

The Quiet Eye in a Throwing and Catching Task:
Visuomotor Skill of children with and without
Developmental Coordination Disorder

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Abstract

Knowing where and when to look is critical for effective performance of visually guided tasks. A gaze strategy termed the quiet eye (QE; the final gaze before the onset of a critical movement) is strongly associated with motor skill proficiency, with earlier and longer QE periods leading to improved visuomotor control. Children with poor motor proficiency, such as those with Developmental Coordination Disorder (DCD), have impairments in the pick-up and processing of visual information, translating into poorly coordinated movements. The purpose of this project therefore was to perform the first examination of the QE strategy in children of different motor coordination abilities and furthermore to investigate the efficacy of task-specific QE training (QET) to improve the skills of children with and without DCD beyond the effects of a standard coaching technique. Study 1 determined that children with low motor coordination had later, shorter QE durations in comparison to coordinated children and as a result, performed worse in a specified motor task (throwing and catching). Study 2 therefore performed two experiments aimed at developing an appropriate but brief QET protocol for children to improve their throwing and catching ability. These experiments found that typically developing children were able to increase their QE durations with QET and this was reflected in a durable improvement in their motor skill execution. The final study examined this QET intervention in children with DCD. This was the first application of QET in a clinical population, and found that children with DCD were able to improve their QE durations, and make robust changes to their visuomotor control. These studies associate a longer QE with motor skill proficiency in children, and provide an important adjunct to current therapeutic intervention for children with poorly developed motor skills.

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My final thanks goes to Andrew Vickers. It was Vickers who started this project to help kids with DCD but never got to complete it, so I would like to dedicate this thesis to his memory.

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Abbreviations and Definitions

The following abbreviations are commonly used throughout this thesis. All are defined at first mention, after which the abbreviation will be used.

Methodological Abbreviations

- QE** Quiet Eye – the gaze strategy denoting the final fixation on a target location or object before the onset of a critical movement.
- QET** Quiet Eye Training – a training protocol teaching individuals to employ the QE strategy using video or verbal instructions.
- TT** Traditional Training – established training or coaching techniques that have been used to improve motor performance.
- BL** The baseline measure – A measure of a variable taken prior to training.
- R1** The first retention – A measure of a variable taken immediately after training has occurred.
- R2** The second retention – A measure of a variable taken after a delay of 6-8weeks of no training or dedicated practice.
- MABC-2** Movement Assessment Battery for Children (2nd edition) – this is a validated assessment of motor coordination ability (Henderson, Sugden & Barnett, 2007).

Population and Grouping Abbreviations

- LMC** Low motor coordination – Children classified as having below average motor coordination ability (although not necessarily a diagnosable developmental disorder).
- MMC** Median motor coordination – Children classified as having average motor coordination ability.

- HMC** High motor coordination – Children classified as having above average motor coordination ability.
- DCD** Developmental Coordination Disorder – A condition that affects the development and learning of motor skills.
- TD** Typically Developing – Children who have no neurological, learning or developmental disorder that affects their motor performance.

Measure Abbreviations

- FT** Flight time – The time (ms) a ball travels in the air. FT1 refers to the throw time (ball release to wall contact) and FT2 refers to the catch time (wall contact to trial end).
- QE1** The targeting QE period that takes place prior to the throw in a throwing and catching task (pre-throw phase). In chapter 3 and chapter 4 Experiment 1, QE1 is defined as ‘the final fixation within 3° of visual angle for 100ms or more on a target location, before to the onset of the throw’. This definition was refined in Chapter 4 Experiment 2 to ‘the final fixation within 3° of visual angle for 100ms or more on a target location, before to the onset of the throw foreswing’.
- QE2** The tracking QE period that takes place prior to the catch in a throwing and catching task (pre-catch phase). Throughout this thesis, QE2 is defined as ‘the final tracking gaze within 3° of visual angle for 100ms or more on the ball, before the onset of the catch’.
- EA** Elbow angle – The angle (°) of the elbow joint measured at the point of the ball contacting the hands of the participant.

Chapter 1: Introduction

1.1 Introduction

In sport, highly skilled performers can execute accurate and well-timed movements that lead to greater task success. However historically the cognitive contribution to the execution of a skilled movement has been overlooked (Moran, 2009). Sensory input is essential for guiding a movement outcome in visually guided tasks, so how sensory information is obtained, processed and acted upon is highly relevant to successful performance. Furthermore, research examining how we can optimise the uptake and processing of sensory information has identified a specific gaze strategy termed the quiet eye (QE; Vickers, 1996, 2007). The QE is a specific gaze or fixation on a visual cue immediately prior to movement, and in adult performers has been shown to distinguish between performers of different proficiencies and performance outcome.

The study of motor skills in children has also demonstrated that some children can execute movements more fluently and accurately than similarly aged counterparts with no discernable motor dysfunction (Lubans, Morgan, Cliff, Barnett, & Okely, 2010). However, there is limited research investigating the differences in sensory and perceptual skills of these high and low skilled children, and whether training the detection and processing of visual information may help children to improve their movement execution. There is a greater body of literature that has focused on determining the visuomotor impairments relating to one specific movement disorder termed developmental coordination disorder (DCD). The existence of a visuomotor deficit in children with DCD appears to be in little doubt (Wilson & McKenzie, 1998), however as yet, it is unclear what effect this condition has on children's gaze strategies during

sports skills. Furthermore no empirical research has investigated the QE in children, with or without DCD.

Therefore the purpose of this thesis was to investigate the QE in 8-10 year old children of different motor coordination abilities and determine whether training the timing and location of the QE to mimic highly skilled children would increase the performance of typically developing children and children with DCD. The hypotheses of this thesis were (1) highly skilled children would have earlier, longer QE durations in comparison to median and low skilled children and (2) by training children with low to median motor skill to lengthen their QE durations, their motor skill performance would also increase over and above the effect of a standard coaching or training technique. The final stage of this thesis was (3) to examine the efficacy of a QET intervention for children with DCD. This is the first study to investigate the QE in a clinical population, and will examine the possibility of QET as an adjunct to therapy for children with DCD.

1.2 Scope of this thesis

The second chapter of this thesis reviews the relevant literature relating to three areas. First, the existing research of visuomotor skill and the QE of expert and novice performers will be considered, particularly from a sport and physical activity viewpoint. The second part will consider DCD in children and particularly the literature relating to the visuomotor skills of these children. The third section of chapter 2 discusses catching skill in children, a relevant motor skill that will be examined throughout this thesis.

Chapters 3-5 are made up of the experimental studies of this project. Chapter 3 addresses the first hypothesis of the thesis, examining the QE in children of different motor coordination abilities. Chapter 4 addresses the second hypothesis, using the elite gaze strategies identified in chapter 3, to formulate and develop a QET protocol (across two experiments) to improve the catching skill of typically developing children. Finally chapter 5 addresses the third hypothesis by applying the QET intervention to children with DCD. The final chapter 6 brings these studies together to discuss their findings, consider theoretical and practical implications and identify future progressions in this field of research.

1.3 List of Publications and Conference Abstracts

1.3.1 Publications

Chapter 3 published as: Wilson, M.R., Miles, C.A.L., Vine, S.J., & Vickers, J.N. (2013). Quiet eye distinguishes between children of high and low motor coordination abilities, *Medicine and Science in Sport and Exercise*, 45(6), 1144-51.

Chapter 4, experiment 1 published as: Miles, C.A.L., Vine, S.J., Wood, G., Vickers, J.N., & Wilson, M.R. (2014). Quiet eye training improves throw and catch performance in children. *Psychology of Sport and Exercise*, 15, 511-515.

Chapter 4, experiment 2 submitted as: Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N. & Wilson, M.R. (under review). Exploring the efficacy of QET for

long-term learning in the catching performance of children, *European Journal of Sport Science (SI)*.

Chapter 5 submitted as: Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N. & Wilson, M.R. (under review). Quiet eye training facilitates catching performance in children with Developmental Coordination Disorder, *Research in Developmental Disabilities*.

1.3.2 Conference Abstracts

Miles, C.A.L., Vine, S.J., Vickers, J.N., & Wilson, M.R. (2012, July). Quiet eye distinguishes between children of high and low motor coordination abilities. *Paper presented at ICSEMIS conference that also hosted British Association of Sport and Exercise Science annual conference, Glasgow, Scotland.*

Miles, C.A.L., Vine, S.J., Wood, G. Vickers, J.N., & Wilson, M.R. (2013, April). Improving catching in children using quiet eye training. *Paper presented at the British Psychological Society, Expertise and Skill Acquisition Network Annual Meeting, Bisham Abby, England.*

Miles, C.A.L. (2014, April). Online prediction of children with and without DCD. *Paper presented at the British Psychological Society, Expertise and Skill Acquisition Network Annual Meeting, Sheffield Institute of Sport, Sheffield.*

Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N. & Wilson, M.R. (May, 2014). Quiet Eye training intervention for children with DCD. *Paper accepted for presentation at UK DCD Conference, Liverpool, England. Conference was cancelled prior to presentation date.*

Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N. & Wilson, M.R. (May, 2014). Quiet Eye training intervention for children with DCD. *Paper accepted for presentation at UK DCD Conference, Liverpool, England. Conference was cancelled prior to presentation date.*

1.3.3 Conference Poster Presentations

Miles, C.A.L., Vine, S.J., Wilson, M.R., Vickers, J.N. (2012, April). Visuomotor control differences in children with high and low movement ability. *Poster presented at the British Psychological Society, Expertise and Skill Acquisition Network Annual Meeting, Liverpool, England.*

Miles, C.A.L., Vine, S.J., Vickers, J.N., Wilson, M.R. (2012, December). Quiet eye training of children in catching: A pilot study. *Poster presented at Sport and Health Science Postgraduate Conference, University of Exeter, England.*

Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N. & Wilson, M.R. (May, 2014). The Effect of a Quiet Eye Training Intervention on Children's Self-Perceptions of Adequacy, Enjoyment and Predilection of Physical Activity. *Poster accepted for presentation at UK DCD Conference, Liverpool, England. Conference was cancelled prior to presentation date.*

Chapter 2: Review of the Literature

2.1. Visuomotor Control and the Quiet Eye

2.1.1. Gaze Behaviour, Visual Search and Eye Tracking

Information gathered from the perceptual systems is used to generate goal-directed movements (Vickers, 2007). Indeed, in their model Van der Molen, Bashore, Halliday, and Callaway (1991) identified three stages of information processing: Stage 1 is the Perceptual Stage where the identification and processing of stimuli takes place. In stage 2, the Central Stage, a response is selected and in stage 3, the Motor Stage, the motor response is programmed and adjustments are made. The visual system in particular is important for detecting information required for the effective performance of many motor skills (Land, 2009) and particularly in sports skills such as ball catching. When performing such a skill, an individual may be exposed to a vast display of visual information from which they must search to identify and attend to relevant visual cues for the effective performance of the task (Mann, Williams, Ward, & Janelle, 2007).

Head and eye movements are therefore required to scan the display to detect and direct relevant visual cues such as a ball onto the fovea of the eye (a sensitive region of the retina) to gather and process more detailed information about its position and movement within the environment (Henderson, 2003). The visual scanning of a display involves two forms of eye movements: rapid movements between objects that allow for practically no conscious processing of visual information (saccades), and the stable fixations that are maintained on an object, target or location for 100ms or longer to allow for information processing. An individual can also use pursuit tracking to pick-up visual

information. This is an eye movement where a moving object or target is tracked or followed with the eyes for minimum of 100ms (Vickers, 2007).

Advances in eye tracking technology and gaze registration systems have allowed researchers to examine the gaze behaviour and visual search of individuals when performing motor skills (see Vickers, 2007 for a review). These studies make the assumption that locus of gaze represents the locus of visual attention, however it must be noted that it is also possible to direct covert attention elsewhere, leaving a question as to whether eye tracking is a reliable measure of attention (Posner, 1980; Posner & Raichle, 1994). Despite these concerns, there appears to be a close link between gaze and attention as in most tasks a shift in gaze is invariably preceded by a shift in attention (Henderson, 2003; Vickers, 2007), especially in visually guided tasks. This evidence is compounded by studies of brain imaging that have found that the shifting of visual attention and gaze are involved with common neural structures in the frontal and parietal lobes (Corbetta, 1998).

2.1.2. Visuomotor Control

Accurate control of gaze to relevant visual information will direct and update motor action (Land, 2009), which is defined as visuomotor control. From a theoretical standpoint, Land (2009) describes three executive systems that are responsible for visuomotor control. These are the gaze, vision and action systems, which are then overseen by a fourth system named the schema system (Figure 2.1 demonstrates how these systems interact). When grasping an object for example, the gaze system is initially responsible for identifying the location of the object, and directing it onto the fovea, which may require head or trunk movements. An eye movement (saccade) allows the gaze system to

fixate the object after which, the hand movement (controlled by the motor system) will begin (after around 0.5 second delay). The visual system supports the motor system by providing updated information to guide and finely tune the movements in order to accurately (and if necessary correctly time) the grasp. The schema system oversees these three systems in relation to task goals, to ensure action is appropriately ordered and coherent (Land, 2009).

Visuomotor control in an interceptive task for example, requires both the gaze and visual attentional systems to detect and read the object flight in order to execute the interception. In the context of Land's (2009) theory, the object must be picked out and recognised by the gaze system (which may also recognise early postural cues from the object projector) and tracked through the air using smooth pursuit tracking to maintain the object on the fovea. The visual system interprets the information being gathered and therefore informs the perceptual processes to guide and adjust the motor response. The schema supervises these systems as they guide and update the hand or foot movements regarding the object direction and speed, as well as adjustments in the flight caused by external factors such as weather or spin in order to effectively intercept or control the object. This example demonstrates 'top-down' attentional control which first leads the eyes and then ultimately the motor action.

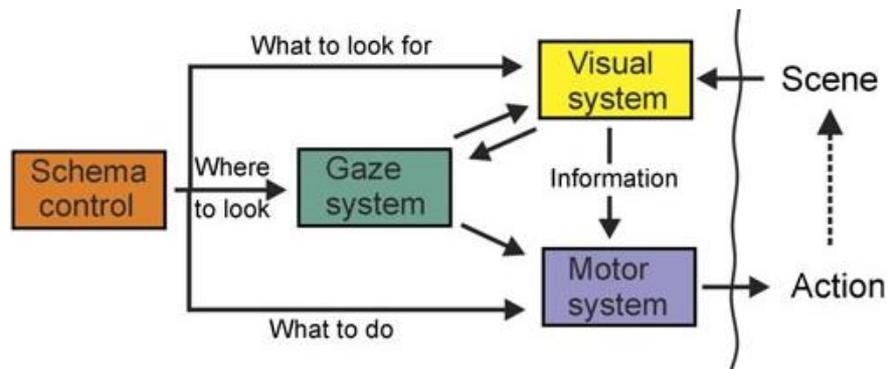


Figure 2.1: *The relationship between the schema, gaze, motor and visual systems, during the performance of a visually guided movement (extracted from Land, 2009).*

2.1.3. Visual and Perceptual Expertise

As individuals learn a new skill, they not only become better able to control and coordinate their body movements, but they also improve their visual control, helping them ignore the irrelevant information in a visual display and concentrate on attending to task-relevant cues at the optimal time (Vickers, 2007). Sailer, Flanagan, and Johansson (2005) investigated eye movements during the learning of an abstract motor task. They found that eye movements in the early stage of learning involved closely guiding and following the cursor they were manipulating. According to Fitts and Posner's model of skill acquisition (Fitts & Posner, 1967), this early stage of learning requires the explicit step-by-step encoding of information, producing slow, erratic and consciously controlled movements. This places high demands on cognitive processing resources of the participant.

