability of coordination with increases in age during a step/clap coordination task in a sample of children aged 4-10 years of age. Wolff, Kotwica and Obregon (Wolff, Kotwica and Obregon, 1998) and Robertson (Robertson, 2001) differences in the stability of coordination between younger children, older children and adults in bimanual tapping and circle drawing tasks respectively. As such, the reduction of variability over time can be seen as a key component of the learning process with older children coordination levels becoming stable. Interestingly, we observed a reduction of the level of variability in the multisensory conditions. The finding that the multisensory condition produced the most stable level of coordination in respective of frequency and age interactions adds further evidence to the potential benefit of multisensory information. The benefit of both auditory and audio-visual stimuli have also been found to enhance stability of coordination in elderly adults during a bimanual coordination task (Blais *et al.*, 2014).

Interestingly, in terms of movement amplitude, children moved over a smaller distance for the -20% frequency and over larger distance for the +20% frequency. This finding is contrary to previous research observed in adults (Hajnal *et al.*, 2009). Children vary their movement amplitude as a means to modulate their performance for any frequencies outside of their preferred frequency. It seems that children adapt their behaviour over a shorter (fast frequencies) or longer distance (slow frequency) to preserve tempo. In this way children can maintain a tempo closer to that of their preferred frequency.

The results demonstrate the preference for visual/audio-visual information rather than auditory information alone in a unimanual coordination task. It is likely than the increased attentional demands that occur when visual information is available (Blais, Albaret and Tallet, 2015). When taken together these findings raise some important questions on the underlying processes behind how children carry out motor coordination tasks. Further studies are required to determine how the coordinative processes are refined during adolescence to reach adult like levels. One can use this paradigm to assess atypically developing children and specifically obese children as we know of visuomotor coordination difficulties in obese adults (Gaul *et al.*, 2016). As expected children demonstrated sub adult levels of coordination and increased variability. However, fundamentally, children were found to demonstrate the same patterns of behaviour in terms of preference of stimuli and frequency as adults, with the best performance occurring on visual and preferred frequency conditions.

Despite the interesting and novel findings presented in the current study, a number of limitations should also be noted. Firstly, the generalizability of the results of this study is limited by the assessment of right-handed children only. This was as a consequence of the design of the experimental apparatus however the selection of only right handed participants is common practice in pendulum based studies (Schmidt *et al.*, 2007;

Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). Furthermore, the present study lacks any complimentary data on the motor or neuropsychological ability of children. Future studies would benefit from the inclusion of such complimentary measures to provide a wider picture of the relationship between rhythmic unimanual coordination and overall cognitive or motor ability. It remains to be seen whether these improvements with age are a result of the improvements in the effectiveness of the sensory integration process, neuromuscular maturation or increased motor experience and learning process. However, as the structure and function of optic array and ear are at a mature level from the age of 2 (Gallahue and Ozmun, 2006). Therefore, it is likely that these improvements are a consequence of both neuromuscular maturation and improvements in sensory integration however the relative weighting of each in perceptual motor coordination are yet to be established.

This study demonstrates that as children get older, the efficiency of the sensory integration of visual, motor and multisensory information improves resulting in improve unimanual coordination. The presence of reduced movement variability in terms of SD CRP (Figure 2A) and improved overall coordination levels as shown in CRP (Figure 1B) in older children is in line with typical views of maturation and growth. A notable finding, which has not been observed in previous studies of adults, was differences in movement amplitude for different frequencies. This could potentially be seen as an adaptive behaviour helping children to maintain coordination levels in adjusting their tempo to the preferred frequency.

4.5 Acknowledgements

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4.6 Link between Chapter 4 and Chapter 5

The purpose of Chapter 4 was to investigate the rhythmic manual coordination ability of children and evaluate how this changed with age. Results show that children's coordination demonstrated typical developmental trajectories with an improvement for older children compared to younger children. Not surprisingly, children's levels failed to reach those of adults previously reported in the literature. Interestingly, we found that children demonstrated altered movement amplitudes for different frequency conditions, with children moving over greater amplitudes for faster frequencies and smaller amplitudes for slower frequencies. This could be a potential control strategy used by children to maintain tempos closer to their preferred frequency. These findings suggest that children's sensory integration processes are slightly less effective in comparison with adults.

Chapter 5 sought to further investigate the sensory integration process as done in Chapter 4, this time examining the role of obesity. This studied aimed to build upon recent evidence suggesting obesity influences the sensory integration process resulting in so called 'sensory integration difficulties' or 'perceptual motor coordination difficulties' (Petrolini, Iughetti and Bernasconi, 1995; D'Hondt *et al.*, 2008; D'Hondt, Deforche, De Bourdeaudhuij, *et al.*, 2011; D'Hondt, Segers, *et al.*, 2011; Gentier *et al.*, 2013). Unlike Chapter 4 however, Chapter 5 examined visual motor coordination in a sample of adult participants as opposed to children. As Chapter 3 and Chapter 4 have demonstrated, children's motor coordination, and the underlying perceptual motor processes are still developing in childhood. Therefore, Chapter 5 sought to examine the influence of obesity in adults to avoid the confounding factor of maturation found in children. It was hoped that this would strengthen the argument for the presence of sensory integration deficiencies in obese individuals.

Chapter 5: Impaired Visual Motor Coordination in Obese Adults

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Abstract

Objective:

To investigate whether obesity alters the sensory motor integration process and movement outcome during a visual rhythmic coordination task.

Methods:

88 participants (44 Obese and 44 matched-control) sat on a chair equipped with a wrist pendulum oscillating in the sagittal plane. The task was to swing the pendulum in synchrony with a moving visual stimulus displayed on a screen.

Results:

Obese participants demonstrated significantly ($p<.01$) higher values for continuous relative phase (CRP) indicating poorer level of coordination, increased movement variability ($p<.05$) and a larger amplitude ($p<.05$) than their healthy weight counterparts.

Conclusion

These results highlight the existence of visual sensory integration deficiencies for obese participants. The obese group have greater difficulty in synchronising their movement with a visual stimulus. Considering that visual motor coordination is an essential component of many activities of daily living, any impairment could significantly affect quality of life.

5.1 Introduction

According to World Health Organization (WHO) figures from 2014, 39% of adults (1.9 billion people) were overweight with more than 600million of these being found to be obese. This is particularly alarming considering the worldwide prevalence of obesity has doubled since 1980. The obesity problem also seems to continue with 42 million children under the age of 5 being either overweight or obese in 2013 (World Health Organization, 2014). Obesity is the major health concern of this generation. Obesity has been linked to increased risk of other diseases such as stroke, cancer, cardiovascular disease, Obstructive Sleep Apnoea (OSA), Type II Diabetes Mellitus (T2DM), hypertension and mental health problems (Lee *et al.*, 2012). In addition obesity has also been found to be associated with increased risk of fall, reduced quality of life and problems with activities of daily living (Rosmond and Bjorntorp, 2000; Corbeil *et al.*, 2001; Fjeldstad *et al.*, 2008). As such, many obese individuals report how clumsiness has affected their daily lives (Mannix *et al.*, 2010). Further to this, subjectively health care practitioners frequently report obese patients as being clumsy or awkward in their performance of fine motor skill activities such as signing forms or tying laces. The increased mechanical constraints placed on individuals as a result of increased adiposity reduce balance and increase risk of falls (Owusu *et al.*, 1998; Corbeil *et al.*, 2001) in addition to reducing physical activity (Ball, Crawford and Owen, 2000).

However a number of studies exist suggesting that differences found in the balance and fine motor skill proficiency between obese individuals and normal weight peers might have a neuro-muscular component as opposed to only be caused by mechanical impairment as traditionally suggested (Petrolini, Iughetti and Bernasconi, 1995; Bernard *et al.*, 2003; D'Hondt *et al.*, 2008, 2009; D'Hondt, Deforche, Vaeyens, *et al.*, 2011; Gentier *et al.*, 2013)**.** A study by D'Hondt et al (2008) investigated balance and postural sway between obese and normal weight children. In this study, children carried out using a traditional 9-hole peg task activity while in altered postural conditions, standing on a balance beam or while seated. As expected, obese children scored worse for the balance beam activity most likely due to the increased demands placed on their postural control due to their excess mass. However, more surprisingly, obese children were also found to score significantly worse than their normal weight peers on the task while in the seated position. Further to this, Gentier and colleagues (2013) found that obese children demonstrate impaired fine motor skills in addition to gross motor skills when compared to their normal weight peers. As fine motor skills are not directly affected by excess mass, this would suggest that other factors exist to impede obese individual's motor control (Gentier *et al.*, 2013). This leads to the suggestion that the problem may lie in the sensory integration process (Petrolini, Iughetti and Bernasconi, 1995; Bernard *et al.*, 2003; D'Hondt *et al.*, 2008; Gentier *et al.*, 2013; Scarpina *et al.*, 2016).

The sensory integration process relies on the complex interaction between the individual, the task being carried out and the environment in which it takes place (Newell, 1986). This relationship between the sensory integration process and motor behaviour has been extensively studied in typically developing adults (Varlet, Marin, Issartel, *et al.*, 2012; Armstrong and Issartel, 2014) and more recently to gain a greater understanding of how this process is altered in autistic (Isenhower *et al.*, 2012) and schizophrenic (Varlet, Marin, Raffard, *et al.*, 2012) individuals. These pendulum-based paradigms allow for the environment, task and individual constraints to be maintained which allows the mechanisms underlying this complex behaviour to be examined. An individuals motor behaviour is the observerable output from the complex interaction between all components of the system (Thelen and Smith, 1994). As an individual's interaction with the environment requires movement, any difficulties with how they control their motor output could have large consequences on their everyday life increasing the complexity, difficulty and attentional costs associated with any motor task and the potential for errors.

Recent research has begun to find association between cognitive performance and obesity (Huizinga *et al.*, 2008; Fedor and Gunstad, 2013). Reviews by Smith et al (2011), Wang et al 2016, Liang et al (2014) and Prickett et al (2015) have found obesity to be associated with cognitive performance over the course of the lifespan. These links between cognitive performance and obesity further strengthen the rationale that obesity may have a neural component. Obesity is also associated impaired motor control across the lifespan which impact upon activities of daily living and health (Smith *et al.*, 2011; Liang *et al.*, 2014a; Wang *et al.*, 2016). Studies in children have shown obese or overweight children perform worse than their normal weight peers in both fine and gross motor skills (Mond *et al.*, 2007; D'Hondt *et al.*, 2008; Gentier *et al.*, 2013). The argument for poor motor coordination potentially being a predictor of future obesity suggested by Gentier et al (2013) and D'Hondt et al (2008) is strengthened by two longitudinal studies (Chandola *et al.*, 2006; Osika and Montgomery, 2008). The first was carried out by Osika and Montgomery (2008) found that teachers assessment of poor coordination at age 7, and standardized motor coordination tests at age 11 predicted obesity at age 33 even when correcting for a range of factors such as gender and social class. Chandola, Deary, Blane and Batty (2006) found that lower IQ scores in childhood were associated with obesity and weight gain in adulthood. These findings suggest that should children underperform at a young age, this could lead to detrimental effects persisting throughout adulthood.

In adults, a number of early studies that have examined the relationship between cognitive performance and obesity failed to control for factors such as diabetes, cholesterol and smoking (Sørensen *et al.*, 1982; Kilander *et al.*, 1997). Since then several studies have found negative relationships between BMI and multiple cognitive domains in adults such as attention, memory, numeracy, executive function and motor control (Liang *et al.*, 2014b; Prickett, Brennan and Stolwyk, 2014). A number of studies have also used imaging techniques to find a negative association between BMI and brain activity and structure suggesting decline in cognitive performance (Taki *et al.*, 2008; Volkow *et al.*, 2009). A study that investigated the relationship between obesity and cognitive function on the participants of the Framingham heart study found adverse effects on cognitive function in obese participants and suggested that earlier onset and long term obesity could adversely effect later cognitive performance (Elias *et al.*, 2003). In adults, research has found increased BMI and BP to be associated with impaired manual dexterity and reduced motor speed (Waldstein and Katzel, 2006). Further to this, a study by Fedor and Gunstad (2013) examined the cognitive function in high level collegiate athletes, some of who's BMI were overweight or obese. Interestingly, it was found that higher BMI was associated with reduced cognitive function, even in the sample expected to have good cardiovascular fitness levels (Fedor and Gunstad, 2013). Of more interest is that, visual motor speed was one of the composites of cognitive function that was found to be significantly negatively associated with higher BMI. This would further support the rationale that obesity influences the sensory integration process rather than solely being a mechanical constraint.