However once the skill has been mastered, the components of the skill are chunked together and eventually become autonomous (Vine, Moore, Cooke, Ring, & Wilson, 2013b). Here the processing demands are much lower and skill execution is fast, consistent and effective. Sailer et al. (2005) observed that once the participants had mastered the skill, their eye movements were directed ahead of the cursor to targets. In a real-world task (simulated surgery), Wilson et al. (2011a) also found that novices made significantly more fixations on their tools, guiding them towards the target, whereas expert surgeons made more timely fixations on the targets they were directing their tools toward. There is strong support therefore for altering the way we teach visuomotor skills to novice performers by directing visual attention to external target-related stimuli rather than the control of limbs or tools (Vine et al., 2013b).

Knowing where and when to look can help an individual to search the visual spatial workspace more efficiently and pick out important task-relevant information. In terms of visual search, using fewer saccades (where theoretically no information is being picked up and processed) and fewer, longer gazes (either static fixations or smooth pursuit) on relevant cues is associated with sporting expertise (Mann et al., 2007; Williams, Davids, Burwitz, & Williams, 1994). It is argued that expert athletes have been exposed to many similar task-specific situations so their perceptual skills are attuned to identifying relevant information (Van der Kamp, Rivas, Van Doorn, & Savelsbergh, 2008). Research has demonstrated that an efficient visual search strategy results in a number of benefits such as better pattern recall and recognition (Williams & Davids, 1995), quicker detection and recognition of objects such as an approaching ball (Allard & Starkes, 1980; Starkes, 1987), and an ability to pick

up early or advanced visual cues from an opponent's posture for example (Piras, Lobiatti, & Squatrito, 2014a).

Expert-novice differences in the number and duration of visual fixations have been demonstrated in many sports such as football (Helsen & Starkes, 1999), volleyball (Piras et al., 2014a), basketball (Vickers, 1996) and martial arts (Perez, Mendez, Manzano, & Collado, 2013; Piras, Pierantozzi, & Squatrito, 2014b) with experts using fewer and longer fixations. However, this pattern of efficient visual search has not always been fully supported in the literature (Moran, Byrne, & McGlade, 2002). Williams et al. (1994) found that experts used more fixations of shorter duration in comparison to novices in a football task, and Helsen and Pauwels (1993) also demonstrated shorter mean fixation durations for elite footballers, leading Moran et al. (2002) to the conclusion that visual search may be context-specific. Martell and Vickers (2004) shed some light on this contrast in findings in their study of a tactical defensive scenario in ice hockey. They found that expert fixation/tracking durations were shorter at the beginning of a play but as the play progressed their durations extended to a final long fixation on a stable target at the end.

Mann et al. (2007) attempted to quantify the perceptual-cognitive differences between expert and novice sports performers in their meta-analysis and review. They were able to conclude that expert performers have a clear perceptual advantage over novice counterparts that in turn reduced their reaction times and increased response accuracy. This in part may be explained by expert performers using the efficient visual search strategy when scanning a visuospatial workspace, but experts were also able to exhibit better visual attention by accurately and optimally timing their fixations to the most information-rich cues to extract the most task-relevant information, reducing the

risk of making oversights and incorrect decisions. Many examples are provided in the sports literature of experts and novices attending to different visual cues at various points during the preparation and execution of a response such as in tennis (Reina, Moreno, & Sanz, 2007; Williams, Ward, Knowles, & Smeeton, 2002b), baseball (Takeuchi & Inomata, 2009) and football goalkeeping (Savelsbergh, Williams, Van der Kamp, & Ward, 2002), however the timing of visual attention on a relevant cue is also important. For example, late target information in a dynamic aiming task can be just as beneficial to performance as full information (de Oliveira, Oudejans, & Beek, 2006; Oudejans, van de Langenberg, & Hutter, 2002). The timing and location of a particular gaze strategy termed the quiet eye (QE; Vickers, 1996) has been identified as key feature of proficient and successful performance (Mann et al., 2007; Vickers, 2007). The QE relates to the final fixation (or tracking gaze) on an object or target, however this gaze strategy considers the initiation of the motor response to be particularly significant; proposing that the important visual information for the execution of a task is gathered in the final fixation before the onset of a critical movement.

2.1.4. The Quiet Eye (QE)

The definition of the QE is the final fixation or tracking gaze on a single location or object within the visuo-motor workspace to within 3° of visual angle for a minimum of 100ms (Vickers, 2007). The onset of the QE occurs before the critical movement in the motor task is initiated, and the offset occurs when the fixation or tracking gaze deviates from the object or location by more than 3° of visual angle, for more than 100ms.

The QE was identified in the meta-analysis of Mann et al. (2007) as a distinguishing factor in perceptual motor expertise; expert performers initiate an earlier and longer QE duration. There are now many examples of this in the literature demonstrating the robustness of the QE in both skill proficiency (e.g. Causer, Bennett, Holmes, Janelle, & Williams, 2010; Janelle et al., 2000; Panchuk & Vickers, 2011; Vickers, 1996; Vickers & Adolphe, 1997) and performance outcome (e.g. Causer et al., 2010; Panchuk & Vickers, 2006; Williams, Singer, & Frehlich, 2002a; Wilson & Pearcy, 2009). Furthermore an earlier, longer QE duration is associated with more successful performance even when a performer is fatigued (Vickers & Williams, 2007) or anxious (Vine et al., 2013b; Vine & Wilson, 2011).

The QE has been extensively studied in static, self-paced aiming tasks (see Vine, Moore, and Wilson (2014) for a recent review), however fewer studies have investigated the smooth pursuit tracking QE used in externally paced interceptive tasks. These tasks are distinctive as they impose a temporal constraint on the participant, which will dictate the available time that an individual can track the object and so initiate a QE before they execute a motor response. This challenge is demonstrated in the study by Vickers and Adolphe (1997) who compared the gaze control of elite and near-elite volleyball players during a serve reception. Their results revealed that despite similarities in the speed and timing of the motor response, the elite players retained a perceptual advantage over the near-elite players which was displayed in their ability to transition from steady fixations on the server prior to ball projection, into the smooth pursuit tracking of the ball (the tracking QE). The elite players were able to locate and track the ball sooner than the near-elite players, leading to a tracking QE on the ball of over 432ms. Critically, however the near-elite players

were not able to initiate any tracking of the ball before the movement onset, so had no QE duration (defined in this study as the final tracking fixation on the ball prior to the first step towards the ball). This would suggest that either the near-elite players are moving towards the ball nearly half a second earlier than the elite players, or as Vickers (2007) postulates, they were late to fixate and track the ball after the serve. In either case, early visual information gathered about the flight of an object is critical to direct that response (e.g. Hayhoe, Mennie, Sullivan, & Gorgos, 2005; Land & McLeod, 2000), even if the individual is capable of making online updates to this movement.

Rodrigues, Vickers, and Williams (2002) also found that low skilled table tennis players were delayed in their onset of the QE, which the authors suggested led to their poorer success in their service response task. The high skilled players however initiated the QE significantly earlier than the low skilled players, so were able to acquire initial visual information earlier in order to better prepare their response. Interestingly, as the movement response velocity and timing was invariant between the groups, this perceptual advantage of high skilled players may be the critical factor underpinning their performance advantage. Causer et al's (2010) use of shotgun tasks enabled them to examine a particular subset of interception skills; those where the target travels away from the participant and is intercepted by an external object (shotgun pellets) launched by the performer. Therefore although this task does represent an externally-paced interceptive action, it could also be classified as a far aiming skill. Despite these task differences, Causer et al. (2010) found that a relative tracking QE was also significantly longer for elite compared to sub-elite performers, and the QE was also longer for successful performance outcomes.

Vine et al. (2014) proposed three explanations for the positive effect of an earlier, longer QE. The first of these was related to attentional control. As previously discussed, it is important to focus visual attention on the correct location at the right time to extract optimal, task-relevant visual information (Land, 2009). In terms of attentional control, Vine et al. (2014) placed the QE within the context of the attentional model of Corbetta and colleagues; who discuss the balance between top-down (goal-directed) and bottom-up (stimulus-driven) attentional systems. The top-down system is involved in linking relevant stimuli (such as visual cues) to a response selection. The bottom-up system however detects salient (often task-irrelevant) information that interrupts the top-down system (Corbetta, Patel, & Schilman, 2008). The QE is proposed to serve the purpose of maintaining goal-directed attention, thereby reducing the impact of external or internal distractions from the stimulus driven system (Vine et al., 2014). By maintaining this attentional focus on relevant visual stimuli during the critical QE period, an individual will be able to pick-up information about the environmental and task parameters that will allow them to programme effective and accurate movements. By becoming distracted however, an individual may 'miss' or overlook important visual cues.

The second explanation is that longer QE durations represent a critical pre-programming period, where the response is planned and organised, resulting in more efficient and accurate movements. In their study of billiards potting, Williams et al. (2002a) observed a longer QE duration for more complex shots indicating that more extensive planning of the movement was required. This is supported by more complex tasks having longer reaction times (e.g. Klapp, 1980), as these tasks require greater processing of the task parameters and interfering environmental factors. Furthermore, evidence suggests the

generation of an internal model is used to predict movement consequences and parameterise a movement (Wolpert, Ghahramani, & Jordan, 1995). A longer QE duration would provide an individual with more time to develop and update this model, which in turn will better guide a movement response (Flanagan & Wing, 1997).

The final explanation proposed by Vine et al. (2014) is that the QE provides an external focus of attention (adverse to an internal focus), which has been extensively associated with superior motor learning and task execution (review by Wulf, 2013). An external focus is described as the attentional focus on the effects of one's movements rather than the movements themselves (Zachry, Wulf, Mercer, & Bezodis, 2005). This has been shown to produce a psychomotor quieting of neurophysiological factors such as heart rate and muscle activity that benefits performance (Moore, Vine, Cooke, Ring, & Wilson, 2012; Radlo, Steinberg, Singer, Barba, & Melnikov, 2002). The constrained action hypothesis has also been used to explain the positive effect of an external focus, suggesting that instructions relating to an internal focus of attention cause an individual to attempt to consciously control their movements, inadvertently interrupting autonomous processes (McNevin, Shea, & Wulf, 2003). An external focus however makes no such constraints on the performances. Skilled performance is a combination of movement effectiveness (such as consistency, accuracy, and reliability) and movement efficiency (fluent, economic and autonomous movements). By adopting an external attentional focus, Wulf (2013) suggests that both these aspects of skilled performance are performed better and the skill acquired sooner. In addition, this theory has recently been successfully transferred to the skill

performance (throwing accuracy) of children with Attention Deficit/Hyperactivity Disorder (Saemi, Porter, Wulf, Ghotbi-Varzaneh, & Bakhtiari, 2013).

Although these three mechanisms are perhaps most relevant to static, self-paced tasks, it is likely that the perceptual benefits underpinning the QE period are a reflection of many aspects. Vine et al. (2014) recommend therefore that further research of these processes be continued. A recent direction of research activity has sought to understand the extent to which the QE might simply reflect a by-product of expertise, or whether it has a functional role in supporting performance. One of the strongest means of supporting a causal role for QE is via a training paradigm; where the impact of being taught a longer QE early in training could be assessed. Performance improvements associated with training the QE would indicate that the QE is indeed the driver of proficiency related differences.

2.1.5. Quiet Eye Training (QET)

The purpose of QET is to direct an individual's visual attention to an optimal target-orientated location prior to the onset of a critical movement. The timing and duration of this gaze is important to optimise the pick-up of relevant visual information, so QET encourages an individual to locate the target rapidly and fixate or track it for an extended period prior to the onset of the movement.

QET studies have so far taken a relatively consistent approach to intervention strategies. These studies use a task-orientated approach, which firstly involves identifying the 'elite gaze strategies' used by expert performers in the task. QET then usually involves a combination of verbal instructions and video feedback to overtly guide a performer's decisions regarding where and when to direct their gaze whilst performing the skill (Vine et al., 2014). There

are two forms of QET that have been explored in sports literature: the training of novices to improve their skill acquisition, and the fine-tuning of the skills of elite performers. The latter of these two training types has received the most extensive investigation, starting with Harle and Vickers (2001) who were the first researchers to explore QET. These authors and others have found that QET benefits the performance of elite athletes, and these benefits are also transferred to competitive environments (Causer, Holmes, & Williams, 2011; Vine, Moore, & Wilson, 2011).

Several studies of QET have also focused on skill acquisition of novice sports performers. Vine and Wilson (2010) investigated QET in golf putting in novice golfers in comparison to standard training and coaching techniques. Results indicated that novices could be taught to replicate the longer QE durations of expert golfers and that this could expedite their learning (albeit non-significantly) compared to participants trained using traditional putting instructions. However, advantages for QET were visible in a transfer pressure test; control participants' QE durations reduced below a threshold and performance faltered, whereas these decrements did not occur for the QET participants. In a follow-up study using a basketball free-throw task (Vine and Wilson, 2011), significant performance advantages for QET were found at both the retention tests and in the pressure condition. Moore et al. (2012) have recently shed light on why QET may be effective; revealing that QET participants demonstrated more efficient psychophysiology (increased cardiovascular and EMG deceleration in the seconds preceding putter-ball contact) and smoother putter path profiles than their traditional trained counterparts.

Despite research demonstrating the benefits of QET in other domains; e.g., laparoscopic surgery (Vine, Chaytor, McGrath, Masters, & Wilson, 2013a; Wilson et al., 2011b) and military shooting (Moore et al., 2014) prior to this thesis project, no studies have investigated the QE or QET in children. Abercrombie (1964) proposed that children could learn to perceive task demands more quickly if they can accurately direct their eyes to a target, and maintain a gaze for longer, as this will limit the proportion of time the irrelevant images will occupy the retina. This suggestion supports the conclusions from the previously discussed research of the QE in adults, and so opens a new avenue for research to investigate whether the QE can also distinguish between motor skill proficiency and performance outcomes in children. Furthermore a perceptual training intervention such as QET may prove to be an effective intervention for children with poor motor skills such as those suffering from the condition Developmental Coordination Disorder (DCD). This condition is discussed in the second part of this literature review.

2.2. Developmental Coordination Disorder (DCD)

2.2.1. Defining DCD

Developmental Coordination Disorder (DCD) is a condition characterised by a marked impairment in the development of motor coordination (in relation to an individual's chronological age) that significantly interferes with activities of everyday life and/or academic achievement (DSM-IV-TR, American Psychiatric Association, 2000). Furthermore these impairments are not a result of any other medical or neurological disorder. Whilst uncertainty still surrounds the precise aetiology of DCD (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013), empirical studies of the condition have shown it to negatively influence academic achievement (Chen, Tsai, Hsu, Ma, & Lai, 2013; Liberman, Ratzon, & Bart, 2013), social development (Chen, Tseng, Hu, & Cermak, 2009; Tseng, Howe, Chuang, & Hsieh, 2007) and long-term physical health (Cairney & Veldhuizen, 2013).