This study aims to specifically investigate the sensory integration process during a visual motor task and whether obesity interacts with it. This study used visual cueing as vision is the dominant sensory modality during many daily living activities (Armstrong *et al.*, 2013). As such, this allowed us to investigate the potential impact of visual motor coordination difficulties in everyday life of obese individuals. To do so, this study utilised a pendulum based paradigm as it has been extensively used in motor control research over the past 20 years to ensure reproducibility(Schmidt *et al.*, 2007; Armstrong *et al.*, 2013). This allowed us to compare performance output between studies assessing normal participants and participants with motor difficulties such as schizophrenia and autism (Isenhower *et al.*, 2012; Varlet, Marin, Raffard, *et al.*, 2012). We hypothesize that obese individuals coordination during a visual rhythmic motor task would be inferior compared to their normal weighted peers. This would lead to the potential for a neuromuscular component previously not accounted for in obesity research currently.

5.2 Methods

5.2.1 Subjects

Forty-four right-handed obese patients and 44 age- and gender-matched controls participated in this study. The obese participants attended the Weight Management Service, an outpatient-based lifestyle-intervention weight management program designed to promote weight management through dietary changes and increased physical activity in St Columcilles Hospital Loughlinstown, Co Dublin, Ireland. All patients had a BMI >40.0 in order to be admitted into the program. Prior to recruitment all participants were screened for any comorbid condition or medication deemed to potentially influence performance. As such patients suffering from diabetic retinopathy, poor vision or had laser eye surgery, osteoarthritis, injury/chronic pain of the right arm, untreated hypothyroidism, stroke, peripheral neuropathy or receiving antipsychotic medication were excluded from the study. A number of participants had OSA (N=18) and T2DM (N=13). All participants were also screened for colour blindness using the Ishihara Test of Colour Blindness short form. All participants had their height, weight and date of birth recorded prior to the assessment. Height was measured to the nearest 0.1cm while standing barefoot using a portable stadiometer (Leicester Height Measure).

Body weight was measured using a mechanical weighing scale (Seca Mechanical Weight Scales Model 761) and corrected to the nearest 0.5kg **(Table 5.1).**

5.2.2 Procedure

This task involved a visual motor coordination task where the participant synchronised his movement with a computer generated stimuli using a hand-held pendulum (Armstrong and Issartel, 2014). Participants sat in a bariatric chair and placed their right arm in a forearm support. The visual stimuli were presented on a screen (Dell Trinitron Ultrascan 1600HS Series CRT Monitor, Model D1626HT) placed 1 meter from the participant at eye level. The visual stimuli consisted of a square (5.2cm x 5.2cm) that faded from red to yellow while oscillating horizontally across the screen on a grey background in a sinusoidal manner with an amplitude of 28cm. The experiment was controlled and run through Matlab using a Graphical User Interface as part of a Psychophysics Toolbox Extension (Kleiner, Brainard and Pelli, 2007). Participants were asked to swing the pendulum forward as the square moved left and backward as the square moved right on the screen synchronizing the endpoint of the movements with the square's endpoints **(Figure 5.1).** Participants were prevented from viewing the pendulum's movements and their forearm by a wooden cover and a cloth curtain.

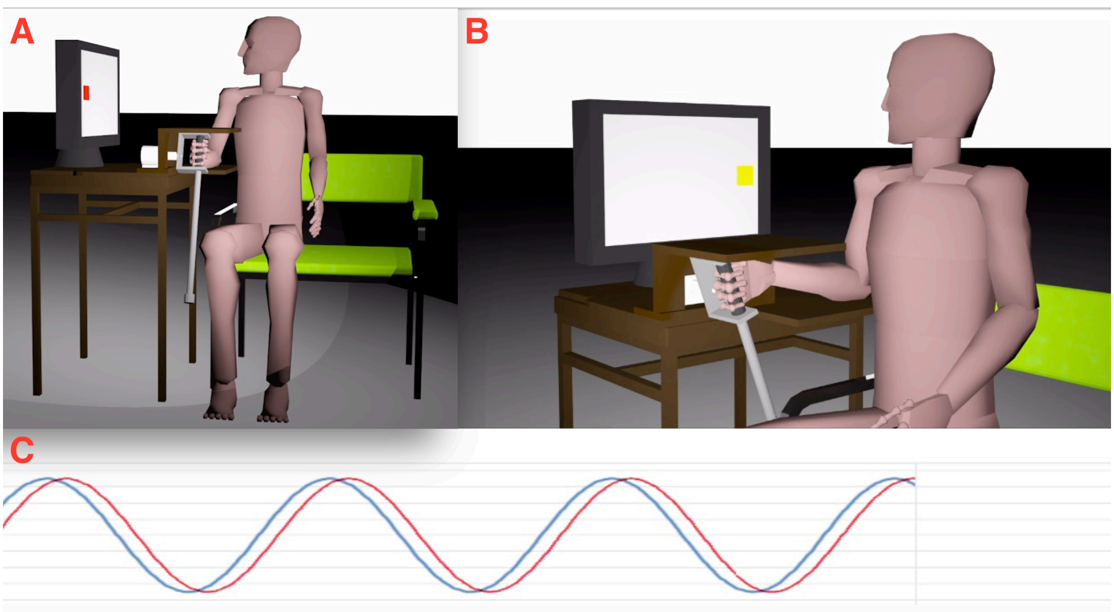

FIGURE 5.1: EXPERIMENTAL SET UP. PARTICIPANTS SAT IN A BARIATRIC CHAIR AND WERE ASKED TO SWING THE PENDULUM FORWARD AS THE SQUARE MOVED LEFT AND FADED TO A RED COLOUR (A) AND BACKWARD AS THE SQUARE MOVED RIGHT ON THE SCREEN FADING TO A YELLOW COLOUR (B) SYNCHRONIZING THE ENDPOINT OF THE MOVEMENTS WITH THE SQUARE'S ENDPOINTS. FROM THE RESTING

POSITION OF THE PENDULUM, PARTICIPANTS SWANG THE PENDULUM TO A 45° ANGLE TO THE LEFT AND A 45° ANGLE TO THE RIGHT. C) PARTICIPANTS' PENDULUM POSITION WAS RECORDED USING A POTENTIOMETER AND COMPARED WITH THE COMPUTER GENERATED STIMULUS (CF. PROCEDURE SECTION).

The experiment consisted of three phases: 1) preferred frequency calculation 2) familiarisation and 3) experimentation. For the preferred frequency calculation participants were instructed to swing the pendulum in a dark room for two minutes at a pace that was 'most comfortable' for them which they could swing at "all day long" (Schmidt *et al.*, 2007). From this, the frequency for the -20% and +20% conditions were calculated. During familiarisation, each subject carried out one practice trial for each of the 3 experimental conditions. The participants received additional presentations of the stimuli if required to ensure understanding of the different experimental conditions.

5.2.3 Experimentation

Following familiarisation phase, subjects carried out 2 blocks of experimentation. One block of the experiment consisted of 3 frequencies (Preferred, +20% and -20%) being played in a randomised order. Participants completed one trial of each of the 3 randomised conditions for each of the 2 blocks. There was a 30 second break after each 40 second trial and a 2- minute break between blocks to prevent fatigue.

5.2.4 Data Reduction

All data was recorded at 100Hz using a Measurement Computing Data Acquisition Device (measurement computing USB-1608FS) for analysis. The degree of coordination between the participant and the stimulus was assessed using continuous relative phase (CRP)(See Figure 5.1C). CRP was calculated using a Hilbert Transform and scaled between 0° (indicating perfect synchrony) and 180° (complete opposite). These two stable states are referred to as in phase or anti phase. For this type of task, it is important to note that that participants' coordination naturally attract to either of these states. The first 10 seconds and last cycle of each trial were removed in order to eliminate distortions caused by Hilbert Transform on the computation. The variability of coordination was assessed using the standard deviation (SD) of CRP calculated from the CRP values. Participants movement amplitude for each trial was also measured. All data was averaged across each of the trials for the 3 experimental conditions.

5.2.5 Statistical Analysis

All statistical analysis was performed using SPSS (IBM SPSS Statistics 19). Independent samples t-tests were carried out to investigate any potential influence of OSA and T2DM on performance. A 3 x 2 x 2 repeated measures ANOVA on CRP, SD CRP, Amplitude and CRP Timing was carried out to examine the influence of Frequency, Weight Group and Gender on visual motor coordination. Sphericity was assessed and the Greenhouse and Geisser's correction for degrees of freedom were applied when sphericity was not met. Post hoc analysis using the Bonferroni correction was carried out.

5.3 Results

TABLE 5.1: TABLE OF ANTHROPOMETRIC MEASURES (MEAN ±STANDARD DEVIATION) FOR AGE, HEIGHT, WEIGHT AND BMI OF PARTICIPANTS DIVIDED BY GROUP.

	Age (years)	Height (m)	Weight (kg)	BMI (kg/m^2)
Normal Weight	45.93 ±10.39	1.71 ±0.12	64.26 ±13.22	22.16 ±1.78
Obese	46.39 ±10.69	1.72 ±0.13	153.84 ±35.19	51.93 ±8.98

Independent samples t-tests revealed no significant difference between subject's effects for OSA and T2DM on each of the variables used.

5.3.1 Continuous Relative Phase (CRP)

There was no significant main effect for frequency $F(1.84, 154.58)=3.12$, $p>0.05$. There was a significant weight group X gender interaction effect $F(1, 84)=4.02$, $p<0.05$. Post hoc tests revealed that CRP scores for the male and female obese group (52.06 and 32.25, 95% CI [42.35, 61.76], [23.39, 41.12] respectively) differed significantly from those of the control group (15.79 and 14.72, 95% CI [6.08, 25.50], [5.86, 23.58]) respectively.

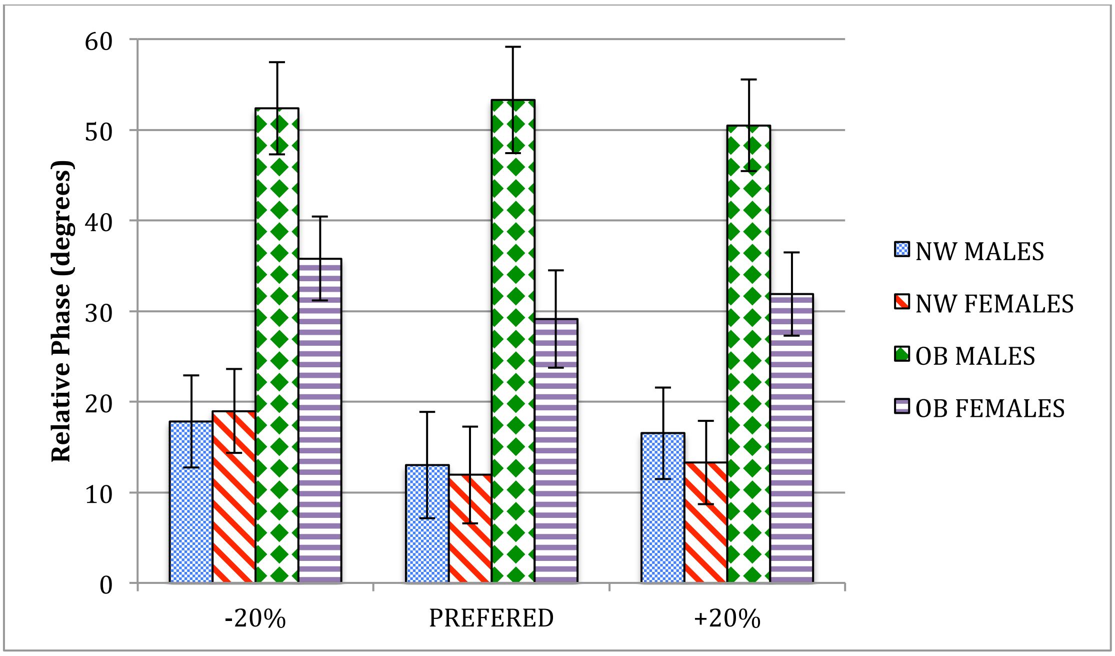

FIGURE 5.2: MEAN CONTINUOUS RELATIVE PHASE (CRP) VALUES SHOWN FOR NORMAL WEIGHT (NW) AND OBESE (OB) PARTICIPANTS DIVIDED BY GENDER FOR ALL 3 FREQUENCY CONDITIONS (-20%, PREFERRED FREQUENCY AND +20%).

5.3.2 Standard Deviation of CRP:

The gender x frequency x weight group ANOVA on SD CRP did not reveal any significant interaction effects. There was a significant main effect found for Group F(1, 84)=283.58, $p<0.01$ with OB group (M=22.16 SD=14.04, 95% CI [19.63, 25.10]) demonstrating significantly more variable coordination compared to the NW group (M=10.36, SD=4.83, 95% CI [7.67, 13.14]). There was a significant main effect for frequency F(1.8, 151.28)=3.38, $p<0.05$. Post hoc tests revealed that participants had significantly more variable coordination, F(1,84)=4.21, $p<0.05$ for the -20% condition (M= 16.64, SD=11.63, 95% CI [14.54, 18.83]) compared to preferred frequency condition (M=14.82, SD= 11.91, 95% CI [12.75, 17.16]). There was no significant main effect found for gender (F(1,84)=1.89, $p>0.05$).