DCD is a heterogeneous disorder as the motor coordination deficits experienced by individuals with the condition are varied (Polatajko & Cantin, 2006); ranging from impairments in gross motor skills such as balance and locomotion to fine motor skills such as manual dexterity (or a combination of the two). There is also a high level of co-occurrence with DCD and other disorders such as Attention Deficit/Hyperactivity Disorder (ADHD; Martin, Piek, & Hay, 2006), Autism Spectrum Disorders (ASDs; Kirby, Sugden, & Purcell, 2014) and specific language/reading impairments such as dyslexia (Crawford & Dewey, 2008). Furthermore, DCD is also not confined to children but can continue into adolescence and adulthood (Cantell, Smyth, & Ahonen, 2003).

2.2.2. Measurement, Diagnosis and Prevalence of DCD

There is currently no 'gold standard' assessment for motor coordination or DCD. However the two most widely used measures are the Movement Assessment Battery for Children (M-ABC, Henderson & Sugden, 1992; revised version: MABC-2, Henderson, Sugden, & Barnett, 2007) and the Bruininks Oseretsky Test of Motor Proficiency (BOTMP, Bruininks, 1978; revised version: BOTMP-2, Bruininks & Bruininks, 2005). These are standardised, validated measures of motor coordination ability used in both research and clinical practice. Both of these measures assess performance on tasks involving fine motor skill, balance and ball skills and provide norm-referencing to quantify an individual's motor coordination ability. The M-ABC/MABC-2 has been more extensively used and validated in recent research (Blank, Smits-Engelsman, Polatajko, & Wilson, 2012; Schoemaker, Niemeijer, Flapper, & Smits-Engelsman, 2012), with Blank et al. (2012) stating that the M-ABC (and MABC-2) is a more sensitive measure compared to the BOTMP and has stronger intra and inter-rater reliability. Furthermore, the MABC-2 has been extensively validated in populations of children in Asia (Hua, Gu, Meng, & Wu, 2013; Wang, Su, & Su, 2012), South America (Ramalho, Valentini, Muraro, Gadens, & Nobre, 2013; Valentini, Ramalho, & Oliveira, 2014), and Europe (Ellinoudis et al., 2011; Schoemaker et al., 2012; Schulz, Henderson, Sugden, & Barnett, 2011; Smits-Engelsman, Niemeijer, & van Waelvelde, 2011; Wagner, Kastner, Petermann, & Bos, 2011). Holm, Tvetter, Aulie, and Stuge (2013) concluded from their study that the MABC-2 (age band 2: 7-11year olds) would make an effective diagnostic tool for movement coordination disorders such as DCD.

Authors of the MABC-2 and other assessments of motor coordination such as BOTMP-2 recommend that scores at or below the 5th percentile in

reference to national norms indicate an individual is highly likely to experience a “severe movement disorder”. This 5th percentile cut-off was also proposed in the Leeds Consensus Statement (Sugden, Chambers, & Utley, 2006) as a diagnosis of DCD, however Blank et al. (2012) suggest in their recommendations for the European Academy for Childhood Disability that such a severe level may lead to children with milder forms of DCD being missed and therefore fail to receive the necessary support for their condition. Blank et al. (2012) suggest that scores below the 15th percentile could therefore be used for the diagnosis of DCD, which has led to a divide in the research with some authors preferring the 15th percentile cut-off (e.g. Beutum, Cordier, & Bundy, 2013; Silman, Cairney, Hay, Klentrou, & Faught, 2011), whilst others use the more stringent 5th percentile, which may be more reliable in ensuring a DCD diagnosis for the purposes of research.

Venetsanou et al. (2011) proposed that currently the MABC-2 cannot be used alone as a gold-standard diagnostic tool for DCD largely due to the heterogeneous nature of the condition, so many studies of DCD use a battery of measures alongside the MABC-2 such as a clinical diagnosis by a health professional, parent/teacher opinion or a further measure of motor control such as a handwriting test to ensure better reliability of the diagnostic criteria. Due to this lack of a standardised diagnostic tool and the variability in cut-off recommendations used in measures such as the MABC-2 and BOTMP-2, the reported prevalence of DCD is varied (Asonitou, Koutsouki, Kourtessis, & Charitou, 2012; Hendrix, Prins, & Dekkers, 2014). The DSM-IV-TR (American Psychiatric Association, 2000) proposes the prevalence of DCD is around 6% of primary-aged children, however studies using more or less stringent diagnostic criteria have suggested this figure may be as low as 1.7% (Lingam, Hunt,

Golding, Jongmans, & Emond, 2009) or as high as 22% (Cermak & Larkin, 2002, p.14).

2.2.3. Visuomotor Control of children with DCD

Measures of motor control such as the MABC-2 provide a researcher or clinician with information regarding the outcome of a movement (e.g. number of steps taken, balls caught), however these tests provide little insight regarding how the motor skills are performed or why a child with DCD has performed poorly on the test (Van Waelvelde, De Weerd, De Cock, Smits-Engelsman, & Peersman, 2004). There appear to be two schools of thought on the aetiology of the motor deficits observed in DCD, with some researchers suggesting these children have problems with the physical execution of a movement (e.g. Deconinck et al., 2006) whilst many others propose that children with DCD experience information processing (or more specifically, visual perceptual) problems that result in imprecise movements (e.g. Cheng et al., 2014; Estil, Ingvaldsen, & Whiting, 2002; Tsai & Wu, 2008; Wilson & McKenzie, 1998) or compensatory motor strategies (e.g. Van Waelvelde et al., 2004).

From an information processing perspective, visual perception and action are inextricably linked as the accurate pick-up and processing of visual information will guide the selection and execution of a motor skill (Land, 2009). Therefore the precise mapping between perception and action is critical for motor coordination (Tsai & Wu, 2008). Although some inconsistencies do exist in the literature regarding visual perceptual impairments in DCD (such as Bonifacci, 2004), the majority of research in this area supports the proposition that children with DCD are less able to pick-up and process visual information compared to typically developing peers, even in tasks where a motor response

is not required (Sigmundsson, Hansen, & Talcott, 2003; Tsai, Wilson, & Wu, 2008; Wilson & McKenzie, 1998).

In their meta-analysis of information processing deficits in children with DCD, Wilson and McKenzie (1998) concluded that a visual spatial processing impairment was the most consistent finding. Visual spatial processing relates to the early stage in the production of a motor response to a stimulus, where the organisation and processing of visual information takes place. In an aiming task, the visual spatial processing of advanced information (or pre-cues) allows an individual to select and pre-programme a response prior to the initiation of a movement. This relates directly to the QE literature where it is proposed that a longer QE gaze will afford an individual more time to process sensory information and parameterise a movement (Vine et al., 2014; chapter 2.1.4).

Wilmot and Wann (2008) however found that when a clear visual pre-cue indicated the exact location of a target (to be grasped), children with DCD were unable to improve their hand response to a level similar to that of typically developing children. Furthermore, when the pre-cue about the target became more ambiguous, the performance of children with DCD was not statistically different from no-cue conditions. Wilmot and Wann (2008) postulated that typically developing children were able to partially plan a movement based on incomplete visual information (prediction) and then update this movement online as more visual information becomes available. They suggested that the DCD children are unable to formulate early predictions based on partial information or execute online modifications, and instead rely on waiting for complete visual information and making end-point corrections to their movements.

Wilmot and Wann's (2008) research would suggest that under time constraints, children with DCD were unable to process the available advanced visual information to select and parameterise an accurate, speeded response (see also Braddick & Atkinson, 2013). Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, and Vingerhoets (2013) also found that children with DCD made fewer anticipatory responses and reacted more slowly to the appearance of visual targets in a task that involved a very simple response (press a button) compared to typically developing counterparts. This effect even occurred when the targets were presented in a predictable temporal pattern. There have been some conflicting findings however: Pettit et al. (2008) found that children with DCD were able to reduce their response times based on partial visual information on simple tasks if speed was emphasised in the task instructions. The response time did however have a negative linear relationship with the quality of visual information, and the children with DCD were still unable to match the response time of typically developing controls.

These studies highlight the visual perceptual impairments of children with DCD that influences their response selection and time. Debrabant et al. (2013) note that these impairments seen in complex tasks such as catching, don't diminish with practice, perhaps because children with DCD are not learning from prior perceptual feedback, resulting in the task remaining novel, and so the perceptual demands of performing the motor skill remaining high. Debrabant and colleagues support this suggestion with evidence of more brain activity during the un-predictive condition for the typically developing children in areas of the prefrontal cortex (involved with executive function) and inferior frontal gyrus (involved with decision making) in comparison to the predictive condition where more autonomous processes took place. In comparison the DCD

children maintained a lower level of activity in both these regions of the brain across both conditions.

One explanation for little increase in neural activation in either condition for the DCD children is the internal modelling deficit hypothesis, which proposes that these children are unable to mentally simulate a movement without performing the overt action (Williams et al., 2011). Tsai, Chang, Hung, Tseng, and Chen (2012) however postulated that the visual processing deficit in DCD was a result of children allocating fewer resources to the evaluation and response to a stimulus, so it is possible that children with DCD do not take the time, or assign the processing resources required for developing an internal model. Therefore, by developing an earlier and longer QE duration on relevant information these children learn to develop better internal models to help them pre-programme a movement. Effective internal forward modelling provides stability to a motor system by predicting the outcome of a movement before the slow sensorimotor feedback becomes available (Williams et al., 2011; Williams, Omizzolo, Galea, & Vance, 2013). Wilson, Thomas, and Maruff (2002) have demonstrated that motor skills of children with DCD can be improved with motor imagery training, which may support more effective forward modelling. These findings would also indicate that a QET intervention that increases processing time and allocates visual attention to task-relevant cues for longer could improve the visuomotor skill of children with DCD.

Additionally, once a motor response has been initiated in children with DCD, Wilmut and Wann (2008) also identified further impairments in making online adjustments to the movement. Mon-Williams et al's (2005) prehension study demonstrated similar findings to that of Wilmut and Wann (2008), however these authors proposed that (in line with Pettit et al., 2008) the 'cost' of making

online adjustments based on partial information was too great for children with DCD due to the resulting increase in spatial errors. Perturbation studies have also been used to investigate online modifications to movements. This method involves a targeting task where occasionally the target is moved or perturbed once an aiming movement has commenced, forcing the participant to make an online adjustment. Typically developing adults are able to make rapid smooth adjustments to their movements when a target is perturbed (Turrell, Bard, Fleury, Teasdale, & Martin, 1998), however Hyde and Wilson (2011a) and Hyde and Wilson (2011b) found that in comparison to typically developing peers, children with DCD were slow and inaccurate when making online corrections to a perturbed target.

It is possible that the impairments in making online modifications to movements are also related to poor detection and processing of visual information. Studies have found that gaze behaviour (such as pursuit tracking) can distinguish between children with and without DCD (e.g. Langaas, Mon-Williams, Wann, Pascal, & Thompson, 1998; Robert et al., 2014) and these impairments to gaze behaviour may also contribute to deficits in motor coordination (Robert et al., 2014). A longer tracking QE on the ball during catching will provide children with more detailed and updated visual information about the trajectory and speed of the ball as it approaches the interception point.

To summarise, children with DCD have deficits in visuomotor control that result in imprecise or compensatory movement strategies. The literature would indicate these children are unable to pick-up and process visual information even in the absence of a motor response (Hyde & Wilson, 2011a; Hyde & Wilson, 2011b). As a result the ability of children with DCD to pre-plan and

organise a movement (prediction), as well adjust their movements to changing task constraints (online visual processing) are impaired in comparison to typically developing peers. QET may be a suitable intervention therefore for overcoming some of these impairments by allocating visual attention to relevant cues and increasing the processing time to help initiate a more accurate response.

2.2.4. Health and Fitness of Children with DCD

Children with DCD are more likely to be overweight or obese than those without the disorder (Cairney, Hay, Faught, & Hawes, 2005a; Hendrix et al., 2014; Zhu et al., 2014). Cairney et al. (2010) found the BMI of children with DCD was on average 15% higher than typically developing peers, and Silman et al. (2011) found a group of children with DCD had a 40% greater body fat percentage than controls. In their systematic review of obesity in children with DCD, Hendrix et al. (2014) found a conclusive positive association between fat mass and DCD.

There is little doubt that the physical health deficits identified in children with DCD are associated with lower levels of physical activity (Cairney et al., 2010; Cairney & Veldhuizen, 2013; Green et al., 2011; Poulsen, Ziviani, & Cuskelly, 2008). Some debate remains regarding the causality of this association, however Cairney and Veldhuizen (2013) proposed that impaired motor function (such as DCD) causes physical inactivity, which in turn increases the risk of obesity and poor cardiorespiratory fitness. Support for this theory comes from Tsai et al. (2014), who found that an intense cardiorespiratory fitness intervention significantly improved motor skill in children with DCD (measured by MABC-2). Cairney and Veldhuizen (2013) do however

acknowledge the possibility of a reverse causality and there is evidence that DCD may cause physiological (Chia, Reid, Licari, & Guelfi, 2013; Ferguson, Aertssen, Rameckers, Jelsma, & Smits-Engelsman, 2014) and mechanical (Hands & Larkin, 2002) inefficiencies during exercise that would result in earlier fatigue compared to typically developing children (Faught et al., 2013).

Regardless of the cause, there is a vast body of literature supporting the association between DCD and lower cardiorespiratory fitness (see review by Rivilis et al., 2011) along with other aspects of poor physical fitness (e.g. Santos, Ribeiro, Pellegrini, Rocha, & Hiraga, 2012).

Another factor in the association between DCD and poor physical health is the emotional response of the children towards physical activity. Several studies have suggested that children with DCD are self-conscious about their impaired motor skills and as a result choose to withdraw from structured physical activities (e.g. Green et al., 2011; Kwan, Cairney, Hay, & Faught, 2013). Bart, Jarus, Erez, and Rosenberg (2011) found that very young children with DCD (4-6 years old) reported significantly lower enjoyment after physical activity even when compared to those with mild developmental difficulties. Lower self-perceptions and poor self-adequacy of children with DCD have been linked with lower engagement in physical activity (Hay & Missiuna, 1998) and ultimately a review by Zwicker, Harris, and Klassen (2013) found that children with DCD experience more feelings of anxiety, depression, low self-efficacy and more social problems than typically developing peers reflecting an overall poorer quality of life. All these factors are likely to contribute to the destructive downward spiral of children with DCD having negative feelings towards physical activities, leading to withdrawal and more inactivity, which is linked with poorer physical and emotional health that further compounds their negative attitude to

physical activity. These factors highlight the importance of studying DCD for greater understanding of the condition and crucially the development of effective intervention strategies to encourage children with the condition to take part in more physical and social activities.

2.2.5. Current Intervention Strategies

There are several approaches to therapeutic intervention that have been used to treat children with DCD both in research and clinical settings such as physiotherapy, cognitive motor training, perceptual or sensory training and chemical or dietary supplementation (see review by Smits-Engelsman et al., 2013). This array of strategies perhaps reflects back to the unclear aetiology of the condition and the heterogenous nature of DCD. However Green, Chambers, and Sugden (2008) found no evidence of DCD subtype affecting a child's response to intervention (beyond the more extreme challenges faced by children with more profound movement problems) and Smits-Engelsman et al. (2013) state that all children with DCD do appear to benefit from some form of intervention.

The intervention strategies for DCD can be categorised into two groups based on their theory and methodology. The first of these groups is the process-orientated approach, which is based on the assumption that not all tasks and activities can be individually taught, so 'teaching for transfer' is required (Sugden, 2007). This approach targets the specific components required to perform a movement or skill such as the sensory, (visual) perceptual and kinaesthetic skills. Snapp-Childs, Mon-Williams, and Bingham (2013) were successfully able to use a sensory-motor intervention (simulated computerised tasks that activate cerebellar and parietal networks) to teach complex motor skills to children with DCD, and Hillier's (2007) review specifically identified the

sensory approach (the most commonly researched intervention method within this approach – involves teaching children to use their senses more effectively to pick-up information) to be highly effective in treating children with DCD. However a lot of the literature identified by Hillier dates back to the early 1990's. More recently researchers have been a lot more sceptical of the benefits of process-orientated interventions (Niemeijer, Smits-Engelsman, & Schoemaker, 2007; Pless & Carlsson, 2000; Smits-Engelsman et al., 2013; Sugden, 2007) as many of the studies have incorporated this approach with other intervention methods or implemented them in a task-specific manner. There is also no clear evidence of the transferability of these skills to other motor skills. Pless and Carlsson (2000) postulated that approaches that utilise a fundamental, skill-specific intervention are most effective in improving the motor skills of children with DCD.

The task-orientated approach has received more research focus of late and these studies have revealed very promising results, with children significantly improving skills measured by the MABC-2 including fine motor control, throwing and catching, and static and dynamic balance (e.g. Ferguson, Jelsma, Jelsma, & Smits-Engelsman, 2013; Jongmans, Smits-Engelsman, & Schoemaker, 2003; Niemeijer et al., 2007; Sugden, 2007; Sugden & Chambers, 2003; Tsai, 2009) as well as more generic skills such as isometric and functional strength and aerobic fitness (Ferguson et al., 2013). This approach directly attends to motor performance and often involves training skills and aspects of motor skills children with DCD perform poorly. Smits-Engelsman et al. (2013) identify two examples of this approach that have proven effective in studies of task-orientated intervention. The first of these is neuromotor task training (NTT) that was conceptualised as a result of the limited efficacy of the

previously popular process-orientated approaches (Niemeijer et al., 2007). NTT involves a personalised child-centred approach, where a therapist implements functional exercises which gradually become more challenging to develop the motor control processes involved in the successful execution of a task. The second example of task-orientated intervention is the cognitive orientation to daily occupational performance (CO-OP). CO-OP has many similarities to NTT, but implies the use of specific cognitive strategies to solve movement problems when executing a motor task to facilitate the skill acquisition (Sugden, 2007). One aspect of this intervention approach is to learn how to generate internal models of a movement (so attempting to overcome the internal modelling deficit hypothesis), which a child uses to guide, check and reflect on movement execution. Smits-Engelsman et al. (2013) recommended the use of task-orientated approaches such as NTT and CO-OP to improve motor performance in children with DCD as they found much larger effect sizes in comparison with process-orientated approaches.

The previously discussed QET intervention is a task-orientated intervention strategy that attempts to improve the perceptual skills of performers to help the pick-up the most pertinent information in a visuospatial display to improve visuomotor control and provide more opportunity for processing of an internal model. Previous tasks used for QET of novices are golf putting, basketball free-throw shooting, and surgical skills training. It could be argued however that none of these tasks are particularly relevant to improving the quality of life for child, so a more appropriate task is considered in the next part of this literature review. Object control and specifically ball catching is a fundamental movement skill (Lubans et al., 2010) that has been associated with higher levels of participation in physical activity. Furthermore, the visuomotor

aspects of catching have been studied in some depth although the QE is yet to be examined in this skill.

2.3. Interception and Catching Skill

2.3.1. Importance of Catching

Fundamental movement skill proficiency is important for the development of sports specific skills (Barnett, van Beurden, Morgan, Brooks, & Beard, 2008a) and the resultant participation in physical activity (Okely & Booth, 2004).

Lubans et al. (2010) identified fundamental movement skills such as locomotor skills (running, jumping, hopping), object control (throwing, catching, kicking, striking) and stability (balancing, twisting). Lubans et al. (2010) concluded from their analysis that the development of these skills during childhood is important for the social, physical and psychological health of both children and adolescents.

Specifically, Barnett, Van Beurden, Morgan, Brooks, and Beard (2009) identified childhood object control proficiency as the most important factor that predicted the amount of time spent in organised moderate-vigorous physical activity and subsequently, this also increased the probability of any participation in adolescent vigorous physical activity. Barnett and colleagues also determined that this greater object control proficiency during childhood is positively linked with higher adolescent cardiorespiratory fitness (Barnett et al., 2008). These studies emphasise the significance of the mastery of ball control skills as a child, as these skills make up an important part of many moderate and vigorous physical activities, playground games and sports played by children and adults. Furthermore object control skills also promote perceived sports competence in children, which is a positive factor in physical activity participation (Barnett et al., 2008).

One specific aspect of this skill that has been most extensively researched in typically developing children and children with DCD is catching. This skill is included in many assessments of motor proficiency (e.g. M-ABC, MABC-2, Test of Gross Motor Development-2 (TGMD-2; Ulrich, 2000), BOTMP, BOTMP-2) as it is a complex motor skill that measures the perceptual and motor aspects of movement execution. In the MABC-2, the catching task involves throwing a tennis ball at a wall 2m away from the participant and catching it cleanly on the return. This task is utilised in this thesis so it is pertinent to discuss the skill of catching for typically developing children and those with DCD.

2.3.2. Catching Skill in Typically Developing Children and Adults

Interceptive skill appears to produce an invariant motor response in adults irrespective of the ability of a performer (Vickers, 2007). Studies of table tennis have revealed that motor response times (such as movement onset, offset, duration and velocity) do not significantly differ depending on participant ability (Bootsma, 1991; Bootsma & Van Wieringen, 1988; Rodrigues et al., 2002). This leads one in the direction therefore of assessing the visual and perceptual abilities of performers in order to distinguish between the abilities of experts and novices.

Van der Kamp et al. (2008) identified two visual perceptual systems that contribute to catching performance in adults. The ventral system gains knowledge about the task environment by recognising the location, size and trajectory of an object and the thrower, therefore identifying action possibilities. The dorsal system takes over later in the skill, providing rapid, implicit information to regulate the on-going movement. The coupling of these aspects

of a skill are likely important to the execution of an interceptive action (Dicks, Button, & Davids, 2010; Savelsbergh, Van der Kamp, Williams, & Ward, 2005; Shim, Carlton, Chow, & Chae, 2005) as Panchuk, Davids, Sakadjian, MacMahon, and Parrington (2013) found that early information gathered from visual search prior to projection results in earlier and longer tracking of the ball and therefore faster and more accurate responses.

When catching fly balls, Oudejans, Michaels, Bakker, and Davids (1999) observed that catchers use head and eye movements to quickly locate and track the ball through the air. When thrown from the hand, catchers with ball skill experience could locate the ball within 100ms and track it for 95% of its trajectory. This 'eye-in-head system', identified by (Sharp & Whiting, 1974, 1975) is the preferred technique when a performer can track the ball for more than 365ms. However when the ball was projected from a machine, the participants in Oudejans et al's study (1999) would take up to 400ms to locate the ball, suggesting that postural cues from the thrower's body regarding the release of the ball are important cues to aid prediction and shifting of gaze.

Hayhoe et al. (2005) noted that in ball catching when a bounce occurs, it is important to relocate the ball on the retina as quickly as possible after the bounce and continue smooth pursuit tracking. This often requires the use of a predictive or anticipatory saccade to a location just beyond the bounce point, which is a demanding skill to perform accurately (Hayhoe et al., 2005; Hayhoe, McKinney, Chajka, & Pelz, 2012; Land & McLeod, 2000) and has been observed as a skill performed more effectively by elite athletes in comparison to near-elite athletes (Vickers & Adolphe, 1997). These saccades are also required if the pursuit tracking system slips or loses the image of the ball on the retina or if an unpredicted deviation or bounce occurs and the pursuit system is

required to catch the ball up. This technique for a bounce catch is relevant to the catching task of the MABC-2 later examined in this thesis.

Although the motor responses of novice and elite adults may not differ much in an interceptive task (Vickers & Adolphe, 1997), this is not necessarily the case for children, as the skill development needs to be taken into consideration. Williams (1992) identified 3 visuomotor strategies of catching that he was able to associate with age. Williams ranked these in order of maturity with the lowest being retrospective-cradling which involved little visual attention on the ball, and cradling the ball with the body to perform the catch. 82% of children at 4 years old used this strategy during 2-hand catching. The second developmental phase of catching is concurrent-clamping where the child attempts to visually track the ball with some degree of success and they 'clamp' the ball between their hands. This strategy is used by 65% of children aged 6 years. The most mature development of catching technique identified by Williams is the predictive-grasping strategy, where the child utilises early visual information during the ball's flight to make accurate predictions resulting in them grasping the ball away from the body. This strategy was used by 88% of children aged 8 years and 100% of children aged 10 years, and Williams notes this skilled catching technique is characterised by rapid and accurate visual appraisal of the ball flight characteristics gathered in the early stages of the flight which ultimately guides the accurate movements of the hands and timing of the grasping action. Furthermore, it would appear good or mature catchers are able to make online adaptations (late adjustments) to their movements during the catch right up until the final 100ms before contact (Astill & Utley, 2008).

2.3.3. Catching impairments in children with DCD

Authors such as Przysucha and Maraj (2010) hypothesised that studying the catching of children with DCD may afford significant insights into the movement organisation of children with the condition. Indeed, children with DCD consistently demonstrate poorer catching performance in comparison to typically developing counterparts (e.g. Asmussen, Przysucha, & Dounskaia, 2014; Astill, 2007; Astill & Utley, 2006; Estil et al., 2002; Przysucha & Maraj, 2010, 2013; Sekaran, Reid, Chin, Ndiaye, & Licari, 2012; Utley, Steenbergen, & Astill, 2007; Van Waelvelde et al., 2004). There are currently no studies of the influence of the QE or any other gaze behaviour in catching performance in children with or without DCD, however a study by Van Waelvelde et al. (2004) provides an insight into these deficits in catching by comparing children with DCD (aged 7.5-9.5 years) to a group of younger typically developing children (aged as young as 5 years) who were matched with the DCD children by their baseline catching score. The authors found that with practice, the younger typically developing children used fundamentally different catching strategies to the children with DCD. The differences observed between these groups centred on grasping errors, with both groups initially making many more grasping errors in comparison to aged-matched (7.5-9.5 years) typically developing children. The children with DCD however persisted with their original catching technique despite numerous errors being made and balls being dropped. This technique involved arms extended in front of them and attempts to clamp or grasp the ball in their hands. In comparison, the younger typically developing children adapted their strategy and used their bodies to cradle or trap the ball to complete the catch as Williams (1992) suggest children of this age would. There has been some suggestion that the movements of children with DCD

when catching are similar to younger children (e.g. Strohmeyer, Williams, & Schaubgeorge, 1991), however the findings of the Van Waelvelde et al. (2004) study support the notion that the movements of children with DCD are not simply delayed, but were indeed different from typically developing peers. Other work has also shown that children with DCD do not simply grow out of their movement impairments (Losse et al., 1991) supporting the view that the development of these children is 'deviant', not delayed (Utley et al., 2007).

2.3.4. Differences in catching technique of children with and without DCD

Researchers have attempted to quantify the differences observed in the catching technique of children with and without DCD by studying the kinematics of their limb movements whilst catching. Astill (2007), Przysucha and Maraj (2010) and Estil et al. (2002) all observed that children with movement problems or DCD exhibit a large number of grasping (or temporal) errors when catching. In their study, Estil et al. (2002) proposed that children with movement problems (scored < 5th percentile on MABC-2) had adapted their technique by waiting to see more of the flight, so reaching for the ball later, and initiating the grasping movement earlier to compensate for poor temporal judgement.

The later initiation of a reaching movement has already been discussed in reference to the findings of Mon-Williams et al. (2005) and Wilmot & Wann (2008) where it was proposed that later reaching movements were made due to an inability of children with DCD to make accurate spatial predictions and online adjustments to movements based on incomplete visual information, or that the cost of making these predictions was too high in comparison to the benefit of an increased response time. It is also possible that the earlier initiation of a grasping movement when catching would limit the child's ability to make online

adaptations to their movement, which may contribute to poorer performance and more grasping errors observed in these studies (Astill & Utley, 2008). As Mon-Williams et al. proposed in their 2005 study, Estil et al. (2002) also suggested that these different movement times created a safety margin in the temporally constrained task so were a compensatory strategy employed to better cope with the children's impairments in visual perception and therefore prediction of the ball direction and speed. However it is important to note, the task used by Estil et al. (2002) represented an important limitation of this study as it involved dividing the two components of a catch (reaching and grasping) into two separate tasks. The movements of the participant in each task were therefore largely constrained and so did not represent a complete catching movement.

A study by Deconinck et al. (2006) did find conflicting results, suggesting that children with DCD had similar grasp initiation times to typically developing children when catching. The simplest explanation for these different findings is the ball speeds used in the studies, with Deconinck et al. (2006) projecting the ball at a faster pace, forcing both groups of children to initiate grasping sooner, and limiting the capacity for typically developing children to utilise online control. Astill and Utley (2008) however produced similar findings to Estil et al. (2002) when using a more realistic (although still laboratory adapted) catching task and this study also used more stringent diagnostic assessment of participants with DCD compared to the Deconinck et al. study (<5th vs <15th percentile on M-ABC).

Astill and colleagues provide further support for kinematic differences of children with and without DCD and the compensatory strategy theory in a series of ball catching studies. Utley, Steenbergen and Astill (2007) considered the

kinematics of arm movements during two handed catching and found that the technique of children with DCD employed less elbow flexion at the point of the catch in comparison to typically developing children who quickly learned to flex their elbows just prior to ball contact to absorb the speed of the ball. Utley et al. (2007) suggested that the lack of flexion used by the children with DCD was because they need to simplify a complex skill such as catching. By reducing the movement around a joint such as the elbow, this results in fewer 'degrees of freedom' that the children have to control. This decrease in elbow flexion was also observed in other studies such as Astill and Utley (2006), Astill (2007) and Przysucha and Maraj (2013) alongside another strategy that involved the linking or coupling of the arms throughout the catch in children with DCD. Coupling of the arms so they moved symmetrically would also support the notion of limiting the degrees of freedom the children with DCD had to control, whereas the typically developing children were able to manipulate the arms separately.