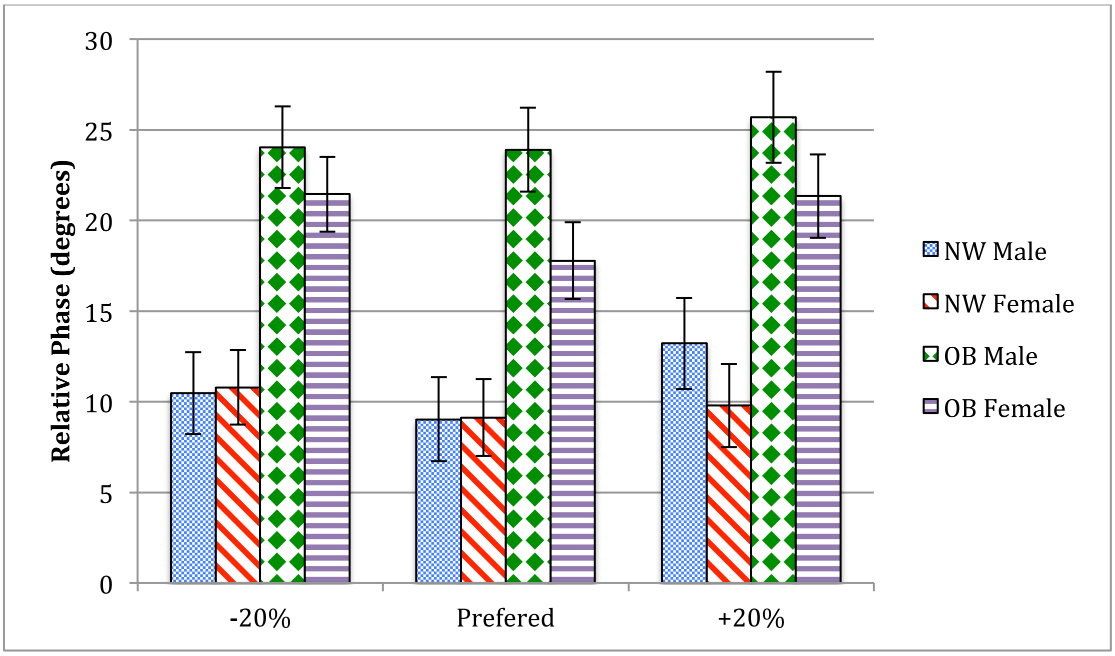

FIGURE 5.3: MEAN STANDARD DEVIATION VALUES SHOWN FOR NORMAL WEIGHT (NW) AND OBESE (OB) PARTICIPANTS BY GENDER FOR EACH FREQUENCY (-20%, PREFERRED FREQUENCY AND +20%).

5.3.3 Amplitude:

There were no significant interaction effects between Gender, Frequency or Weight Group found for participant's amplitude. There was a main effect found for Weight Group $F(1,84)=10.69$ $p<0.01$ with the obese group being found to swing the pendulum with 24% greater amplitude (M=61.04, SD=17.57, 95% CI [55.34, 65.50]) compared to the control group (M=49.29, SD=20.40, 95% CI [43.53, 53.68]). There was also a significant main effect for Gender, $F(1,84)=15.71$ $p<0.01$ with females swinging the pendulum over a 30% greater amplitude (M=61.68, SD=18.41, 95% CI [56.83, 66.52]) compared to male participants (M=47.36, SD=18.77, 95% CI [42.05, 52.66]). There was a significant main effect found for frequency, $F(1.75, 146.61)=11.42$, $p<0.01$. Contrasts carried out revealed that participants swung the pendulum at a significantly greater amplitude, $F(1,84)=25.40$ $p<0.01$, for -20% conditions (M=52.29, SD=18.58, 95% CI [48.11, 55.44]) compared to preferred speed conditions (M=57.48, SD=20.89, 95% CI [52.83, 60.66]).

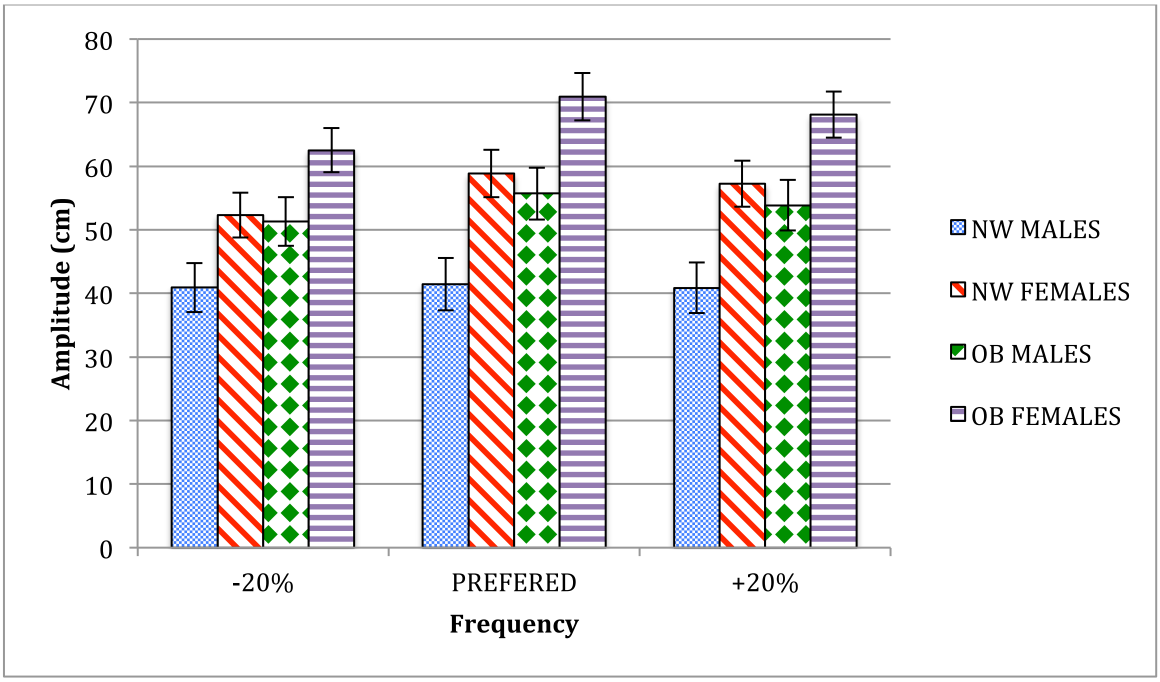

FIGURE 5.4: MEAN AMPLITUDE VALUES OVER WHICH PARTICIPANTS SWUNG THE PENDULUM SHOWN FOR NORMAL WEIGHT (NW) AND OBESE (OB) PARTICIPANTS DIVIDED BY GENDER FOR ALL 3 FREQUENCY CONDITIONS (-20%, PREFERRED FREQUENCY AND +20%).

5.3.4 Standard Deviation of Amplitude

There were no significant interaction effects between Gender, Frequency or Weight Group found for SD of participant's amplitude. There was no significant effect found for Frequency ($F(1.83, 153.36)=1.69$, $p>0.05$). There was a significant main effect for Weight Group $F(1,84)=19.25$, $p<0.01$ with obese participants demonstrating higher variability in their amplitude (M= 6.93, SD=3.88, 95% CI [6.11, 7.61]) when compared to normal weight controls (M=4.57, SD=2.73, 95% CI [3.76, 5.26]). There was also a significant main effect found for Gender $F(1,84)=6.79$, $p<0.05$. Further investigation found that female participants demonstrated more variable amplitude (M=6.38, SD=3.76, 95% CI [5.67, 7.10]) compared to males (M=4.99, SD=3.15, 95% CI [4.20, 5.77])

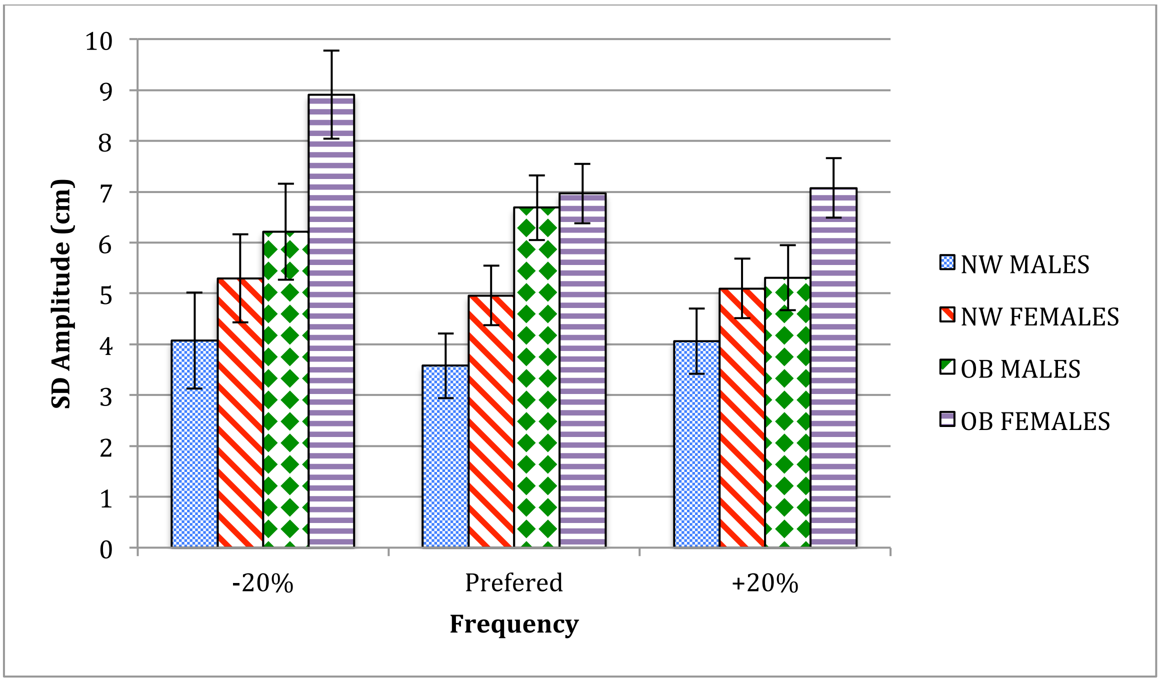

FIGURE 5.5: MEAN STANDARD DEVIATION OF AMPLITUDE SHOWN FOR NORMAL WEIGHT (NW) AND OBESE (OB) PARTICIPANTS DIVIDED BY GENDER FOR ALL 3 FREQUENCY CONDITIONS (-20%, PREFERRED FREQUENCY AND +20%). GREATER VALUES IMPLY A GREATER DEGREE OF VARIABILITY IN THE AMPLITUDE THAT PARTICIPANT SWUNG.

5.4 Discussion

We found that obese participants demonstrated lower and more variable coordination levels with greater amplitude of movements than their normal weight peers. As this experimental paradigm controls the mechanical and environmental factors that frequently influence motor behaviours of individuals, this leads us to question the source of these differences. One potential hypothesis is that that these differences result from problems with the underlying perception and integration of sensory information that govern the movement process.

The values for CRP obtained for the obese group were significantly higher than the normal weight group whose performance coincide with values found in previous research (Armstrong and Issartel, 2014). This finding indicates that obese subjects had greater difficulty in synchronizing their movements and maintaining their synchrony with the stimulus (Figure 5.2). The obese group also demonstrated significantly higher values for SD CRP indicating more variable coordination (Figure 5.3). This unstable pattern of coordination is a demonstration of their need to constantly readjust their coordination with the stimulus. It is important to note that usual performance values, for pendulum task, are around 20° (Schmidt *et al.*, 2007). Hence, such a task is considered as quite simple with performance-ceiling values reached after 2-3 familiarisation trials. We can then expect a direct transfer of this low performance level on their ability to coordinate movement during everyday life activities such as brushing ones' hair or using utensils to eat directly affecting individual's quality of life. In addition, visuo-spatial coordination is a vital component of more complex forms of movement such as those involved in many forms of physical activity, sports participation or while driving a car. In addition to this, movement tasks that also require increased cognitive load such as decision-making, would be an additional demand on the sensory integration process underlying movement and further increase the task difficulty for these individuals. This could prove to be an additional barrier to participation in many forms of physical activity.

In terms of movement amplitude, the obese group also demonstrated greater (Figure 5.4) and more variable (Figure 5.5) amplitude of movement compared to their normal weight counterparts. In addition, the increased variability of the amplitude for the obese group also reveals the control of the pendulum swing is reduced. The lack of consistency in repetitive task reveals that the task difficulty for the obese group is higher in comparison with the normal weight group. The movement patterns stability is an indicator of the control a person has in continuous repetitive situations. The support of the forearm and natural frequency of the pendulum (which requires little force to drive) during the experiment could be seen to remove any biomechanical influence of musculature or mass of the arm. This finding suggests that obese individuals may employ a slightly different coordinative strategy to synchronize their movements with the stimulus compared to normal weight individuals. It could be the case that obese individuals alter the amplitude over which they swing to help maintain a similar angular velocity as a compensatory measure to aid synchrony with stimulus. This finding suggests that obese individuals employ different behavioural strategies in the coordination of movement to overcome barriers experienced during the task.