A more detailed kinematical analysis of these movements during catching found that the children with DCD did initiate later reaching and earlier grasping movements, as was found in the study by Estil and colleagues (Astill & Utley, 2008), and these authors certainly don't rule out the suggestion that this is a compensatory strategy for impairments in the visual perception, prediction or parameterizing of movements. Indeed, Utley and Astill (2007) demonstrate that children with DCD may attempt to plan the reaching phase of the catch in advance of temporal constraints by holding their extended arms out in a position they anticipate intercepting the ball. This is a time-efficient technique that limits the amount of movement required under the severe temporal constraints of a catch affording the child more time to process the visual information as it becomes available. Lefebvre and Reid (1998) used a virtual

visual occlusion paradigm to demonstrate the necessity of increased processing time for children with DCD during a catching task. This study found that typically developing children were significantly more accurate than those with DCD at predicting the direction of a thrown ball (projected on a screen in front of them) when it was occluded at 100ms and 200ms after projection. At 300ms after projection, the children with DCD were able to increase the accuracy of their predictions. These findings suggest that children with DCD do require more visual information or processing time to accurately predict ball flight. Other studies such as Wilmut and Wann (2008) have also found that an increased processing time available between the appearance of a visual cue and the requirement to respond also improves the speed and accuracy of the movements of children with DCD. However since the study by Lefebvre and Reid (1998) there have been no further studies of visual perception of children with DCD during a catching task.

This evidence would suggest that a QET intervention – guiding where and when to look to find the most useful target related information to plan and control the subsequent catch attempt – may be an effective strategy for improving the catching skill of children with DCD, and this is the overarching aim of this thesis. However, the QE has never before been studied in typically developing children, so the first aim of this thesis is to investigate the QE during a catching task of children with a range of movement skills. By including children with high motor ability in this initial phase, we will learn more about the ‘expert’ gaze strategies and QE durations of children in comparison with median and low skilled children. It is these expert gaze strategies that will then be used to construct the QE training protocols.

The second phase of this project is to investigate whether QET is transferable to children. This form of training was conceptualised in adults and athletes, so it is likely some methodological adaptations will need to be made to make this intervention appropriate for typically developing children. The final phase of this project will be to apply a QET intervention to children diagnosed with DCD to determine the potential effectiveness of this form of intervention for improving catching skill. This literature review presents evidence that an improvement in visuomotor performance through QET can enhance an ability such as catching skill, which has the potential for physical, social and psychological benefits in children suffering from DCD.

Chapter 3

Study 1: The Quiet Eye distinguishes between children of high and low motor coordination abilities

The study in this chapter was published as Wilson, M.R., Miles, C.A.L., Vine, S.J., & Vickers, J.N. (2013). Quiet eye distinguishes between children of high and low motor coordination abilities, *Medicine and Science in Sport and Exercise*, 45(6), 1144-51.

3.1. Introduction

Effective motor coordination is critical for the performance of functional movements underpinning physical activity and cardio-respiratory fitness in children and adolescents (Barnett, Van Beurden, Morgan, Brooks, & Beard, 2008b; Hands, 2008; Lubans et al., 2010). It is well known that children with low motor coordination (LMC) score lower in cardiovascular endurance, balance, body composition and movement time than their typically developing peers (Hands, 2008; Lubans et al., 2010). Children with LMC also suffer from deficits in motor programming and attentional control (Tsai, 2009; Tsai, Pan, Chang, Wang, & Tseng, 2010) but much less is known about how deficits in how they mentally interact with the world underlay their physical deficits. Although studies have documented perceptual differences between LMC and typically developing children (Langaas et al., 1998; Mon-Williams et al., 2005; Wilmut & Wann, 2008) these have been carried out using laboratory tasks where there has been no attempt to couple the child's visual perception of the task environment with their movements as a real world task is performed.

Gaze registration techniques provide an insight into how external visual information is used to guide and control goal-directed motor actions (Land, 2009). Research has shown that children with impaired motor coordination use less effective gaze strategies in controlled laboratory reaction time (Emes, Vickers, & Livingston, 1994), visual tracking (Langaas et al., 1998; Robert et al., 2014), and cued reach-to-grasp (Wilmut & Wann, 2008) tasks. While laboratory tasks provide strong internal control, they therefore provide limited transferability to the sort of dynamic, interceptive tasks relevant to sport and physical activity. For this reason, there has been a call from researchers to

extend the gaze analysis paradigm to more ecologically valid, 'real-life' tasks (Langaas et al., 1998; Wilmut & Wann, 2008).

The extensive body of literature in the sporting domain that has revealed a perceptual-cognitive advantage for expert performers (Mann et al., 2007) provides a useful departure point for research examining motor coordination in children in more ecologically valid settings. Expert performers direct high acuity foveal vision to the right place at the right time to provide accurate and timely information to the neural systems controlling goal-directed movements (Land, 2009; Vickers, 2007). This strategy, termed the Quiet Eye (QE), has been proposed to reflect a critical period of cognitive processing during which the parameters of a motor skill, such as force, direction and velocity are fine-tuned and programmed (Mann et al., 2007; Vickers, 1996). A growing body of research has revealed the consistent expert-novice differences with respect to the timing and duration of QE in both self-paced far-aiming tasks and interceptive tasks (see Mann et al., 2007; Vickers, 2007; Vine et al., 2014 for reviews).

The current study seeks to be the first to translate the knowledge about proficiency-related differences in QE in adults, to children of varying levels of motor coordination ability. Children with poor motor skills struggle particularly with the high degree of accurate coordination required to effectively perform dynamic interceptive tasks (Astill & Utley, 2006; Astill & Utley, 2008). We have therefore chosen to examine a throwing and catching task, as not only should it successfully differentiate motor ability, but also, this skill is a critical component of many sports and playground games. We hypothesise that more coordinated children will have a superior visuomotor strategy on both the targeting and tracking phases of a throw-and-catch task than children with low coordination.

Specifically, children with high motor coordination ability will reveal earlier and longer targeting QE periods (QE1) during the pre-throw phase, and earlier and longer tracking QE periods (QE2) on the ball prior to the catch attempt, than children with low motor coordination ability. As this strategy will provide advanced target information by which to accurately plan the catching action, coordinated children should also make more successful catches.

3.2. Methods

3.2.1. Participants

Fifty-seven children (29 female, 28 male) were recruited from Year 5 classes in two primary schools in the South West of England (mean age = 10.4 years, SD = 0.47). Prior to commencing the study, ethical approval was gained from a local ethics committee, and informed written parental and participant consent was provided. Participants attended individually and were tested in a school classroom provided for the duration of the research.

3.2.2. Tasks / Assessment

The MABC-2 was used to determine a motor coordination score for each participant (Henderson et al., 2007). The test was designed to identify and describe impairments in the motor function of children and as was discussed in chapter 2.2.2, the MABC-2 is one of the most highly validated and widely used measures in both clinical and research settings (Schulz et al., 2011). The MABC-2 consists of eight tasks designed for three age bands (3-6, 7-10, and 11-16 years old), incorporating manual dexterity, aiming and catching, and

balance elements. The child's performance on each of these tasks (either a score for accuracy or completion time) are age-adjusted and converted to standardised scores. An overall score is then computed which can be converted to a population percentile to aid diagnosis (Henderson et al., 2007).

3.2.3. Apparatus

Each participant was fitted with an Applied Science Laboratories Mobile Eye gaze registration system (ASL; Bedford, MA), which measures momentary point of gaze at 30Hz. The system incorporates a pair of lightweight (78g) glasses fitted with eye and scene cameras, and a portable recording device – a modified digital video cassette recorder (VCR). Gaze data was collected wirelessly to digital videotape and an experimenter held the VCR behind the participant to ensure that relevant objects were within the field of view. All testing equipment was provided with the MABC-2 assessment pack and standard testing procedures were followed.

3.2.4. Experimental Protocol

Participants completed all eight tasks from the MABC-2 in line with the instructions in the manual (Henderson et al., 2007). The eye tracker was calibrated at the outset of the testing period and at the start of each new task, as the scene camera sometimes had to be adjusted to ensure that the field of view included the objects of interest. While gaze data was collected for all tasks, we were most interested in the throwing and catching task (task 4) for the reasons discussed in chapter 2.3.1. In this task, the participant stood behind a line marked on the floor 2 meters from a blank wall. The participant was then instructed to throw a tennis ball against the wall and attempt to catch it cleanly

in their hands. They were instructed to only use their hands to catch the ball (not to gather it against their chests) and to not allow it to bounce on the floor before it reached them. They were allowed to step forwards to catch the ball once they had thrown it. The task was first explained to the participant by a researcher and then demonstrated once. Participants were then given 5 practice trials to reduce practice effects, before completing 10 experimental trials with the outcome of each being recorded (catch / no catch) (Henderson et al., 2007).

3.2.5. Catching Performance

Catching performance was indexed by both an absolute score out of ten, expressed as a percentage (number caught cleanly x 100 / 10), and a standardised score - accounting for age differences - taken from tables in the MABC-2 manual (range 5–15; Henderson et al., 2007). The standardised score was calculated for each task using tabulated to age norms that were published as part of the MABC-2 (Henderson et al., 2007).

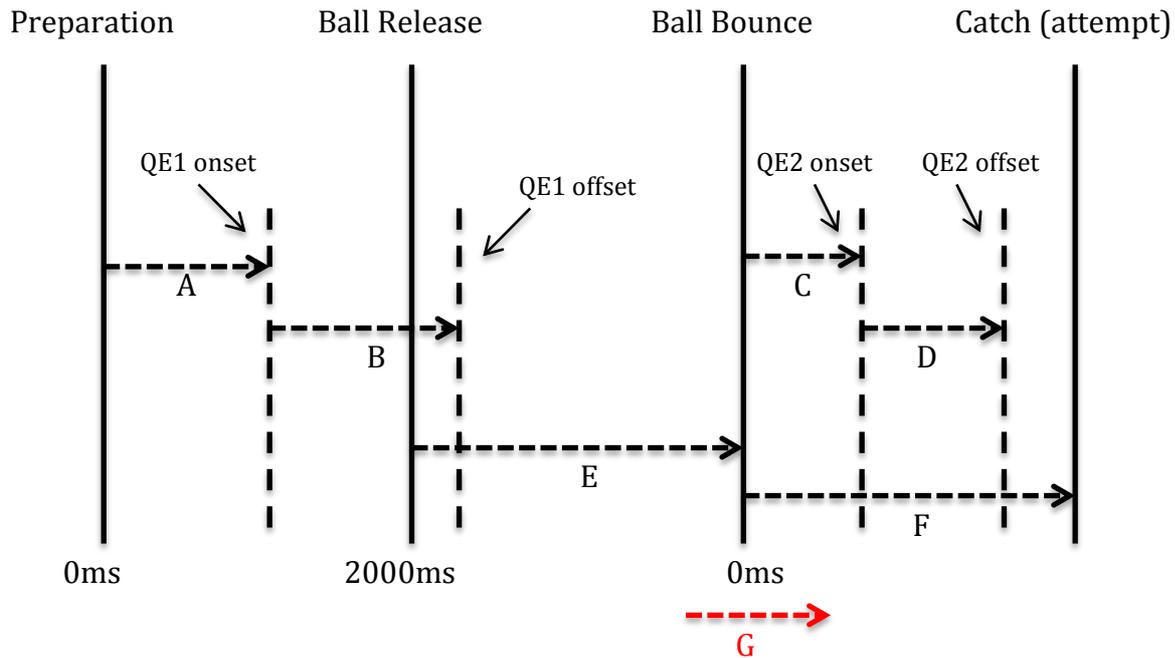
3.2.6. Ball Flight Times

Ball flight time (ms) was recorded as a proxy measure of how the throw and catch were performed. Two specific phases were identified: Flight Time 1 (FT1; throw: hand – wall) was defined as the time from ball release to wall contact and reflects the speed and trajectory of the throw (Time 'E' in Figure 3.1). Flight Time 2 (FT2: rebound: wall – hand) was defined as the time from wall contact until the ball was either caught, struck the participant's body or another surface, or passed the initial throw line (Time 'F' in Figure 3.1). FT2 is dependent on both the initial throw parameters, and the catching technique

employed; e.g., how early the participant attempts to intercept the ball. Total flight time (TFT: hand – hand) was calculated by summing the two sub-components. Ball flight times (ms) were recorded from the gaze registration system's scene camera and analysed in a frame-by-frame manner for each attempt.

3.2.7. QE Measures

The gaze data was downloaded from digital tapes to a computer (Lenovo Thinkpad R500) using Eyevision software (ASL). The location and duration of gaze was then analysed in a frame-by-frame manner for each throw, using Quiet Eye Solutions vision-in-action software (www.QuietEyeSolutions.com). The QE is “a final fixation or tracking gaze that is located on a specific location or object in the visuomotor workspace within 3° of visual angle (or less) for a minimum of 100ms” (Vickers, 2007, p11). This generic definition is operationalized for each task in relation to three consistent components: its onset, offset, and duration (time from onset to offset). Chapter 2.1.4 describes how earlier and longer QE periods are indicative of more expert-like performance, whether they are fixations to a stationary target, or a tracking gaze on a moving object (Vickers, 2007). Figure 3.1 provides a schematic representation of how the QE variables were operationally defined with respect to the key actions and outcomes of the throw and catch task. All trials where a QE onset and offset could be determined were included to help calculate a mean value for each participant, to be used in subsequent analyses (see Results).



A = QE1 onset time (ms): Calculated from a standard 'origin' (Ball Release - 2000ms)

B = QE1 duration (ms): Offset time - onset time (N.B. offset might be before or after ball release)

C = QE2 onset (ms): Calculated from a standard 'origin' (0 - ball bounce on wall)

D = QE2 duration (ms): Offset time - onset time

E = Flight time 1 (ms): From ball release to ball bounce

F = Flight time 2 (ms): From ball bounce to catch attempt/ trial end

G = Correction fixation location (mm): Fixation that takes place during the ball bounce

Figure 3.1: A schematic representation of how the gaze variables were defined relative to the key action points (preparation, ball release, ball bounce on wall, and catch [attempt]).

QE1. The onset of the (Targeting) QE1 was defined as the start of the final fixation (within a 3° area on the wall) prior to the critical targeting action (Vickers, 2007; Vine, Moore & Wilson, 2014) - the release of the ball. As with other QE research for throwing tasks (Vickers, 1996; Wilson, Vine, & Wood, 2009), the onset is reported relative to a standardised preparation phase - set at

2000ms before the ball release (Time 'A' in Figure 3.1). Offset occurred when the gaze deviated off the fixated location (by 3° or more) for more than three frames (100ms). QE1 duration was therefore defined as the duration between QE1 onset and offset (ms: Time 'B' in Figure 3.1).

QE2. In interceptive tasks such as catching, pursuit tracking on the object occurs prior to the hands contacting the ball (Adolphe, Vickers, & Laplante, 1997; Panchuk & Vickers, 2009; Rodrigues et al., 2002). (Tracking) QE2 onset (ms) was the first gaze on the ball as it travelled towards the participant (Time 'C' in Figure 3.1). Offset occurred when the gaze deviated off the ball by more than 3° for three frames (100ms) as it travelled towards the participant, or when the trial ended (end of ball FT2). QE2 duration was defined as the duration between QE2 onset and offset (ms; Time 'D' in Figure 3.1). To control for differences in throwing and catching strategies, we also calculated QE2 onset and duration relative to ball FT2 (Time 'F' in Figure 3.1) (Causer et al., 2010; Causer et al., 2011). The relative QE measures were therefore calculated as: $(QE2 \times 100) / FT2$.

Correction fixation (location). Previous research of interceptive tasks that include a bounce or deviation (e.g., Land & McLeod, 2000) has suggested that elite performers are better at predicting the point of bounce on a surface in interceptive tasks. This fixation represents a link from the targeting QE1 fixation into the QE2 gaze. A more accurate fixation to the location of the bounce would be advantageous, as it is much more efficient to direct a quick saccade to a future location and maintain gaze steady there, than attempt to follow the fast-moving object (Land & McLeod, 2000). Children with better coordination should be better able to predict the bounce point during ball flight, making corrections from their initial fixation point (QE1), to a location nearer to where the ball hits

the wall. By maintaining a steady gaze at this point, information about the ball trajectory can be processed more effectively (e.g., Vickers & Lewinski, 2012). The correction fixation (>100ms; Time 'G' in Figure 3.1) therefore occurs at the moment that the ball contacts the wall. Its location (mm) was measured in relation to the location that the ball contacted the wall (mm). To calculate the correction fixation location, an object of known length was placed in view of the scene camera for each trial. The distance from the participant's final fixation location on the wall, and the ball bounce location was measured on screen and scaled relative to the fixed object.

3.2.8. Data Analysis

The MABC-2 performance data was recorded using a standardized answer booklet and scored in accordance with the test protocol; including age corrections and standardisation procedures (Henderson et al., 2007). A tertiary split was then performed on the MABC-2 percentile scores for the sample; creating a high motor coordination group (HMC), a median motor coordination group (MMC), and a low motor coordination group (LMC). One-way analysis of variance analyses (SPSS Version 19) were computed to compare differences in MABC-2 score, catching performance, ball flight, gaze and QE measures, between these three groups. Effect sizes were calculated using partial eta squared (η_p^2) for omnibus comparisons and Bonferroni corrected post hoc tests were used to interrogate significant main effects. The corrected alpha level was $p = .002$. To determine the extent of a link between QE1 and QE2, regression analyses were conducted. This would indicate if a longer QE1 predicted a more accurate correction fixation, and furthermore, if a more accurate correction fixation could predict an earlier QE2 onset.

As significant group differences in the visuomotor variables of interest may be due in part to functional differences between 'catch' and 'no-catch' attempts (LMC will have fewer successful catches than HMC participants), we also ran the ANOVAs on caught trials only. Mediation analyses were finally computed to determine whether any gaze measures mediated between-group differences in catching performance, using the *MEDIATE* SPSS custom dialog (Hayes & Preacher, 2012). This process determines the total, direct and indirect effect of group on catching performance, through a series of proposed mediators, allowing inferences to be made about the indirect effects using percentile bootstrap confidence intervals. The gaze variables were individually entered into this analysis as a potential mediator to determine to what extent each measure facilitated the group differences that are observed in catching score.

3.3. Results

The gaze data of some participants was of poor quality and could not be accurately coded. In order for a participant to be included in the analyses a minimum criterion of 3 code-able trials out of 10 was set for each QE variable (see degrees of freedom for each analysis). A second analyst blindly scored 10% of the code-able trials (1 from each participant) and inter-rater reliability was assessed using the inter-observer agreement method (Thomas, Nelson, & Silverman, 2011). This analysis revealed a satisfactory level of agreement at 92.5% (Moore et al., 2012).

3.3.1. Movement Assessment Battery for Children-2

Motor coordination ability varied across the sample of 57 children (mean MABC-2 percentile rank = 51.05; *SD* = 26.38; range = 97.90). Four participants

were classified as 'highly likely' to have a clinical movement disorder (Developmental Coordination Disorder; DCD); scoring below the 5th percentile of a population norm (Henderson et al., 2007). A further four children were found to be 'at risk' of having DCD as they scored below the 16th percentile. At the high end of the range, two children scored at or above the 95th percentile, demonstrating excellent movement coordination, and a further ten children scored at or above the 84th percentile.

A tertiary split of the sample population was performed based on MABC-2 percentile rankings. The LMC group contained 16 participants (6 female, 10 male) with a mean MABC-2 score of 64.06 ($SD = 13.12$), and mean percentile rank of 18.76 ($SD = 8.58$). The MMC group contained 25 participants (10 male, 15 female) with a mean MABC-2 score of 79.24 ($SD = 3.96$) and percentile rank of 50.52 ($SD = 10.92$). The HMC group was made up of 16 participants (8 female and 8 male) with an average MABC-2 score of 91.13 ($SD = 3.61$) and mean percentile rank of 84.19 ($SD = 7.02$). The ANOVA yielded a significant effect of group on MABC-2 score, $F_{(2,54)} = 50.49$, $p < .001$, $\eta_p^2 = .65$, and percentile rank, $F_{(2,54)} = 196.41$, $p < .001$, $\eta_p^2 = .88$. The Bonferroni corrected comparisons revealed significant differences in movement coordination score and percentile rank between all three groups (p 's $< .001$). Age was not significantly correlated with percentile rank, $r = -.16$, $p = .242$, or MABC-2 score, $r = -.18$, $p = .182$, and independent t -tests showed there was no significant difference between genders in percentile rank; $t_{(55)} = 0.93$, $p = .358$, or MABC-2 score; $t_{(55)} = 1.30$, $p = .200$. The MABC-2 data are presented in Table 3.1.

3.3.2. Catching Performance

ANOVA yielded a significant group difference in percentage number of balls caught, $F_{(2,54)} = 18.78$, $p < .001$, $\eta_p^2 = .41$, and the standardised catching

score, $F_{(2,54)} = 16.46$, $p < .001$, $\eta_p^2 = .38$. Bonferroni corrected comparisons revealed that the HMC group performed significantly better than either the MMC (mean differences: balls caught = 29% score = 2, p 's $< .001$) or the LMC groups (mean differences: balls caught = 57% score = 5, p 's $< .001$), however the MMC group did not perform significantly better than the LMC group (mean difference = 30%, $p = .002$ for balls caught and mean difference = 3, $p = .048$ for score). Age was not significantly correlated with catching performance, $r = -.15$, $p = .274$, although boys were better at catching than girls, $t_{(55)} = -2.33$, $p = .024$. The catching performance data are presented in Table 3.1.

Table 3.1: Mean (S.E.M) movement ability and catching performance data for LMC, MMC, and HMC groups.

	LMC	MMC	HMC	F(2,54)
MABC-2 Score ¹	64.06 (13.12)	79.24 (3.96) ^a	91.13 (3.61) ^{a,b}	50.49***
MABC-2 % Rank	18.76 (8.58)	50.52 (10.92) ^a	84.19 (7.02) ^{a,b}	196.41***
Catching Performance (% caught)	35.00 (32.86)	62.00 (27.84) ^a	91.88 (12.76) ^{a,b}	18.78***
Catching Performance (Standardised Score)	7.50 (2.66)	9.12 (2.52) ^a	12.44 (2.28) ^{a,b}	16.46***

¹ MABC-2 score range = 73.

Note: Letters (a and b) indicate significant differences from LMC and MMC group values respectively. * $p < .05$; ** $p < .01$; *** $p < .001$.

3.3.3. Ball Flight

ANOVA revealed no significant group differences in either FT1 (throw), $F_{(2,45)} = 2.06$, $p = .140$; FT2 (rebound), $F_{(2,45)} = 0.44$, $p = .645$; or TFT, $F_{(2,45)} = 1.58$, $p = .217$. The ball flight data are presented in Table 3.2.

Table 3.2: Mean (S.E.M) ball flight times (ms) for LMC, MMC, and HMC

groups.

	LMC	MMC	HMC	$F_{(2,45)}^1$
Flight time ¹ (throw)	363.54 (60.73)	351.86 (94.31)	305.39 (74.76)	2.06
Flight time 2 (rebound)	506.42 (46.33)	515.86 (72.81)	496.49 (33.63)	0.44
Total flight time (throw + rebound)	869.96 (96.43)	867.14 (121.66)	806.46 (77.54)	1.58

¹ Degrees of freedom for ball flight and ²Total flight time were (2,44).

Note: No significant group differences found.

3.3.4. (Targeting) QE1

Onset. ANOVA revealed a significant difference in the time to QE1 onset between the groups, $F_{(2,44)} = 8.30$, $p = .001$, $\eta_p^2 = .27$. Bonferroni corrected comparisons demonstrated that the LMC group had significantly later onsets than the HMC (mean difference = 173ms, $p < .001$) but not the MMC group (mean difference = 99ms, $p = .012$). While the MMC group also had a later onset than the HMC group, this difference was not significant (mean difference = 74ms, $p = .076$). QE1 onset data are presented in Table 3.3.

Offset. There were no significant differences in the offset time, $F_{(2,44)} = 2.19$, $p = .124$, with all groups ending their fixation on the wall at around the point of ball release (see Table 3.3).

Duration. There were significant differences in the duration of QE1 period between groups, $F_{(2,44)} = 10.12$, $p < .001$, $\eta_p^2 = .32$. Bonferroni corrected comparisons revealed that the LMC group approached significance in their shorter QE1 periods in comparison to the MMC (mean difference = 151ms, $p = .003$) and significantly shorter HMC (mean difference = 237ms, $p < .001$) groups. While the MMC group also had a shorter QE1 period than the HMC group, this difference not significant (mean difference = 87ms, $p = .098$). QE1 duration data are presented in Table 3.3.

Table 3.3: Mean (S.E.M) QE1 variables (ms) for LMC, MMC, and HMC groups.

	LMC	MMC	HMC	F(2,44)
QE1 onset	1705.98 (84.72)	1607.06 (112.57) ^a	1533.32 (135.10) ^a	8.30 ^{**}
QE1 offset	1964.97 (60.43)	2016.80 (105.88)	2029.70 (84.45)	2.19
QE1 duration	258.99 (88.19)	409.74 (151.99) ^a	496.38 (170.69) ^a	10.12 ^{***}

Note: Letters (a and b) indicate significant differences from LMC and MMC group values respectively. * $p < .05$; ** $p < .01$; *** $p < .001$.

3.3.5. Tracking QE2

Onset. ANOVA yielded an almost significant group difference in the time to QE2 onset, $F_{(2,40)} = 3.10$, $p = .056$, $\eta_p^2 = .13$. As this finding approached significance, post hoc analyses were carried out. These revealed that the effect was largely driven by the LMC group having later onsets than the HMC group

(mean difference = 121ms, $p = .018$). The effect of standardising this time with respect to FT2 (Relative QE2 onset) was negligible, $F_{(2,40)} = 3.14$, $p = .054$, $\eta_p^2 = .14$. QE2 onset data are presented in Table 3.4.

Offset. The ANOVA on both the absolute QE2 Offset data, $F_{(2,40)} = 2.85$, $p = .069$, $\eta_p^2 = .13$ and the Relative QE2 Offset data, $F_{(2,40)} = 2.68$, $p = .081$, $\eta_p^2 = .12$, also only approached significance. Again, this effect was driven by the significant differences in offset between LMC and HMC groups (mean differences = 51ms and 10%, p 's = .022 and .027 respectively). QE2 offset data are presented in Table 3.4.

Duration. ANOVA revealed a significant difference for the duration of the QE2, $F_{(2,40)} = 13.66$, $p < .001$, $\eta_p^2 = .41$. Bonferroni corrected comparisons showed that the LMC group had a near significantly shorter QE2 duration than the MMC group (mean difference = 54ms, $p = .005$) and a significantly shorter QE1 duration in comparison to the HMC group (mean difference = 110ms, $p < .001$). The MMC group also had a near significantly shorter QE2 duration than the HMC group (mean difference = 55ms, $p = .007$). When the QE2 duration was standardised to account for FT2, the between groups ANOVA remained significant, $F_{(2,40)} = 12.29$, $p < .001$, $\eta_p^2 = .38$. Bonferroni corrected differences remained significant. QE2 duration data are presented in Table 3.4.

3.3.6. Correction Fixation

Correction Fixation. ANOVA yielded a significant difference between groups in the location of the correction fixation, $F_{(2,44)} = 3.34$, $p = .045$, $\eta_p^2 = .13$. Bonferroni corrected comparisons revealed that although not quite significant this was driven primarily by a difference in fixation duration between the LMC and HMC groups ($p = .013$). ANOVA also found a significant difference between groups in the location of the correction fixation, $F_{(2,44)} = 8.85$, $p = .001$,

$\eta_p^2 = .37$. The LMC group was less accurate than the MMC group ($p = .004$) and was significantly less accurate than the HMC group ($p < .001$). The regression analysis revealed that a longer QE1 duration significantly predicted a more accurate correction fixation location ($R^2 = .17, p = .003, b = -.67$). Furthermore, the location of the correction fixation also significantly predicted the variance in QE2 onset ($R^2 = .36, p < .001, b = .82$), indicating that a more accurate correction fixation resulted in an earlier QE2 onset. This analysis provides evidence of a link between the QE1 and QE2 periods. The correction fixation data are presented in Table 3.4.

Table 3.4: Mean (S.E.M) QE2 variables and the correction fixation location for LMC, MMC and HMC groups.

	LMC	MMC	HMC	F(2,40)
QE2 onset (ms)	207.06 (55.51)	172.88 (66.96)	148.00 (44.64) ^a	3.10 ¹
Relative QE2 onset (%)	40.58 (10.49)	35.57 (13.15)	29.00 (8.12) ^a	3.14 ²
QE2 offset (ms)	353.08 (21.87)	373.38 (67.55)	403.78 (44.84) ^a	2.85 ³
Relative QE2 offset (%)	70.61 (8.59)	74.47 (13.02)	80.54 (7.01) ^a	2.68 ⁴
QE2 duration (ms)	146.02 (53.20)	200.50 (49.00) ^a	255.78 (53.07) ^{a,b}	13.66 ^{***}
Relative QE2 duration (%)	29.94 (11.91)	41.31 (9.11) ^a	50.92 (10.61) ^{a,b}	12.29 ^{***}
Correction fixation location (mm)	237.09 (45.80)	117.10 (19.42)	55.55 (19.11)	8.85 ^{***}

¹ $p = .056$; ² $p = .054$; ³ $p = .069$; ⁴ $p = .081$

Note: Letters (a and b) indicate significant differences from LMC and MMC group values respectively. * $p < .05$; ** $p < .01$; *** $p < .001$.

3.3.7. Caught Trials Only

When only the trials that resulted in a catch were subjected to the same ANOVA as described previously for all codeable trials, the significant main effects for QE1 onset and duration, QE2 duration (absolute and relative) and correction fixation location all remained, but were reduced. Table 3.5 provides a detailed summary of the ball flight and QE data for caught trials only.

Table 3.5: Mean (S.E.M) Ball flight and gaze variables for caught trials only, for LMC, MMC and HMC groups.