The significant effects found for frequency for measures of variability of coordination and amplitude of movement for both obese and normal weight groups are also in line with previous research on normal population (Armstrong and Issartel, 2014). As expected, the -20% condition is more difficult to synchronize when compared to other preferred frequencies or +20%. This is likely the result of a greater control being needed when swinging at a tempo below the eigenfrequency of the pendulum or their preferred tempo. However, the group differences observed suggests that the obese groups performance is consistently poorer than their normal weight peers regardless of the task difficulty. Surprisingly, we also found a gender differences in terms of the amplitude and variability of amplitude. This unexpected and interesting finding is new and rarely found in coordination-based experiments. However, as a gender vs. weight group interaction effect was found for CRP, this has led us to tentatively suggest that there may also be differences in the strategies men and women use to coordinate. However, as there is very little evidence demonstrating gender differences in coordination-based literature at present, it potentially could be the result of differences in the proprioception ability or muscle mass between males and females that is influenced by obesity. The coordination of movement (identification of stimulus, and coordinated movement patterns in response to stimulus) is a vital part of the successful completion of many activities of daily living in addition to the engagement in physical activity. As such, difficulties in the integration of sensory information to aid coordination could lead to a vicious cycle of inactivity. At present, obese individuals everyday activities are often impeded due to mechanical constraints of excess mass. These visuo-spatial difficulties demonstrated in this article can be seen as an additional barrier, which obese individuals are faced to deal with on a daily basis. The present study adds substantial weight to the hypothesis that the sensory integration process is affected by obesity. However, it is currently unclear how obesity influences this process or whether the difficulties result from problems in the perception, programming or initiation stage of movement. Future studies may be able to address whether these difficulties are as a result of the differences in the attentional process or gaze strategies employed by normal weight and obese groups through the use of eye tracking software. In addition to this, future studies could ensure subjects swing in the frontal plane with the stimulus presented directly in front of them to eliminate any additional attentional demand placed on subjects as a result of being required to turn their head. In the current study we sought to specifically examine the sensory integration process of a visual motor task while controlling for the mechanical constraints associated with obesity.

The presence of differences between groups suggests variation in both ability and quality movement control mechanism as a result of obesity. This dissimilarity supports the findings of previous studies suggesting the existence of sensory integration deficiencies between obese and normal weight subjects (Petrolini, Iughetti and Bernasconi, 1995; Bernard *et al.*, 2003; D'Hondt *et al.*, 2008; Gentier *et al.*, 2013; Scarpina *et al.*, 2016). It remains to be seen if these sensory integration problems exist prior to obesity and can be seen as a contributing factor to becoming obese or whether the development of obesity leads to detrimental consequences for the sensory integration process. In order to answer this question, future research needs to be carried out on children to see if these difficulties emerge over time or whether they exist prior to obesity rather than as a consequence. If these sensory integration difficulties exist prior to and/or as an additional contributing factor to becoming obese, it could allow for the development of targeted interventions to help tackle these difficulties to avoid individuals descending into a downward spiral of physical inactivity as a result of coordination difficulties. Alternatively, this opens the door to questions on whether this sensory integration difficulties is a consequence of the various physiological changes which occur due to obesity i.e. altered neurotransmitter function, hormonal changes or nerve signalling (Wang *et al.*, 2016). One such hypothesis set out by Scarpina et al (2016) tentatively suggests that differences in sensory integration between obese and normal weight controls could result from the influence of increased levels of pro-inflammatory cytokines on the excitation/inhibition balance that regulates neural oscillatory activity. Whatever the source of these differences, the sensory integration of information is a complex phenomenon that emerges as a result of the influence of all the elements within an individual and from the environment around them. As such it is likely that distorted neurotransmitter function, hormonal imbalances and altered nerve signalling, as a result of increased adiposity, could all contribute to impaired sensory integration process. A final consideration is the influence of subclinical cognitive impairment such as altered executive function, attention or visuo-spatial performance. Evidence exists to suggest obesity influences neurocognitive function in adults (Liang *et al.*, 2014b). Future studies are merited in order to investigate the relationship between obesity, motor control and neurocognitive functions.

In conclusion, this study suggested visual motor coordination is impaired for obese patients. This finding raises numerous questions in relation to the etiology of these problems, the extent to which these differences influence an individual's life and whether these problems can be remedied or alleviated. Similarly, as we live in a multisensory environment, future studies are also merited to investigate the influence of obesity on multisensory integration process.

5.5 Ethics:

Ethical approval was granted by Dublin City University Research Ethics Committee (DCUREC/2011/038). Prior to commencement of the research study, informed consent from participants was obtained.

5.6 Acknowledgements:

This research was carried out through funding granted by the Irish Research Council (GOIPG/2014/1516).

5.7 Link between Chapter 5 and Chapter 6

Chapter 5 sought to examine the role which obesity plays in the sensory integration process during a visual manual coordination task using a handheld pendulum. The results demonstrated that obese adults exhibit significantly altered visual motor coordination compared to lean weight controls. Interestingly, obese adults demonstrated poorer performance than those found in children in Chapter 4. This finding demonstrates a marked contribution to the existing literature outlining the impact of obesity on normal sensory integration. This prompts us to question how these sensory integration difficulties influence obese individuals performance of many activities of daily living.

The ability or control the speed and accuracy of reaching are a key feature of many activities of daily living. Chapter 6 aims to explore the effect of obesity on the ability to coordinate the speed and accuracy of a manual aiming task. Secondly we sought to examine whether increased postural demands, as a result of a manipulation of target orientation, would increase task difficulty and amplify group differences between obese, overweight and normal weight groups. It was hypothesised that obese individuals would demonstrate difficulties in the ability to effectively coordinate speed and accuracy of movements and subsequently display increased movement time and movement variability in a discrete Fitt's task experimental paradigm.

Chapter 6: "It's not what you do its the way that you do it": The influence of obesity on the speed and accuracy of a discrete aiming task.

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Abstract

The ability to control speed and accuracy of goal directed aiming tasks underpins many activities of daily living. Recent evidence has begun to suggest that obesity can influence the control of movement (D'Hondt *et al.*, 2008; Gaul *et al.*, 2016). This study evaluated motor performance and movement kinematics of 183 normal weight, overweight and obese participants using a discrete Fitt's task on a digital tablet. In addition, tablet orientation was manipulated in an attempt to modify postural demands and thus task difficult. Results demonstrated the traditional relationship between target distance and target width in both tablet orientations for all weight groups. Interestingly, no significant differences were found for movement time between the groups, while movement kinematics differed between weight groups. Obese participants demonstrated significantly higher peak acceleration values in the horizontal tablet orientation when compared to their normal weight and overweight counterparts. Further to this, obese participants made significantly more errors than normal weight and overweight groups. These findings suggest that obese individuals have altered control strategies compared to their normal weight peers.

6.1 Introduction

Obesity is a major public health concern which is linked with increased risk of cardiovascular disease, stroke, cancer, non-insulin-dependent (type II) diabetes mellitus, hypertension, depression and obstructive sleep apnoea (Lee *et al.*, 2012). Overweight (OW) and obesity levels have reached epidemic levels. According to World Health Organization (WHO) figures from 2014, 39% of men and 40% of women aged 18+ were OW (Body Mass Index (BMI) >25kg/m^2) and 11% of men and 15% of women being OB (BMI >30kg/m^2) (World Health Organization, 2014). This equates to almost 2.5 billion adults being OW or obese (OB) worldwide. The rate of growth is another concern with the prevalence of obesity growing worldwide from 3% and 6% in men and women respectively in 1975 to 11% in men and 15% in women in 2014 (World Health Organization, 2014).

Traditionally obesity has been "considered a problem of the belly rather than of the brain" (Knecht, Ellger and Levine, 2008). More recently however, there has been mounting evidence suggesting a relationship between obesity and cognitive function (Benito-Leon *et al.*, 2013; Miller and Spencer, 2014; Prickett, Brennan and Stolwyk, 2014; Bove *et al.*, 2016). Multiple studies have found differences in variety of facets of cognitive function such as visuospatial skill, memory, and attention, mathematical ability and motor skill, throughout the lifespan (Liang *et al.*, 2014a; Prickett, Brennan and Stolwyk, 2014; Wang *et al.*, 2016). A number of studies have found altered sensory integration in OB individuals (D'Hondt, Deforche, De Bourdeaudhuij, *et al.*, 2011; Gentier *et al.*, 2013; Wan *et al.*, 2014; Gaul *et al.*, 2016; Scarpina *et al.*, 2016). A recent study by Gaul et al. (2016) suggested that obesity affects the sensory integration process in a motor task. This study found morbidly OB adults demonstrated significantly poorer performance during a visual motor synchronisation task when compared to a healthy weight control group (Gaul *et al.*, 2016).

Perhaps the greatest evidence seems to support the argument for obesity altering typical cognitive processes exists in terms of executive function. Executive function is generally defined as the "higher level or "meta-cognitive" function that manages other more basic cognitive functions in relation to goal directed behaviour (Etnier and Chang, 2009). As such, executive function is frequently considered as consisting of activities such as the planning, coordination, initiation and stopping of behaviours and the processing of information related to them (Kramer *et al.*, 1994; Alvarez and Emory, 2006). To date, a variety of measures have been used to measure executive function including Stroop Colour Word Test, Go–No–Go, Trail-Making and Tower of London tasks (Allan, Johnston and Campbell, 2011). Schwartz and colleagues (2013) found that a larger volume of visceral fat was associated with lower performance on tests of executive function in a sample of 983 adolescents. Lokken, Boeka, Austin, Gunstad and Harmon (2009) also found poorer executive function in a smaller sample (N=25) of extremely OB (BMI > 99^{th} percentile) adolescents who were seeking treatment.

The effect of an elevated BMI and/or increased fat mass has also been observed in studies of adults in addition to in children and adolescents. Boeka and Lokken (2008) also found significant differences between extremely OB (BMI>40) adults in measures of executive function such as planning, problem solving and mental flexibility when compared to normative data. Similarly, Gunstad, Paul, Cohen, Tate, Spitznagel and Gordon (2007) also found that elevated BMI in OW and OB adults resulted in poorer executive function when compared to NW counterparts. Worryingly, a number of longitudinal studies have found associations between midlife obesity and risk for poor neurocognitive and executive function have been reported (Cournot et al., 2006; Fitzpatrick et al., 2009; Gunstad et al., 2010; Gustafson, 2008; Kivipelto et al., 2005; Whitmer et al., 2005, 2008). Cournot et al. (2006) found that higher baseline BMI is associated with greater cognitive decline over 5 years in areas of selective attention, memory and executive function. Futher to this, Gunstad and colleagues (2010) suggested that higher body composition at baseline is associated with a greater decline in general cognitive and executive function over time. This has led to body composition being considered as a risk factor for the future development of neurodegenerative diseases such as Alzheimer's Disease (AD) and Dementia (Kivipelto *et al.*, 2005; Whitmer *et al.*, 2005; Beydoun, Beydoun and Wang, 2008; Crichton *et al.*, 2012). However, there is currently insufficient evidence to determine whether poor executive function contributes to excess weight gain or whether obesity causes this reduced executive function (Lokken *et al.*, 2009; Bove *et al.*, 2016). Regardless whether cause or affect, the extent to which reduced cognitive function in overweight and OB individuals impacts on their everyday remains to be seen.

The successful completion of reaching and grasping actions is a part of an individual's daily life. These actions require the ability to appropriately coordinate the speed and accuracy of an individual's movement. This trade-off between movement speed and accuracy is known as 'Fitts' law', which is defined by a linear increase of movement time with the increased difficulty of an aiming task (Fitts, 1954, see Meyer, et al., 1988 and Plamondon & Alimi, 1997, for reviews). As such, difficulties in the integration and performance of goal directed reaching tasks could impair the effective performance of many activities of daily living such as brushing ones hair, feeding oneself or picking up items (Kirby, Edwards and Sugden, 2011). As obesity is already known to negatively impact an individual's quality of life and influence performance of activities of daily living (ADL) as a result of the mechanical consequence of excess weight, any such motor control difficulties could increase the difficulty of everyday tasks (Rosmond and Bjorntorp, 2000). This study employed a discrete version of the Fitts' task in order to measure the "pure movement" execution rather than the inherited error from the previous movement in the reciprocal Fitts' task using a digital tablet (Guiard and Olafsdottir, 2011). The authors sought to examine whether individuals with different BMI categories (NW, OW and OB) demonstrated differences in terms of speed and accuracy as well as on the kinematics organization of movement during an aiming task. A secondary addressed question was to determine whether manipulation of tablet orientation altered task difficulty and subsequently highlighted any between group differences that might exist due to altered BMI.