	LMC	MMC	HMC	F	Degrees of Freedom
Ball flight 1 (ms)	314.54 (31.81)	316.46 (41.05)	308.95 (76.20)	0.08	(2,36)
Ball flight 2 (ms)	490.47 (43.33)	480.50 (55.92)	502.89 (33.63)	0.73	(2,31)
Total ball flight (ms)	799.79 (64.70)	794.28 (65.93)	814.97 (78.01)	0.29	(2,31)
QE1 onset (ms)	1735.36 (69.82)	1556.54 (142.31) ^a	1535.65 (136.05) ^a	7.54**	(2,36)
QE1 offset (ms)	2000.01 (30.25)	2010.95 (90.94)	2029.03 (84.54)	0.37	(2,36)
QE1 duration (ms)	264.65 (89.40)	454.41 (145.08) ^a	493.38 (170.80) ^a	7.34**	(2,36)
QE2 onset (ms)	196.36 (53.26)	184.56 (64.36)	149.55 (43.74)	1.86	(2,31)
Relative QE2 onset (%)	39.45 (9.82)	38.87 (13.00)	29.09 (8.05) ^{a,b}	3.05 ¹	(2, 31)
QE2 offset (ms)	389.79 (70.11)	388.16 (60.15)	408.80 (53.18)	0.42	(2,31)
Relative QE2 offset (%)	79.36 (11.50)	80.86 (9.28)	81.18 (7.62)	0.09	(2,31)
QE2 duration (ms)	193.43 (29.74)	203.60 (47.23)	259.25 (61.43) ^{a,b}	5.31**	(2,31)
Relative QE2 duration (%)	39.54 (4.58)	43.36 (9.46)	51.17 (11.04) ^{a,b}	3.87*	(2,31)
Correction fixation location (mm)	178.34 (26.39)	83.43 (17.23)	32.41 (14.84) ^{a,b}	6.32**	(2,31)

¹ $p = .062$

Note: Letters (a and b) indicate significant differences from LMC and MMC group values respectively. * $p < .05$; ** $p < .01$; *** $p < .001$.

3.3.8. Mediation

To check whether catching performance had been significantly facilitated by any of the gaze variables, group (coded: 1 = HMC; 2 = MMC; 3 = LMC) was entered as the independent variable, catching performance score as the dependent variable, and the significant gaze measures from the ANOVA individually entered as mediators. Results from bootstrapping (based on 10,000 sampling rate) indicated that there were significant indirect effects for correction fixation location (95% CL = 2.71 to 8.48) and QE2 duration (95% CI = 2.80 to 24.00). This means that the variance in these measures between the three groups indirectly facilitated the catching performance of each of the groups. When caught trials only were considered, no gaze variables mediated the significant group performance differences.

3.4. Discussion and Conclusions

This was the first published study to measure the QE in children, providing a novel examination of processes underpinning differences in children's motor coordination ability. A strength of the study was that it used an ecologically valid interception task (throwing and catching), that not only has relevance to sport and playground games, but has been shown to have predictive validity in many studies (Schulz et al., 2011). We hypothesised that children with high motor coordination ability would reveal a perceptual-cognitive advantage over less coordinated children. Specifically, we predicted that they would demonstrate earlier and longer targetting QE fixations (QE1; pre-throw), and earlier and longer tracking QE gaze (QE2; pre-catch). We also performed additional mediation analyses in order to better understand which (if any) of these gaze differences mediates catching ability. Until recently, this final step is

seldom performed in the QE or motor expertise literature (Moore et al., 2012), and is necessary to avoid over-inflating the importance of 'matching' group effects across variables of interest.

There was a wide performance range across the eight MABC-2 tasks, and it was possible to classify three distinct groups of movement ability (Table 3.1). There were significant differences in catching ability between the three groups (Table 3.1) and significant differences between the low and high motor coordination ability children in nearly all the QE measures (Tables 3.3 and 3.4). Interestingly, there were no significant differences in any of the ball flight measures, suggesting that the HMC group's performance advantage was not (solely) due to differences in the way the task was performed (e.g., speed and trajectory of throw and position of catch; Table 3.2). Rather, this advantage was underpinned by differences in visuomotor control during both the pre-throw and pre-catch phase of the task.

In the pre-throw phase of the task, HMC and MMC participants revealed earlier and longer QE1 durations. Indeed the HMC group's QE1 duration was nearly twice as long as that of the LMC group (500ms vs 260ms; Table 3.3). This finding mirrors that in research examining far aiming performance in adults, where the longer preparatory fixation is postulated to provide a quiet period to plan the ensuing motor response (Vine et al., 2014). As there was no specific target to throw to (unlike with most far aiming, targeting skills) it is interesting that ability-related differences in the QE1 duration were still evident, despite the lack of precision required. The correction fixation location indicates that the HMC participants used this processing time to help to predict in advance where the ball would bounce and thus provide more time to track the ball's final flight

to their hands (Land & McLeod, 2000). This provided an important link between the QE1 and QE2 for effective task performance.

In the pre-catch phase of the task, there were differences between the HMC and LMC participants in all QE2 measures examined (Table 3.4). The fact that the pre-catch gaze behaviours were more discriminatory is not surprising, given the increased precision required in this interceptive catching element, compared to the throwing element of the overall task. Most notably, near significant differences in both the onset and offset of the tracking gaze led to significant differences in the duration of QE2 between all three groups; 30%, 41%, and 51% of rebound time (FT2) for the LMC, MMC and HMC groups respectively. Not only was this the only process measure to reveal similar significant effects as the catching performance data between all three groups (Table 3.1), but the formal tests of mediation also revealed that differences in QE2 duration to be a significant predictor of group variances in catching performance.

Encouragingly, the significant group differences in both QE1 and QE2 durations remained even when unsuccessful catching attempts were removed prior to running the ANOVA (Table 3.5). Not surprisingly this re-analysis had the largest effect on the values of the LMC group, who caught the fewest attempts. They improved on nearly all the gaze measures when catches only were considered, most notably increasing the accuracy of their correction fixations (improving by 58mm), which assisted an earlier QE2 onset, and therefore led to a significant improvement in their relative QE2 duration by 10% (from 29% to 39%). This finding was unsurprising, as studies with adult participants have also found significant intra-individual effects in QE, in addition to inter-individual effects: with successful attempts categorised by longer QEs than unsuccessful

attempts (Mann et al., 2007; Vickers, 2007; Vine et al., 2014). While the significant effects in the ANOVA remained, the mediation analysis was no longer significant, therefore it could no longer be concluded that QE2 duration significantly facilitated the group differences in catching performance.

The question remains – why do the shorter QE periods of LMC children affect their performance in this way? The QE is postulated to provide the external spatial information needed by the brain (in conjunction with prior knowledge) to decide what it is going to do and how it is going to do it (Vickers, 2007). In effect the QE aids a prediction function in visuomotor control – helping performers to process novel transformations relating actions to their sensory consequences (Flanagan, Bowman, & Johansson, 2006; Flanagan, Vetter, Johansson, & Wolpert, 2003). The catching component of the task is simplified if a consistent relationship between the throw and the rebound can be established. We postulate that the HMC group's superior prediction is assisted by the extended information processing time facilitated by the longer QE durations during both targeting and tracking. This postulation is supported by QE research in other interceptive tasks with adults, such as returning serve in volleyball (Adolphe et al., 1997) and table tennis (Rodrigues et al., 2002), as well as shotgun shooting (Causer et al., 2010) and hockey goal tending (Panchuk & Vickers, 2009).

Further support for this expectation is provided by research demonstrating that this ability to predict and calibrate movements based on sensory feedback may be impaired in children with movement coordination difficulties (Astill & Utley, 2006, 2008; Hyde & Wilson, 2011a; Mon-Williams et al., 2005). Indeed, Wilmot and Wann (2008) have demonstrated in a relatively abstract desktop task, that children with DCD are slower in parameterising a

movement on the basis of predictive motion than typically developing children. In relation to the current study, LMC children may have greater difficulty in determining the consequences of using a particular level of force when throwing. We suggest that this may not be due to limitations in physiology and/or biomechanical characteristics, but to deficits in identifying relevant targets in space; allocating sufficient visual attention to that location to be successful; and predicting the consequences of the ensuing action. These children therefore base their catching movement on inaccurate cues, formulate inaccurate motor plans and gain inappropriate feedback due to inhibited perception and sensory feedback – driven in the main by their shorter QE periods.

There are some caveats to the findings presented, which are reflective of limitations in the study design. While using a standardised task with existing normative comparisons was a strength of the study, the MABC-2 protocol also added some constraints. First, the low number of trials meant that it was difficult to examine intra-individual differences in visuomotor control in participants who were at either end of the ability spectrum: thirteen participants caught all ten attempts, whereas seven caught none. The power of the analyses was reduced when participants had to be omitted for having insufficient successful trials to analyse (Table 3.5). Second, the scoring system is rather imprecise and fails to distinguish between better and poorer attempts, where the end result was still a failed catch. The imprecision of the dependent variable in the mediation analyses may therefore partially explain why more potential mediators were not found. Future studies could seek to apply more precise qualitative judgments of catching performance, which may be more sensitive to differences in visuomotor strategy (Przysucha & Maraj, 2010). A third limitation of the study,

reflected in the findings of the mediation analysis for the caught trials, was that other unconsidered variables are clearly important for the successful completion of the task. While we found no differences in our proxy measure of how the task was performed (ball flight times) this is a rather crude measure. Future research could look to perform more detailed movement kinematic analyses of the participants during the task to further our understanding of the processes underpinning successful interception skill in children (Astill & Utle, 2006, 2008; Mazyn, Savelsbergh, Montagne, & Lenoir, 2007).

While the results of this first study investigating the QE in children needs to be replicated for other tasks, they suggest that children with high movement coordination are better able to predict ball flight during the interceptive task of throwing and catching a ball. This interpretation is supported by previous QE research in interceptive tasks with adults (Adolphe et al., 1997; Causer et al., 2010; Panchuk & Vickers, 2009; Rodrigues et al., 2002), and by research examining more abstract tasks in adults (Flanagan et al., 2006; Flanagan et al., 2003), and in children with DCD (Astill & Utle, 2006, 2008; Hyde & Wilson, 2011a; Wilmut & Wann, 2008). The findings also suggest that task-orientated interventions designed to improve such prediction may be useful to support children with conditions like DCD. There may therefore be utility in designing QE training interventions for basic interceptive tasks like catching that are important building blocks to increased physical activity. Previous research has supported the efficacy of such training interventions in other interceptive tasks with skilled adults (Adolphe et al., 1997; Causer et al., 2011), and for targeting tasks with novice performers (Moore et al., 2012; Vine & Wilson, 2010, 2011). While such interventions will need to be specifically tailored to the needs of children with motor coordination difficulties, there is evidence to suggest that

QE training may have additional benefits for psychological constructs related to control and beliefs about success (Wood & Wilson, 2012). It is recognised that children with DCD have lower beliefs about their ability to be successful in performing movement skills (Cairney et al., 2005b) and may therefore especially benefit from QE training.

To conclude, the current study was the first to examine the QE phenomenon in children and answers the call from researchers to examine the processes underpinning movement coordination difficulties in 'real-life' tasks (Langaas et al., 1998, Wilmut & Wann, 2008). Children with low motor coordination ability demonstrated impaired visuomotor control and performance in a throwing and catching task that were related to an inability to accurately locate and track the ball as it rebounded off the wall. These results need to be replicated with other tasks, but there appears to be utility in exploring the application of QE training to populations outside of adult sport performers. Such interventions may help children with low motor coordination to break the negative cycle linking low motor skill competence with low levels of physical activity and cardio-respiratory fitness.

3.5. Future Directions

By establishing the visuomotor (QE1 and QE2) differences that contribute to the varying motor coordination abilities of children, we have addressed the first aim of this thesis. This finding also allows us to draw similarities to the adult QE literature, where studies have demonstrated that novice adults have shorter and later QE durations in comparison to elite counterparts (Mann et al., 2007; Vickers, 2007). It would therefore be interesting to explore if children with low motor coordination can be trained to

adopt 'expert-like' gaze behaviour (cf. novice adults; Moore et al., 2012; Vine & Wilson, 2010, 2011). These studies demonstrate that a performer can improve and become more robust in their execution of a motor skill with QE training (QET). The second aim of this thesis was to determine the effectiveness of QET in children at improving their throwing and catching ability. Therefore the second study of this thesis (chapter 4), makes the first attempt to adapt the QET interventions originally developed for adults, to teach the gaze behaviours of the highly coordinated children observed in the present study to children of a moderate to low motor coordination ability.

Chapter 4

Study 2: Developing Quiet Eye Training for Typically Developing Children

Experiment 1 of this chapter was published as Miles, C.A.L., Vine, S.J., Wood, G., Vickers, J.N. & Wilson, M.R. (2014). Quiet eye training improves throw and catch performance in children, *Psychology of Sport and Exercise*, 15, 511-515. Experiment 2 was funded by the Waterloo Foundation.

Experiment 2 of this chapter has been submitted as Miles, C.A.L., Wood, G., Vine, S.J., Vickers, J.N. & Wilson, M.R. (under review). Exploring the efficacy of QET for long-term learning in the catching performance of children. *European Journal of Sport Science (SI)*.

4.1. Introduction

It has been well documented that children's motor skill competence is an important factor for a healthy and active lifestyle (chapter 2.2.4; Haga, 2008). Indeed, significant inverse correlations have been reported between children's motor coordination abilities and their body mass index (D'Hondt et al., 2013). Effective interventions that help children improve their performance in the fundamental motor skills underpinning physical activity, playground games, and sport may therefore have clinical health benefits. The current study seeks to apply a novel, brief intervention approach - quiet eye training - to the learning of a particular fundamental motor skill; throwing and catching.

Children have generally learned the skill of ball catching by age ten, however, some children still find this task difficult (e.g. Przysucha & Maraj, 2010). Chapter 3 examined the gaze behaviour of children of varying motor coordination abilities in a throw and catch task in order to better understand the causes of these difficulties using Vickers' (1996) QE concept, which has reliably been shown to differentiate skilled performance in both targeting and interception tasks (see Vickers, 2007). The QE has been proposed to reflect a critical period of cognitive processing during which the control parameters of a motor skill are programmed (see chapter 2.1.4 for further detail).

Chapter 3 found significant group differences in both the duration of the targeting QE (preceding the throw) and the tracking QE (preceding the catch attempt). It was proposed that more coordinated children have significantly longer targeting (QE1) durations that assisted with better predictions (e.g. more accurate correction fixations) to the critical ball-wall bounce point. With their gaze focused on this location these children were closer to, and therefore better able to shift onto an earlier and longer tracking (QE2) duration resulting in better

catching performance than the less coordinated children. It was therefore suggested that the targeting and tracking QE durations represented the time needed to organise the neural networks underlying the throw and catch actions respectively. By extending QE1 duration, more coordinated children made more accurate throws, which in turn meant that they were able to initiate an earlier (and hence longer) QE2 duration to support the catch attempt.

The aim of the current study is to develop and assess the efficacy of a quiet eye training (QET) intervention for throwing and catching in children, based on the findings of the cross-sectional study in chapter 3. Experiment 1 of this study piloted a QET intervention, whilst experiment 2 expanded and adapted this methodology to improve the validity of the intervention and develop any weaknesses determined from experiment 1. This second experiment also examined the durability of QET over a 6-week period.

While QET has not previously been used with children, previous research has demonstrated that it can expedite the skill learning process of novice adult performers (see Vine et al., 2014 for a recent review). For example, Vine and Wilson (2011) demonstrated that novice basketball players who were taught to use a long QE fixation on the hoop prior to free-throw shooting had a greater increase in free-throw accuracy (pre- to post-test) than those trained using biomechanical cues. In line with these findings, we hypothesise that the QET children in the current study will reveal longer QE durations following training than their TT counterparts. Additionally, we hypothesise that although both groups of children are likely to improve their catching performance following training; this effect will be greater for the QET group.

4.2. Experiment 1: Methods

4.2.1. Participants

38 children (mean age, 10.32 years, $SD = 0.57$) were recruited from two year-five (4th grade) classes in two primary schools and were randomly assigned to a QET or TT intervention group. The study received ethical approval from a local ethics committee prior to testing and the children and their parents provided informed written consent.