6.2 Methods

6.2.1 Participants

A total of 183 adult participants (see Table 1) with full data sets were included in this study as part of an interactive exhibition at a science gallery. Participants were screened in advance with a questionnaire and were included if they were free from any health implications which could impair their performance in the task. As such, all participants had normal or corrected vision, were free from injury/chronic pain of the hand, arm or shoulder and weren't receiving any medication that may cause drowsiness. All participants had their height, weight and body fat measured and BMI calculated prior to participation. This data was used to divide participants into groups based on their Body Mass Index (kg/m^2)(BMI) according to the criteria set by the WHO (WHO, 2000).

6.2.2 Apparatus and Task

Participants were seated comfortably at a table, facing a graphics tablet (Wacom Ultra Pad A3) placed in both horizontally and vertical positions mounted on a custom rotating stand on the table in front of them. Left-right motion of a hand-held stylus displaced a cursor on the tablet screen via ICE software developed by Marseille University Lab. The task was to move the cursor, represented by a red vertical line spanning the full height of the tablet, between two targets depicted on the screen as fast and as accurately as possible (i.e. Fitts' task). The target was a rectangle of a given width at a given distance (depending on the Index of Difficulty (ID)) with a height corresponding to the height of the screen. Movement was recorded along both horizontal and vertical axis; analysis focused solely on movement along the X-axis. The position of the stylus on the graphics tablet was sampled at a frequency of 150 Hz.

6.2.3 Recordings and Procedure

A session consisted of 64 discrete aiming movements from one target to the other in 2 different orientations (32 Horizontal and 32 Vertical). A total of 4 separate experimental conditions, made up of a combination of 2 different target width (Small and Large) and two distances (Close and Far). Small and Large target conditions corresponded respectively to 0.8 cm and 3 cm targets' width. Close and Far targets corresponded respectively to 15 and 40 cm distances between centres of the targets. This led to participants performing at four levels of task difficulty: ID = 3.32, 4.73, 5.23 and 6.64 with $ID = \log_2 (2D/W)$ (Fitts, 1954). During the experiment, the participants carried out the 4 Blocks of 8 trials (4 conditions x 2 repetitions) in both Horizontal and Vertical orientations. As such, the experiment consisted of one testing session of the following design: 2 Tablet orientations X 4 Blocks X 4 Conditions X 2 repetitions of each condition. The order of trials was randomized across all blocks and the order of which orientation was displayed first was counterbalanced across all participants to remove any order effects. Errors were defined as an overshoot, i.e. movement beyond the external edge of the target outside area. In an event of an undershoot, the trial would continue until the cursor reached the target. A familiarization phase was included at the beginning of each block of trials with a different tablet orientation. This phase included participants being presented with one trial for each of the 4 conditions while receiving verbal instructions from the experiment moderator and on screen visual instruction. The first trial for each condition in each block in addition to all familiarization trials were not analysed to avoid transient behaviour in the analysis.

6.2.4 Data analysis

The position time series were filtered with a dual-pass, second-order Butterworth filter, using an 8 Hz cut off frequency. Velocity and acceleration were subsequently derived using a 3-point central difference technique. The analysis focused on movement time (MT, in sec), percentage of overshoot (in %), peak velocity (PV, in $m.s^{-1}$), peak acceleration (PA, in $m.s^{-2}$) and percentage of acceleration time (in %). The first two trials and last trial for each condition were removed from the analysis to eliminate any learning effects. For each session, measures were averaged across the remaining 5 trials for each of the 4 conditions. For each trial, movement time (MT) was defined as the time taken from movement initiation (when 5% of PV was reached) to entry of the opposite target (Missenard and Fernandez, 2011). Determining the number of trials that the participant moved beyond the external edge of the target and dividing it by total number of trials calculated percentage Overshoot.

6.2.5 Statistical analysis

Repeated-measures ANOVAs were performed between BMI categories (OB, OW and NW), Orientation (Vertical and Horizontal), Target Width (Small and Large) and Target Distance (Close and Far) as factors. Sphericity was assessed for each dependent variable and the Greenhouse–Geisser's correction was applied when sphericity was not met. Post hoc analysis using a Bonferroni correction was used in order to detail significant effects. Statistical significance was set a $p<0.05$.

TABLE 6.1: DESCRIPTIVE STATISTICS SHOWN FOR PARTICIPANTS DIVIDED BY WEIGHT CATEGORY.

	Normal Weight	Overweight	Obese	Total
N (% of Total)	107 (58.5%)	58 (31.7%)	18 (9.8%)	183 (100%)
Male/Female	37/70	33/25	7/11	77/106
Age ± SD (yrs)	34.18 ± 14.09	38.97 ± 14.42	41.72 ±16.55	36.44 ± 14.63
Weight ± SD (kg)	63.34 ± 8.17	79.90 ± 10.20	100.73 ± 16.81	72.26 ± 15.60
Height ± SD (cm)	170.56 ± 8.52	172.36 ± 10.12	170.94 ± 9.84	171.17 ± 9.17
BMI ± SD (kg/m^2)	21.72 ± 1.77	26.79 ± 1.36	34.34 ± 4.00	24.57 ± 4.44

6.3 Results

6.3.1 Movement Time

There was a significant interaction effect found between tablet orientation and target width, $F(1,180)=5.51$, $p<0.02$, $\eta_p^2=.014$. Post hoc tests revealed that participants' movement time was significantly greater for vertical orientation (M=. 83, SE=.04, 95% CI [.76, .91]) compared to in a horizontal orientation (M=.73, SE=.04, 95% CI [.67, .79]) when the target was small (Δ=13.7%). Post hoc tests also revealed significantly greater movement time for vertical orientation (M=.72, SE=.03, 95% CI [.66, .78]) compared to horizontal orientation (M=.66, SE=.03, 95% CI [.61, .72]) when the target was large (Δ=9.1%)(Figure 1). There was also a significant main effect found for target distance $F(1,180)=143.68$, $p<0.01$, $\eta_p^2=.25$, with all participants having greater movement times when the target was further away (M=.83, SE=.03, 95% CI [.76, .89]) compared to the closer target distance (M=.65, SE=.03, 95% CI [.60, .70]) There was no significant interaction effects found for BMI category and tablet orientation, width, or distance or any main effect found for BMI category, $F(2,180)=1.08$ $p>0.05$.

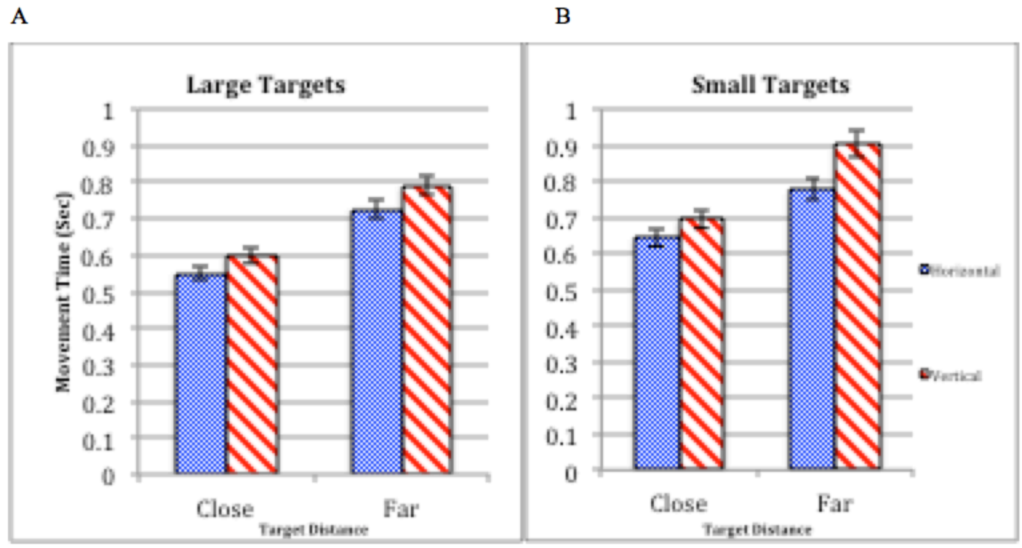

FIGURE 6.1: PARTICIPANT MOVEMENT TIMES FOR ALL 4 CONDITIONS DIVIDED BY HORIZONTAL AND VERTICAL TABLET ORIENTATIONS.

6.3.2 Peak Acceleration

There was a significant interaction effect found between orientation and BMI category, F(2,180)=3.63, p<0.05, η_p^2=.04. Post hoc tests revealed that the OB individuals had significantly higher values for horizontal conditions (M=624.73, SE=90.76, 95% CI [445.63, 803.82]) compared to vertical conditions (M=451.19, SE=88.87, 95% CI [275.83, 626.55]) (Δ=38.5%) when compared to their NW (M=499.57, SE=37.23 95% CI [426.12, 573.03] and M=530.12, SE=36.45, 95% CI [458.2, 602.04]) (Δ= -5.8%). and OW (M=499.35, SE=50.56 95% CI [399.58, 599.13] and M=486.89, SE=49.51 95% CI [389.2, 584.58]) peers (Δ= 2.6%) respectively (Figure 2). There were also significant interaction effects found between distance and orientation, F(1,180)=5.92, p<0.05, η_p^2 =.03. Following post hoc analysis it was revealed that there were significantly higher values for peak acceleration in horizontal orientation (M=696.43, SE=55.6, 95% CI [586.73, 806.14]) compared to vertical orientation (M=603.05, SE=53.07, 95% CI [498.32, 707.78]) when the targets where far away (Δ= 13.4%). There was also a significant main effect found for target width, F(1,180)=4.33, p<0.05, η_p^2=.02, with participants demonstrating greater peak acceleration values for large targets (M=522.21, SE=34.69, 95% CI [453.76, 590.66]) compared to smaller targets (M=508.41, SE=32.58, 95% CI [444.12, 572.71]).

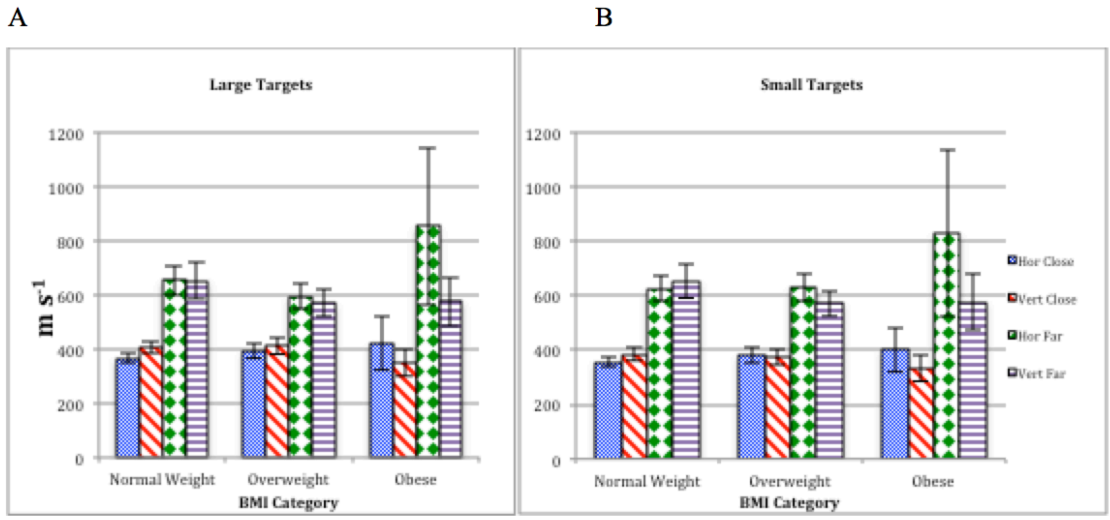

FIGURE 6.2: PEAK ACCELERATION VALUES SHOWN FOR NW, OW AND OB PARTICIPANT GROUPS WHEN THE TARGET WIDTH WAS LARGE (A) AND SMALL (B) IN BOTH HORIZONTAL AND VERTICAL CONDITIONS.

6.3.3 Peak Velocity

There was a significant interaction effect found between tablet orientation and target distance, F(1,180)=21.98, p<.01, η_p^2=.11. Post hoc tests revealed significantly higher peak velocities for the horizontal orientation (M=120.05, SE=4.58, 95% CI [111.02, 129.08] compared to vertical orientation (M=108.52, SE=4.41, 95% CI [99.82, 117.22]) when the target was further away (Figure 3). There was also a significant main effect found for target width, F(1,180)=21.49, p<0.01, η_p^2=.11, with higher peak velocities for large targets (M=86.37, SE=2.96, 95% CI [80.53, 92.21]) compared to small targets (M=84.35, SE=2.87, 95% CI [78.70, 90.01]). There was no significant interaction effect found for BMI category and tablet orientation, width or distance, or any main effect for BMI category on its own, F(2,180)=0.27, p>0.05.

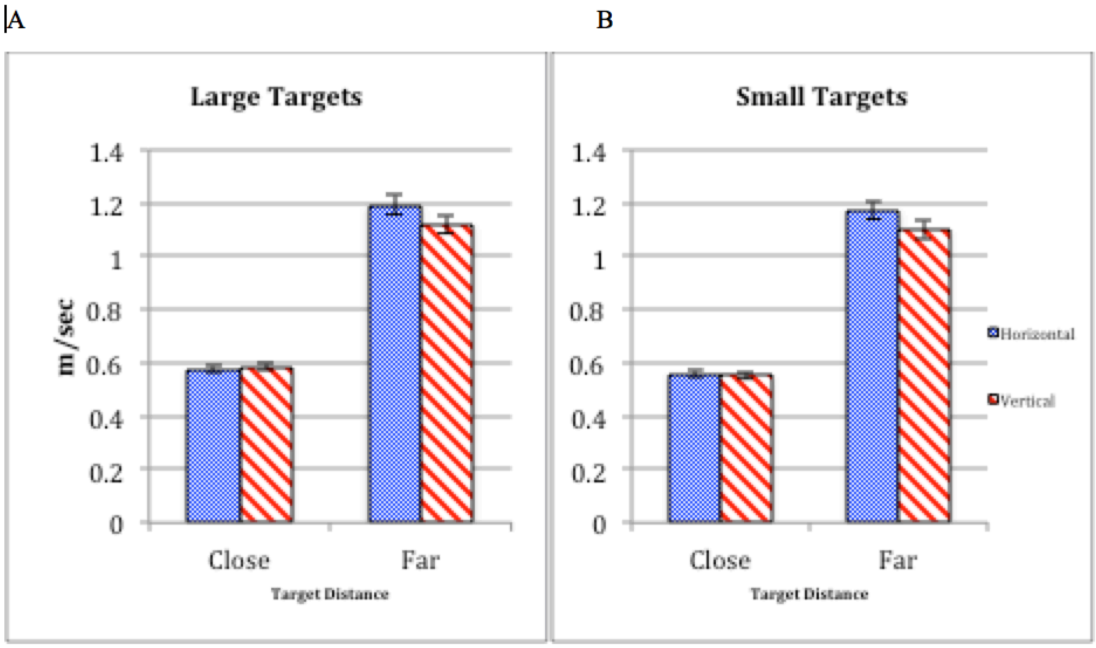

FIGURE 6.3: PEAK VELOCITY VALUES SHOWN FOR BOTH HORIZONTAL AND VERTICAL ORIENTATIONS WHEN THE TARGETS WERE CLOSE AND FAR WHEN THE TARGET WIDTH WAS LARGE (A) AND SMALL (B) IN BOTH HORIZONTAL AND VERTICAL CONDITIONS.

6.3.4 Percentage Acceleration

There was significant interaction between BMI category and target distance F(2,180)=3.85, p<0.05, η_p^2=.04. Post hoc tests showed that both NW and OW participants spent a significantly greater percentage of time accelerating in the conditions when the targets were further away (M=43.50%, SE=.57, 95% CI [42.37, 44.63] and M=45.38%, SE=.78 95% CI [43.84, 46.92]) compared to when they were close (M=42.20%, SE=.66 95% CI [40.89, 43.50] and M=42.11%, SE=.90, 95% CI [40.34, 43.88]) (Δ= 1.3% and 3.3%) (Figure 4). There was also a main effect found for width, F(1,180)=86.21, p<0.01, η_p^2=.3, with participants spending significantly great percentage of time accelerating when the target were large (M=44.26%, SE=.59, 95% CI [43.09, 45.42]) compared to when the target was small (M=41.59%, SE=.59, 95% CI [40.43, 42.76]). There was no significant interaction effect found between BMI category and Orientation. However, there was a trend for OB participants, F(2,180)=2.68, p=0.06, to spend less time in the acceleration phase while the tablet was in the vertical orientation (M=40.84%, SE=1.40, 95% CI [38.10, 43.58]) compared to when in the horizontal position (M=43.52%, SE=1.75, 95% CI [40.06, 46.98]) (Δ= 2.7%). This is in contrast to OW (M=44.27% and 43.23%) and NW (M=42.82% and M=42.87%) participants (Δ= -2.3% and Δ=0.1% respectively).

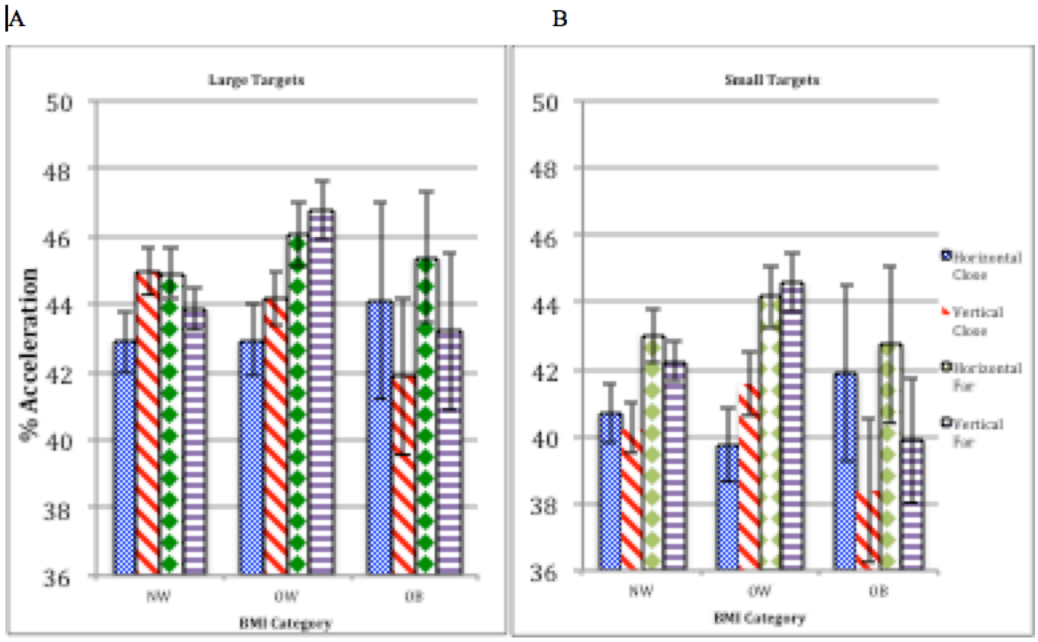

FIGURE 6.4: PERCENTAGE OF TIME SPENT IN ACCELERATION PHASE OF MOVEMENT SHOWN FOR NW, OW AND OB PARTICIPANT GROUPS WHEN THE TARGET WIDTH WAS LARGE (A) AND SMALL (B) IN BOTH HORIZONTAL AND VERTICAL CONDITIONS.

6.3.5 Overshoot

There was a significant interaction effect found between BMI category and target distance, F(2,180)=3.67, $p<0.05$, η_p^2=.04. Post hoc analysis revealed OB (M=13.33, SE=1.92, 95%CI [9.54, 17.13]) participants to overshoot the target a significantly higher number of times compared to NW (M=6.45, SE=0.79, 95%CI [4.89, 8.00]) and OW (M=6.21, SE=1.07, 95%CI [4.01, 8.32]) peers only when the target distance was further. There was a significant main effect found for target width, F(1,180)=178.02, $p<0.01$, η_p^2=.50. Participants made more errors when the target was small (M=16.68, SE=1.21 95% CI [14.30, 19.06]) compared to when the targets were large (M=1.74, SE=0.34, 95%CI [1.07, 2.42]).

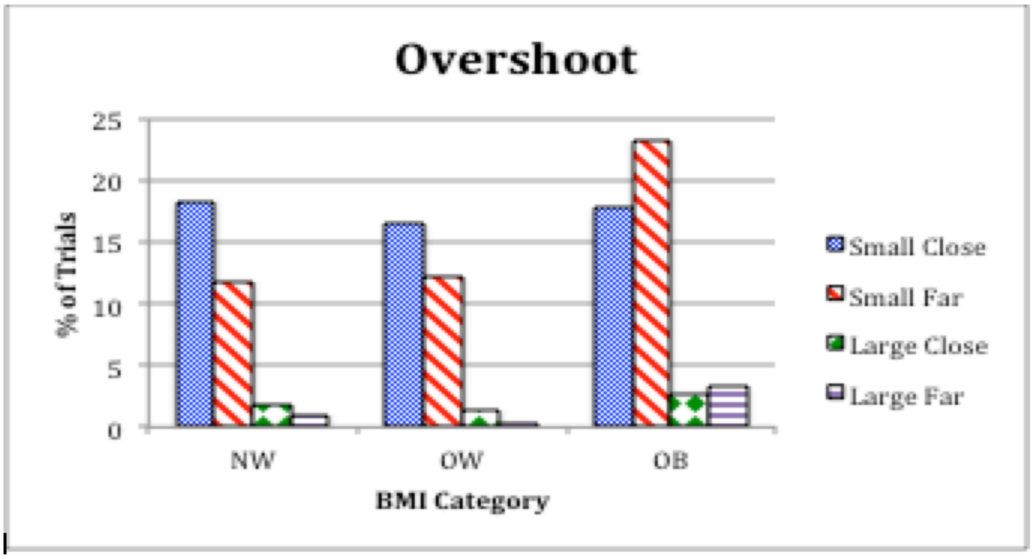

FIGURE 6.5: PERCENTAGE OF TRIALS THAT PARTICIPANTS OVERSHOT TARGET WIDTH SHOWN FOR NW, OW AND OB GROUPS FOR ALL 4 CONDITIONS

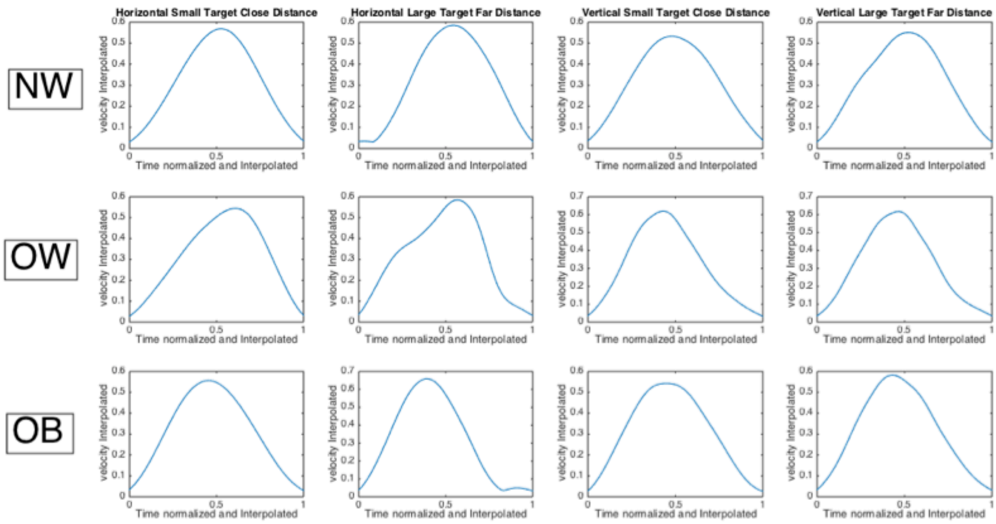

FIGURE 6.6: TYPICAL VELOCITY PROFILES SHOWN FOR NORMAL WEIGHT (NW), OVERWEIGHT (OW) AND OBESE (OB) GROUPS FOR SMALL TARGET CLOSE DISTANCE (COLUMN 1 AND 3) AND LARGE TARGET FAR DISTANCE (COLUMN 2 AND 4) IN HORIZONTAL (COLUMN 1 AND 2) AND VERTICAL ORIENTATIONS (COLUMN 3 AND 4).

6.4 Discussion

The results obtained in this study found that despite exhibiting comparable Movement Times (Figure 6.1) to their NW and OW counterparts, OB participants demonstrated altered speed and accuracy of movement and higher number of errors than their NW and OW peers. In addition, this study not only found that increases in target distance and reduction in target width increased task difficulty coinciding with Fitt’s Law but that adjusting tablet orientation also served to modify task difficulty. Finally, the modification of tablet orientation was found to highlight differences between BMI categories in terms Peak Acceleration, Percentage Acceleration and number of Overshoots.

Further to the existing evidence showing altered motor skill in OB individuals (Smith *et al.*, 2011; Wang *et al.*, 2016), this study found OB participants demonstrated different Peak Acceleration (Figure 6.2) and Percentage Acceleration (Figure 6.44) and higher number of errors (Figure 6.5) than their NW and OW peers during a manual aiming task. Surprisingly, there was no significant difference found between BMI categories for overall movement time regardless of tablet orientation, target distance or target width. This unexpected and interesting finding suggests that OB participants are able to maintain an equivalent level of performance in terms of movement time to their NW peers. However, as we looked in greater depth at the movement kinematics, differences between groups emerged, demonstrating underlying differences in the control mechanisms in use. OB individuals demonstrated higher peak acceleration values when compared to NW and OW peers when their arm was supported in the horizontal orientations (Figure 6.2). However this difference disappeared, in a vertical condition, which suggests the increased postural/mechanical demands of supporting an arm resulted in altered movement control strategy. Secondly although non significant, there was a trend for OB individuals to demonstrate higher peak velocities than their peers for horizontal orientation but lower peak velocities when in the vertical orientation (Figure 6.3). This was particularly true when the target distance was further away (Large Far and Small Far). It is unexpected to find between group differences for peak velocity but not to observe differences in movement time. This suggests despite moving faster during the first phase of movement, OB participants still take the same amount of time to complete the task. Further analysis of movement also revealed that OB participants' percentage of time in the acceleration didn't differ significantly between the most difficult conditions (Small Close and Small Far) while both NW and OW groups did. As the distance between targets increased between Small Close and Small Far, NW and OW participants spent significantly higher percentage of their MT in acceleration phase (Figure 6.4). However, OB participants' percentage acceleration did not differ significantly across task conditions.

The speed–accuracy trade-off is generally viewed as the consequence of both MT and movement endpoint variance minimization (Meyer *et al.*, 1988; Harris and Wolpert, 1998). As we can separate participant's movements into two distinct phases: ballistic and corrective, it appears that OB participants' behaviour in each of these phases differs from their NW and OW peers (Figure 6). Although depending on the task constraints in terms of target distance, target width and tablet orientation, in the first phase, OB participants demonstrate greater peak acceleration and achieve peak acceleration earlier in their movement and a trend for higher peak velocities. This finding in conjunction with the results for movement time suggests that OB demonstrate greater impulsivity in the initial ballistic phase of movement. A parallel can be found in studies examining response inhibition in OB individuals. These studies found that OB individuals demonstrated a more impulsive nature and a poorer response inhibition mechanism compared to NW peers. (Lokken *et al.*, 2009; Hendrick *et al.*, 2012; Reyes *et al.*, 2015; Brockmeyer *et al.*, 2016). These higher peak accelerations in the ballistic phase of movement result in greater variance and, therefore, extended deceleration phases to make the required adjustments to maintain accuracy thus maintaining the same overall movement time. When in the vertical orientation, OB participants spent a lower percentage of time in the acceleration phase and more time in the corrective phase when their arm was unsupported, particularly when the target was smaller or further away. This could be a result of OB participants utilizing a slightly more conservative approach on conditions where they feel at risk of making errors.

The presence of between group differences for number of errors is another interesting finding. Its normal to undershoot targets initially to avoid costly time/energy overshoot errors (Burkitt *et al.*, 2015). We found that OB participants demonstrated significantly greater instances of error compared to their NW and OW peers particularly for the most difficult conditions (Figure 5). This can be seen as difficulty in the fine control of movement and specifically in the corrective phase of movement. This phase, which deals with the refinement and adjustment of movement, is an essential component of fine motor skill. These results seem to suggest that OB participants have difficulty in the utilisation of online feedback during movement. This requires them to spend a greater amount of time applying corrective adjustments at the end of their movements. Therefore, the lack of movement time differences is a result of a balancing between faster initial movements and greater time spent adjusting at the end of movements. This in essence means the initial movement time gains earned as a result of greater peak acceleration and peak velocities are required to offset costly overshoots and corrective measures at the end of the movement. A study by Heath, Hodges, Chua and Elliot (1998) found that participants initial ballistic movements tended to be determined prior to movement initiation and free from online adjustment. It seems that OB participants demonstrated a greater ballistic phase of movement that results in higher movement variability that requires greater adjustment in the second phase of movement and the associated increase in time decelerating (Harris and Wolpert, 1998). When taken altogether, these differences in movement kinematics demonstrate OB participants operate slightly difference motor control strategies dependent on the task constraints such as target distance, target width and orientation of tablet. This can effectively result in less efficient movement and potentially leading to more energy expenditure. Overall, OB participants seem to demonstrate a more varied array of movement characteristics compared to their NW and OW peers when the tablet was in a vertical orientation. This perhaps suggests the presence of thresholds where added postural demands of supporting ones arm in a vertical orientation interfere with movement control on goal directed aiming tasks. However, the lack of incremental group differences between OB, OW and NW individuals can perhaps be seen as contrary to the traditional standpoint that excess mass acts as a mechanical constraint. These findings suggest that OB individuals are capable of altering their motor behaviour in order to preserve motor outcomes which acutely sacrificing speed or accuracy.

The ability to coordinate movement while preserving speed and accuracy underpins all goal-directed aiming tasks. The successful completion of many activities of daily living such as picking up items, brushing ones teeth or buttoning a shirt rely on this ability. As such, difficulties in the preservation of the speed and accuracy balance affect the interaction between individuals and the environment around them. The presence of group differences for OB participants in the quality of movement adds further evidence to the hypothesis that obesity disrupts the typical sensory integration process (D'Hondt, Deforche, De Bourdeaudhuij, *et al.*, 2011; Gaul *et al.*, 2016). As participation in physical activity often relies on the ability to coordinate movements quickly and accurately albeit on a whole body level, problems in this process can result in difficulties participating in such activities. This study adds further weight to the argument for underlying perceptual motor difficulties in OB individuals.

The findings that corroborate those traditionally obtained for Fitts' task paradigms highlights the potential for these approaches to be applied in a more ecological setting. Nevertheless, a number of limitations of this study exist. The less controlled setting and convenience sample recruited poises a number of limitations to this study and reduces the generalisability of the results obtained. Firstly, as this study took place in a public exhibition, the lack of a controlled setting may have resulted in increased distraction of participants. Secondly, the unbalanced numbers in terms of BMI category, age and gender also limit the generalisability of the findings, despite the distribution of numbers in each BMI category providing an population representative sample of the prevalence of overweight and obesity in Ireland. Finally, the authors were also unable to collect additional data on factors which might have been useful in investigating the relationship this relationship such as number of years participants were OW or OB, SES, Comorbidities or physical activity levels or complimentary measures of cognition such as executive function. Despite the limitations discussed, the current study provides a novel approach to the investigation for the potential presence of perceptual motor difficulties in obesity. However further research is required to determine whether these problems emerge as a result of the physiological changes when one becomes OB or whether these difficulties exist prior and contribute to becoming OB as a result of a vicious cycle of inactivity.

6.5 Ethics

Ethical approval was granted by Dublin City University's research ethics committee (DCUREC/2011/038). Prior to participation in the exhibition, informed consent from participants was obtained.

6.6 Acknowledgements

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Chapter 7: General Discussion

7.1 Overview of the Research

The series of studies presented in this thesis serve to further research on motor skill and motor coordination and examine the influence of age and obesity on the processes underlying the coordination of movement. As such, this thesis provides an overview of the current level of fine motor skill in Irish children and demonstrates their lack of proficiency compared to international normative data. Further to this, Chapter 4 sought to establish a baseline for visual motor coordination using a rhythmic coordination task in children. Finally, the purpose of Chapters 5 and 6 was to highlight the influence of obesity on motor coordination with a view to uncovering perceptual motor difficulties. When taken together, the findings presented in this thesis aim to further the current lack of research on fine motor skill proficiency, the motor coordination process and the effect of obesity on motor coordination.

7.1.1 Fine Motor Skills

Fine motor skills play an important role in children's engagement in many activities of daily living such as getting dress or feed themself. In addition, poorer fine motor skill proficiency is associated with reduced academic achievement, social engagement and physical activity participation. As such, they make an important contribution to typical development in children. Chapter 3 examined the current level of fine motor skill proficiency in Irish primary school children. Results showed that Irish children fell below the normative levels prescribed by the BOT-2. The finding of levels falling below normative values is a trend that has also been seen in the literature for FMS. This finding coincides with reduced physical activity levels and increased time engaged in sedentary behaviours also being reported in the literature. These findings further emphases the influence which environmental constraints have on motor development (Thelen and Smith, 1994). The implications of this finding could have wide ranging consequences including academic achievement, cognitive development and/or quality of life. As fine motor skill proficiency requires the precise organisation and control of movement, the findings presented in Chapter 3 prompted us to examine in finer detail the motor coordination process in children.

7.1.3 Motor Coordination

The ability to coordinate movements with an external stimulus has been extensively studied in the literature. As such, it has led to the establishment of an in depth understanding on how we coordinate with a variety of stimuli including visual, auditory, tactile or a combination of stimuli. More recently, a move has been made toward gaining a greater understanding of how these principles apply to special populations such as those with Autism (Fitzpatrick *et al.*, 2016), Social phobic (Varlet *et al.*, 2014) and Schizophrenia (Varlet, Marin, Raffard, *et al.*, 2012). Chapter 4 aimed to build upon our understanding of how these principles apply to typically developing children and how these processes are influenced by maturation by exploring the rhythmic motor coordination in a pendulum task.

The results of Chapter 4 found that children demonstrated similar patterns for rhythmic manual coordination found in adults, with a preference for visual stimuli rather than auditory and better performance on preferred frequency conditions. As expected, children demonstrated poorer and more variability in performance as measured by CRP and SD CRP, compared to those found in adults. The results also showed that traditional patterns for maturation were observed in level of coordination, with performance improving with age and the oldest children demonstrating the best coordination while still being substantially lower than those observed in adults in a similar task (Armstrong and Issartel, 2014). A number of different patterns, not previously observed in adults, were observed in Chapter 4. Firstly, in terms of movement amplitude, children demonstrated significantly different movement amplitudes for different frequencies. Therefore, it seems that children's movement amplitude was temporally linked, with smaller amplitudes observed for slower movement frequencies. Further to this, children were unable to benefit from the availability of multiple sources of sensory information, with no improvement in coordination in the multisensory condition compared the vision only condition. A final point of note is the finding that coordination level of children in Chapter 4 were better than those found in obese adults in Chapter 5. This further suggests the influence of obesity on the ability to coordinate movements.

This study demonstrates that children exhibit similar behaviours to those seen in adults while still falling below adult levels of coordination. It is likely that the lack maturity of children's perceptual systems is the source of children's lower level of coordination and increased movement variability compared to adult levels. As such, as children get older their sensitivity to stimuli and ability to refine the efficiency of the sensory integration process is likely to result in improved coordination levels. Recent evidence has begun to suggest that obesity also has an effect on the sensory integration process.

7.1.4 Obesity

There is a strong evidence base presented in the literature demonstrating the influence of obesity on motor development and the motor control process. This has led to obesity being associated with reduced physical activity levels, poorer cardiorespiratory fitness and motor skill proficiency. Traditionally, the influence of obesity on motor behaviour has been seen to be a consequence of the mechanical constraints associated with excess mass such as impaired balance, heavier limbs and effort required to move increased adiposity. However, the findings of this thesis add further support to the suggestion that obesity has an underlying neurocognitive component and as such, alter the normal sensory integration process (D'Hondt *et al.*, 2008; Gentier *et al.*, 2013).

Chapter 5 and Chapter 6 of this thesis sought to examine the role of obesity in the organisation and control of visual motor behaviour. These two studies, in contrast to Chapter 3 and 4, utilised an adult cohort rather than children to investigate this relationship. As demonstrated in Chapter 3 and 4, children's perceptual motor ability is still developing throughout childhood and adolescence. Therefore, it is unclear whether any observed differences in obese children are a consequence of their weight or the various changes taking place as part of the maturation process. As such, the studies presented in Chapters 5 and 6 sought to establish the relationship between obesity and motor coordination irrespective of the confounding factor of maturation. It was hoped that this would establish a baseline for the influence of obesity on motor coordination that future studies could investigate in children.

Chapter 5 examined visual motor coordination in a sample of super obese adults (BMI>50kg/m^2). The results indicated that obese individuals had significant difficulty in coordinating their movements with a visual stimulus. This finding is particularly interesting given that the experiment controlled for the additional postural requirements of obesity by being carried out in a seated position and having the arm supported. Further results from Chapter 5 demonstrated increased movement variability and significantly different movement amplitudes in obese participants compared to NW controls. These differences in motor behaviour suggest that obese individuals organise and control their movements in a different way. Chapter 6 further analysed how being overweight or obese influenced the organisation and control of movement in discrete version of a Fitts' Task. Surprisingly, there was no significant differences found between groups in terms of movement time, with NW, OW and OB individuals all demonstrating increases in movement time as task difficulty increased thus adhering to Fitts' Law. However, when the movement kinematics was examined, obese individuals were found to demonstrate higher values for peak acceleration and peak velocity compared to NW participants when their arm was supported. Despite moving faster, the lack of differences in movement time implies that that obese individuals velocity profile is different to that of NW. As we can divide reaching tasks into ballistic and corrective phases it would seem that obese individuals demonstrate greater velocity and acceleration in the ballistic phase and thus spend greater time in the corrective phase of movement in an attempt to preserve movement time. This altered movement strategy can be likened to the findings of Chapter 5 suggesting obese individuals employ slightly altered motor control mechanisms as a means to compensate for the difficulties experienced as a result of obesity. During aiming movements, the corrective phase of movement requires individuals to utilize the available sensory information to make adjustments as a means to avoid costly time/energy overshoot or undershooting errors. This processes requires individuals to integrate multiple sources of information and make the appropriate refinement of movement. The finding that obese individuals made significantly greater number of errors further suggests obese adults have difficulty in effectively carrying out the sensory integrating process.

Together, the studies presented in Chapter 5 and Chapter 6 add further evidence to the case for underlying sensory integration issues in obesity. These studies suggest that that obesity may interfere with how motor behaviour is organised and controlled in tasks that have minor mechanical influence. However, it still remains to be seen whether these motor coordination difficulties are a consequence of the various neurobiological changes that occur from becoming obese or whether these difficulties exist prior to, and are a contributing factor, to becoming overweight or obese. This is primarily a consequence of the source(s) of these sensory integration difficulties being poorly understood. The existing research has highlighted a number of potential influences including altered brain structure, hormone deregulation, oxidative stress and brain inflammation (Smith *et al.*, 2011; Wang *et al.*, 2016). Given the dynamic nature of the sensory integration process, it is likely that difficulties occur due to the interplay between some or all of these mechanisms. The results of these studies serve to strengthen the argument for the presence of perceptual motor difficulties in obesity. In addition, the findings presented in Chapter 5 and 6 in conjunction with those in Chapter 4, pave the way for the relationship between obesity and motor coordination to be further examined in children.

7.2 Implications of Research

7.2.1 Intervention

The findings of this thesis leads to the potential benefit of sensory integration/motor coordination interventions to address the motor coordination difficulties experienced by obese individuals.

Sensory Integration Therapy (SIT) is a form of therapy based on Ayres Sensory Integration theory frequently used by occupational therapists to treat individuals with functional disorders of sensory integration or neurological disorders such as Autism or ADHD. Sensory integration therapy refers to a range of activities tailored to meet specific the needs of individual. These unique treatments are frequently referred to as sensory diets and can include balance treatments, movement therapies and exposure to various forms of sensory information such as visual, auditory or tactile. This type of approach aims to encourage the nervous system to become more organised in its response to stimulation through repetition and gradual increases of complexity of the tasks.

An intervention, which specifically targets the sensory integration process similar to SIT, could potentially help address the coordination difficulties experienced by in obese individuals. This approach could facilitate individuals in adapting to the increased mechanical, physiological and neurological constraints as a consequence of being obese. This type of intervention may be particularly useful in childhood as a means to reduce or potentially remove the sensory integration and associated motor coordination difficulties experience by overweight or obese children.

Ultimately, the aim of any such intervention should be to preserve/improve the quality of life experienced by individuals. As coordination of movement is a key component of many activities of daily living encounter on an everyday basis, motor coordination proficiency can be seen as a key feature which impacts upon quality of life. Therefore any future interventions targeting obesity should consider the inclusion of a motor coordination component in addition to physical activity, exercise and/or diet. Further to this, in severely obese individuals, efforts should be made to tailor interventions to prioritize the maintenance of functioning and quality of life (World Health Organization, 2001). Occupational therapy approaches for obese individuals to the functioning of an individual. Interventions containing coordination training could lead to the increasing in visual motor coordination and the associated benefits in terms of activities of daily living, self efficacy or even physical activity. Given the evident to show the long term consequences of poor motor competence on psychological wellbeing, social engagement and physical activity participation, early intervention to tackle coordination difficulties are likely to tackle difficulties prior to children disengaging from these activities and developing long term patterns of avoidance and not participation.

Alternatively, should these sensory integration difficulties exist prior and be a contributing factor to becoming obese, interventions targeting the motor coordination process could potentially reduce children's risk of becoming obese later in childhood, adolescence or adulthood.

7.2.2 Early Identification

As a baseline for motor coordination in typically developing children has now been established, future studies investigating the influence of obesity on motor coordination of children is merited. The potential for these sensory integration difficulties to exist prior to obesity is another interesting implication of the research. This opens the door to the use of sensory integration assessments as a means to identification children at risk to becoming overweight or obese in the future. This early identification might enable intervention to be carried out prior to the physical manifestations of obesity. This is in contrast to the viewpoint that coordination difficulties are just a stage which children 'grow out of'(Losse *et al.*, 1991). This could play a significant role in the battle to fight obesity by targeting the most at risk and delivering more tailored prevention strategies in contrast to the greater time and financial implications of obesity treatment. As children's physical activity and sedentary behaviour patterns are developed in childhood and track into adolescence, early identification and intervention to those most at risk could help establish positive physical activity patterns and greater self-efficacy.

7.2.3 Altered Environmental Demands

We now live in a society were the environmental demands placed on individuals, adults and children, differ substantially than those required 50 years ago. As such, children are faced with new challenges, new sources of information and new skills which they must master to interact with the environment around them. For example, children in primary school frequently have computer classes where they practice skills like typing or using a mouse. In addition, classrooms now often have other forms of technology such as digital tablets or interactive whiteboards that are used as a part of evolving teaching methodologies. This is stark contrast to the paper and pencil-dominated classrooms of the early 90's found by McHale and Cermak (1992). As such, children are not exposed to the opportunities to practice graphomotor skills such as pencil grip or handwriting as was the case in the past. Therefore is not surprising that children's level of fine motor skill falls below expected levels. This poses the question whether we value handwriting as much as we did in the past? Is it a dying art? In Finland, the government have taken the step to remove the teaching of cursive handwriting as a compulsory element of the primary school curriculum and replaced this time with skill such as typing.

This kind of generational shift have been seen before such as the value associated with being able to start a fire, navigate via a map or speak Latin, all diminishing over time. Often the reduction in the value of these skills is a result of the availability of alternatives or the need to meet new environmental demands. It may be the case that modern children are developing a new range of fine motor skills that better meet the demands of the modern environment at the expense of traditional measures of fine motor skill proficiency. Examples include swiping; tapping and pinching movement that are required to interact with touch screen devices like mobile phones or digital tablets. These skills are not a component of any motor skill assessment at present and thus we are unable to measure children's proficiency in these skills. However anecdotal evidence from observation of young children shows that even very young children are capable of demonstrating proficiency in these skills.

This shift in societal values may have consequences on the teaching practices that we employ and the mediums with which we typically assess academic achievement. However as the skills required to interact with digital devices have limited tactile information associated with them, children may still be losing valuable sensory experiences that are vital for their development. Traditional fine motor skills frequently require the manipulation of 3D objects which exposes children to varied textures, shapes, sizes and weights in additional to requiring activities requiring prehension and grip. As activities of daily living still require these skills, a lack of practice in the various aspects of fine motor skill proficiency such as precision, manual dexterity and upper limb coordination should have consequences on children's ability to successfully engage in such activities.

7.3 Strengths

This thesis employs a dynamic systems approach to examine the interrelated relationship between environmental, task and organismal constraints on motor behaviour.

The results presented in Chapter 3 establish the current state of fine motor skill proficiency in an Irish context. This study is the first to our knowledge, to specifically examine the current state of fine motor skill proficiency and how it relates to normative data. As fine motor skill proficiency is associated with academic achievement and require for many activities of daily living, establishing the current state of fine motor skill proficiency provides useful evidence on children's motor skill development and highlights that fine motor skill competence is adhering to trends of reductions in proficiency levels as seen in gross and fundamental movements skills.

Chapter 4 provided evidence to evaluate the sensory integration process in a sample of 71 typically developing children using a pendulum task. This sample size can be considered large in comparison to previously conducted studies using the sample approach (Varlet, Coey, *et al.*, 2012; Varlet, Marin, Issartel, *et al.*, 2012; Armstrong *et al.*, 2013; Armstrong and Issartel, 2014). This study utilised a classically used experimental paradigm in a previously unexamined population. As such, it provides original results on how children coordination their movements with visual, auditory and multisensory stimuli and information on how the quality and stability of coordination differs between younger and older children. In addition, this study provides a baseline from which future studies can examine motor coordination and the underlying processes in atypical children such as those with DCD or who are obese.

Chapter 5 provided clear evidence demonstrating an altered sensory motor integration process during a visual coordination task. The relatively large sample size recruited (N=88) and the stringent recruitment methodology can be seen as strengths of this study. Obese participants were individually matched control participants of the same age and gender to control for age and gender influences. Further to this, the exclusion of participants with any other medical conditions or taking medication that could impair performance can be seen as significant strengths of the research.

Chapter 6 provided a novel approach to investigate the influence of obesity on the speed and accuracy of manual coordination. Once more, this experiment examined this emerging potential relationship using classical used experimental methodology. The sample size (N=183) can again be seen as strength of the experimental design. This study also benefits from the use of well-validated experimental design to add further weight to the argument for underlying perceptual motor difficulties in obesity. In addition to this, the use of a public exhibition as a forum to conduct scientific research can be deemed a success and, therefore, a strength of the study given the implications of carrying out the study in a traditional laboratory based setting.

When taken together, this series of studies serve to both establish an understanding of motor coordination in children in addition to highlighting the presence of motor coordination difficulties as a result of obesity. In doing some, the results presented can have important health-related implications for both children and adults.

7.4 Limitations

Despite the studies in this thesis presenting novel and substantial findings in terms of the influence of obesity on motor coordination and the current level of fine motor skill proficiency in children, a number of limitations can be raised.

The results shown in Chapter 3 have identified that Irish children fail to meet normative levels for fine motor skill proficiency. Similar findings have been seen in Belgium and Australian children (Bardid *et al.*, 2015). Although the results presented show that each age group fell below normative levels, the lack of longitudinal data means we are unable to determine whether children eventually catch up and meet levels seen in normative data. A follow up study is currently being carried out to help answer this question but is beyond the scope of this thesis.

Chapter 4 provided significant insights into how the immature sensory integration process influences manual coordination. However the study was unable to recruit a significant number of overweight and obese children to explore the influence of obesity on this process. It was hoped that enough children from higher BMI categories would be recruited to carry out between groups analysis however the parents of obese children tended to opt out of providing consent to participate in the study. As such, the low numbers of children meant there was a lack of statistical power to investigate this relationship. In addition, as the sensory integration process is still developing in childhood, separating the influence of obesity from the influence of the various biological changes occurring as part of the maturation process would prove difficult.

The findings outlined in Chapter 5 demonstrate significant impairments in obese adults visual motor coordination and suggest difficulties in the sensory integration process as have been alluded to in the literature. However, the convenience sample of obese patients in addition to the extreme level of obesity (BMI>50kg/m^2) in the sample may limit the generalisability of the findings to other obese individuals (BMI>30kg/m^2). In addition to this, we were unable to control for the number of years which participants were obese or the previous physical activity levels, sport participation, socio-economic status or cognitive function.

The limitations outlined above for Chapter 5 also apply in Chapter 6 given the recruitment of participants and execution of the experiment as part of a public exhibition. This relatively uncontrolled setting in addition to the unequal distribution of the groups (58.5% NW, 31.7% OW and 9.8% OB) may limit the generalizability of the findings. Despite these limitations, the finding that results adhered to Fitts' Law suggests the robust nature of the experimental paradigm employed. In addition, the unequal distribution of weight groups, although population representative, were outside the experimenters control given the experimental design.

7.5 Directions for future Research

The relationship between motor development, obesity and cognitive function can be seen as a dynamic process. The studies presented in this thesis examine fine motor skill proficiency and motor coordination and obesity on a cross sectional basis. As such, longitudinal studies are required to investigate how this relationship between motor coordination, obesity and cognitive function changes over time.

At present, the evidence showing whether sensory integration difficulties are a consequence or a predictor of obesity is inconclusive. As such, future studies that seeks to determine whether obesity is a cause and or a consequence of these sensory integration difficulties. In order to do this, future research is needed to investigate this relationship in children and examine how this relationship develops longitudinally. The establishment of a causal relationship can facilitate the development of interventions to tackle sensory integration difficulties in and effort to combat obesity or treat obesity to avoid the development of coordination difficulties as a consequence.

7.6 Conclusion

The studies presented in this thesis have provided 'food for thought' on how socio-environmental factors – specifically obesity, influence the sensory integration process and motor coordination (excuse the pun). The findings outlined in Study 1 demonstrate that Irish children are developing their fine motor skills at a different trajectory to normative data collected in the past. It may be the case that children develop at a slower rate and reach maturation levels later than expected. However, given the prevalence of activities requiring fine motor skill proficiency in everyday life, these findings shouldn't be taken lightly. Study 2 showed children demonstrated similar patterns of movement to those seen in adults in a rhythmic coordination task but highlighted that a less efficient sensory integration process is responsible for sub adult levels of coordination. This study establishes a baseline for coordination levels in typically developing children and facilitates future research in investigating how this process develops over time. Together Study 3 and Study 4 add further support to the case for the presence of motor coordination difficulties in obese individuals. These chapters provide evidence to demonstrate that these changes are not solely mechanical in nature as the traditional excess mass hypothesis by demonstrating impairments in tasks involving limited influence of mass. These problems are likely to contribute to an already reduced quality of life by adding increased difficulties to the coordination of movement. However, it remains to be seen if these differences exist prior to becoming obese and can be view as a contributory factor or whether these difficulties are a result of the various physiological changes from becoming obese. The studies presented in this study highlight the influence of socio-environmental factors on typical motor development. However as motor development is a continuous process over the lifespan of an individual, further longitudinal studies are required to specifically examine the influence of factors on motor development.

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