4.2.2. Task

The same catching task from study 1 was used from the MABC-2 to assess throwing and catching ability (see chapter 3.2.4 for details of this task). As in study 1 and prescribed by the test (Henderson et al., 2007), performance was assessed over 10 trials.

4.2.3. QET and TT Training Interventions

The training phase of this study involved the QET and TT groups being shown a series of 3 instructional videos created for each intervention. Each of these videos was followed by a set of related practices guided by a researcher. The sets of QET and TT videos were created to be as similar as possible, using a split-screen, vision-in-action approach (Vickers, 2007), presenting a synchronised view of an individual performing the task (right half of the screen) and concurrent footage from the eye-tracker revealing momentary point of gaze (left half of the screen). For the TT videos, the movement video was highlighted with a red border and the gaze footage dimmed (to make it less noticeable). For

the QET videos the gaze data was highlighted and the motor data dimmed.

Both views remained available to the participants to provide them with a more complete view of the task, particularly as the QET group were receiving instructions relating to both the movement and their gaze behaviour.

Table 4.1 provides a summary of the content of the QET and TT instructional videos for the three phases of training. The QET videos were based on training the key QE behaviours uncovered in study 1 (chapter 3.3.4 and 3.3.5) for this task, first placing an emphasis on focusing gaze on a location on the wall to which they wanted to throw the ball prior to the throw (QE1), then quickly locating and continuously tracking the ball as it came towards them prior to the catch (QE2). The TT instructional videos were based on 'best practice' for learning throwing and catching and emphasised a smooth arm swing through to the release of the ball when throwing, followed by assuming a readiness position and holding the hands in front to cushion the ball during the catch (Bunker, Hardy, Smith, & Almond, 1994). These include the instruction 'watch the ball' which is similar to the QET directive however, because this instruction to watch the ball is so widely used to coach this skill, it is necessary to keep this in the TT instructions to retain a fair comparison between traditional and QE instructions.

Table 4.1. A summary of the instructions provided in the training videos for the quiet eye training (QET) and traditional training (TT) interventions for experiment 1.

	QET video	TT video
1. Throw	[General introduction] “See how the girl takes her time to aim at a spot on the wall before she throws? For a good throw, you’ll need to pick a spot or target to aim at. To aim, focus your eyes on this target and count to two before you start to throw. Remember; aim at your target, count to two and throw.”	[General introduction] “The girl pauses before she starts a smooth even swing of her arm as she releases the ball. For a good throw, pause for the count to two in order to prepare. Then your arm needs to swing smoothly right through your release. Remember; pause and count to two, then use an even swing with a smooth release.”
2. Catch	“Can you see how the girl keeps her eye focused on the ball tracking it all the way as it flies back into her outstretched hands? It’s really important that you focus very hard on watching or tracking the ball as it comes back to you. When catching, track the ball right back into your hands. Remember; track the ball from as soon as you see it, until it’s into your hands.”	“Can you see how the girl watches the ball right into her outstretched hands? It’s really important that you watch the ball into your hands. Focus on the ball as it comes into your outstretched hands. Remember; watch the ball all the way into your hands.”
3. Link	[Reemphasise the first two training points] “The girl keeps her eye on the ball throughout its bounce off the wall. This is an important part in linking the throw and the catch. To link the skills you need to look right at the ball as it hits the wall as if trying to read the writing on it. This is very important to improve your catching. Remember; look right at where the ball is hitting the wall. Concentrate on watching it bounce.” [Final summary of all three points]	[Reemphasise the first two training points] “After throwing the girl puts her hands together and reaches out in front of her as the ball approaches. This is called the ready position. To link the skills, you need to have your palms stuck together so there are no gaps for the ball to creep through. Then hold your hands out in front of you to cushion the ball safely back in. Remember; get your hands out in front of you with your palms stuck together in the ready position.” [Final summary of all three points]
Total runtime of QET video = 179seconds; TT video = 167seconds.		

4.2.4. Procedure

Testing and training sessions took place during the school day in a classroom that was dedicated to the study. Participants were tested individually and on arrival were fitted with an Applied Science Laboratories (ASL; Bedford, MA) Mobile Eye XG gaze registration system (a similar system to that described in chapter 3.2.3, although not identical). Once calibration was complete, the gaze data were recorded wirelessly at 30Hz onto a laptop (Lenovo R500 Thinkpad) using Eye Vision Software (ASL). The throw and catch task was first explained and demonstrated by the experimenter, and then participants were allowed five practice attempts (as per MABC-2 instructions; Henderson et al., 2007). Participants then completed ten pre-test trials before being randomly assigned to their training group.

The process was the same for both groups across the three phases of training. After watching each training video, the participants were asked to summarise the key points in order to check their understanding, before completing a prescribed number of practice trials. The first phase of the intervention was termed the throwing phase. The participants watched the first instructional video, and then completed 30 practice trials, throwing the ball against the wall. The second phase was the catch phase and again, after watching the second video, the experimenter delivered 30 throws to the participant from a distance of 2m. These throws consisted of 10 central throws, 10 to the right and 10 to the left of the participant, delivered in a randomised order. If a throw was deemed by the researcher to be out of the participant's reach, the throw was repeated. For the final phase the videos focused on the transition between the throw and catch elements of the task, so for the TT group this meant presenting their hands in the 'ready position', whilst the QET

instructions related to locating and tracking the ball earlier and for longer. Then for a final time, the participant completed 20 trials of the full MABC-2 throw and catch task.

During each set of the practices, after every fifth attempt the researcher reviewed the QET or TT instructions that related to that phase to the participant. Following a brief rest, participants completed 10 post-test trials of the MABC-2 task with no instructions (as pre-test). Total time for the testing and training was approximately 40-50 minutes and participants were allowed to rest between phases if required.

4.2.5. Measures

Many of the measures used in this study are identical to those used in study 1. Therefore they are not described here in detail as reference can be made to chapter 3.2.

Catching performance. Each participant's catching score out of ten during baseline and retention conditions was converted to a percentage success score as was done in study 1.

Ball flight times. The ball flight times were calculated using frame-by-frame analysis (30 Hz) of the Mobile Eye scene camera. Two of the measures of flight time are taken from study 1: FT1 (from release to wall contact) and FT2 (from wall contact to trial end).

Quiet eye. QE definitions also remain the same as study 1, described in chapter 3.2.7 and illustrated in Figure 3.1, however to reiterate, QE1 (pre-throw), was the final targeting fixation on the wall prior to the ball release. QE2 (pre-catch) was the final tracking gaze on the ball before the catch attempt (i.e., when the non-throwing hand joined the throwing hand). QE2 **onset** was the

time from the ball contacting the wall to the initiation of QE2. The correction fixation measure demonstrated a strong link between these two QE measures in chapter 3, where longer QE1 durations increased the participant's accuracy in their prediction of the throw direction and timing as it contacted the wall, leading to an earlier QE2 onset. To reduce the number of variables in the following studies this measure was not taken as it can be assumed the association measured by the correction fixation between a longer QE1 and earlier QE2 onset remains consistent in this MABC-2 throwing and catching task.

4.2.6. Data Analysis

While all children who volunteered for the study completed training and testing, not all were included in subsequent analyses. The purpose of this work was to determine if QET could improve the catching performance of typically developing children, therefore those who exhibited expertise in this skill at pre-test had to be excluded. There is also a ceiling effect in this task, which meant that children who scored highly at pre-test were unable to improve their scores. This meant fourteen participants were excluded due to expert baseline performances, as they caught 90% ($n = 4$) or 100% ($n = 10$) of attempts at pre-test. A further two participants were excluded (one from each group) as outliers, due to their z-score for delta catching performance being more than two standard deviations away from the mean. Finally, six participants could not be included, as incomplete gaze data meant that a manipulation check of QE durations post training could not be performed. This resulted in 16 participants being included in the analysis (QET group: $n = 5$ females, 3 males; TT group: $n = 7$ females, 1 male). Although this smaller sample size lowers the power of the

findings, Vine and Wilson's (2011) study with novice basketball players also only had 8 participants in each group, but revealed a significant interaction effect for free throw success percentage ($p = .007$, $\eta_p^2 = .419$, power = .840). In that study, the QET group had a significantly greater training effect (from 29% at pre-test to 66% at post-test) compared to the TT group (from 34% at pre-test to 54% at post-test).

All code-able throw and catch attempts for each participant were analysed and a mean value for each variable in each condition computed for use in subsequent analyses. Similarly to study 1, a second analyst blindly scored 10% of the code-able trials and inter-rater reliability was assessed using the inter-observer agreement method (Vine & Wilson, 2011). This analysis revealed a satisfactory level of agreement at 86.1%. Mixed design factorial ANOVAs (intervention group: QET/TT x condition: pre-test/post-test) were performed on the performance, ball flight and QE dependent variables. Effect sizes were calculated using partial eta squared (η_p^2) for omnibus comparisons. Bonferroni corrected post hoc tests were used to interrogate significant interaction effects.

Mediation analyses were computed to determine whether QE1 or QE2 mediated between-group differences in catching performance, using the MEDIANTE SPSS custom dialog (Hayes, 2013). This process determines the total, direct and indirect effect of the group on catching performance, through a series of proposed mediators, allowing inferences to be made about the indirect effects using percentile bootstrap confidence intervals. All data was analysed using SPSS (version 19).

4.3. Experiment 1: Results

4.3.1. Descriptive Statistics

The 16 participants identified for inclusion in the analysis were randomly allocated to the QET and TT groups. The skewness and kurtosis statistics for baseline performance were between the ranges for normal distribution (skewness $-1/+1$, kurtosis $-1/+2$). Each group had 8 participants (TT = 5 males, 3 females; QET = 7 males, 1 female). There was also no significant difference between the baseline catching performance of the QET and TT groups $t_{(14)} = .99$, $p = .339$.

4.3.2. Catching Performance

The ANOVA revealed no significant main effect for intervention group, $F_{(1,14)} = 0.03$, $p = .874$, $\eta_p^2 < .01$, or test, $F_{(1,14)} = 3.56$, $p = .080$, $\eta_p^2 = .20$. There was however a significant interaction, $F_{(1,14)} = 6.97$, $p = .019$, $\eta_p^2 = .33$. Follow up tests revealed that while there was a significant improvement in the catching performance of the QET group from pre- to post-test ($p = .004$), there was no significant improvement for the TT group ($p = .670$). There were no significant group differences in catching accuracy at pre- ($p = .339$) or post- ($p = .294$) test^{1,2} (Figure 4.1, Table 4.2).

¹ Note that converting the catching success percentage scores to standardised scores, accounting for age differences (Henderson et al., 2007) made no difference to these findings.

² We did also adopt a 10 point measure to describe each catch attempt (based on Pryzsucha & Maraj, 2010): 0 = no reaction; 3 = delayed reaction, no ball contact; 5 = ball contacts hands; 7 = fumble; 9 = fumble but re-grasped; 10 = clean catch / hands only). This more fine-grained measure of catching revealed a similar pattern to the objective MABC-2 score, however, the interaction effect marginally failed to reach significance, $F_{(1,14)} = 4.13$, $p = .062$, $\eta_p^2 = .23$, power = .47. The QET group's score increased from 6.4 ($SEM = 0.54$) to 7.3 ($SEM = 0.60$), while the TT group's score did not change: 6.8 ($SEM = 0.39$) at pre-test and 6.8 ($SEM = 0.48$) at post-test. This data was filmed from an external camera capturing at 25Hz (Canon MD101).

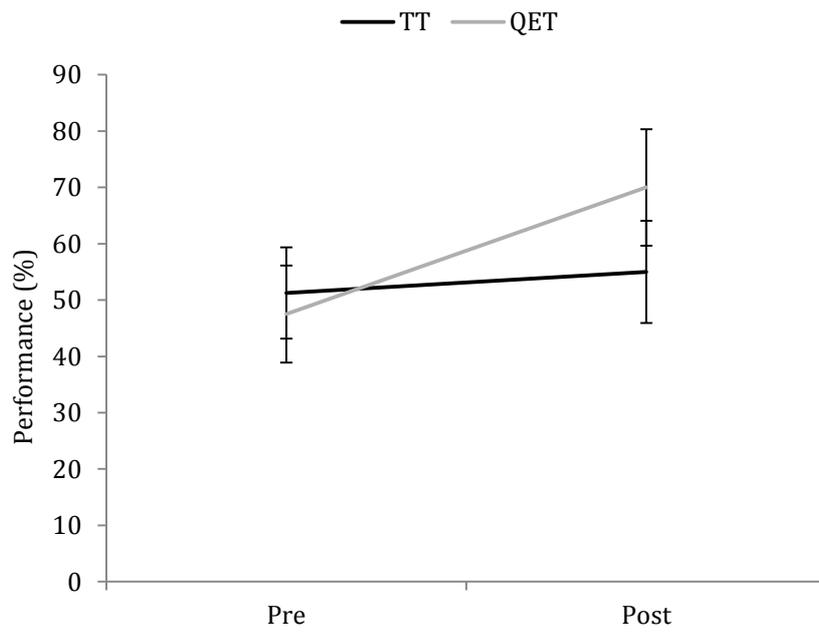


Figure 4.1: Experiment 1 – catching performance of QET and TT groups from pre- to post-training. (Error bars are S.E.M).

4.3.3. Ball Flight Times

On 6 trials of the 320 analysed, a FT measure could not be calculated because we could not detect the ball release or ball bounce from the Mobile Eye scene camera.

FT1. There was no significant main effect for intervention group, $F_{(1,14)} = 0.25$, $p = .625$, $\eta_p^2 = .02$, but there was a significant main effect for test, $F_{(1,14)} = 12.47$, $p = .003$, $\eta_p^2 = .47$. No significant interaction effect was found, $F_{(1,14)} = 0.75$, $p = .747$, $\eta_p^2 = .01$. Both groups displayed longer ball flight times from hand to wall at post- compared to pre-test (Figure 4.3 (a), Table 4.2).

FT2. The ANOVA revealed no significant main effect for intervention group, $F_{(1,14)} = 1.47$, $p = .245$, $\eta_p^2 = .10$, or test, $F_{(1,14)} = 0.79$, $p = .390$, $\eta_p^2 = .05$, or interaction effect, $F_{(1,14)} = .01$, $p = .918$, $\eta_p^2 < .01$ (Figure 4.3 (b), Table 4.2).

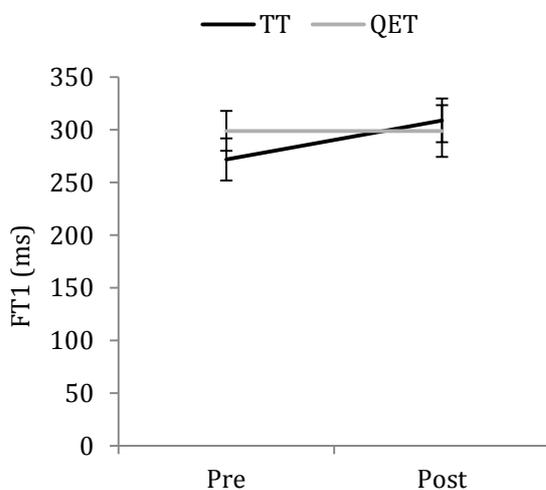


Figure 4.2 (a)

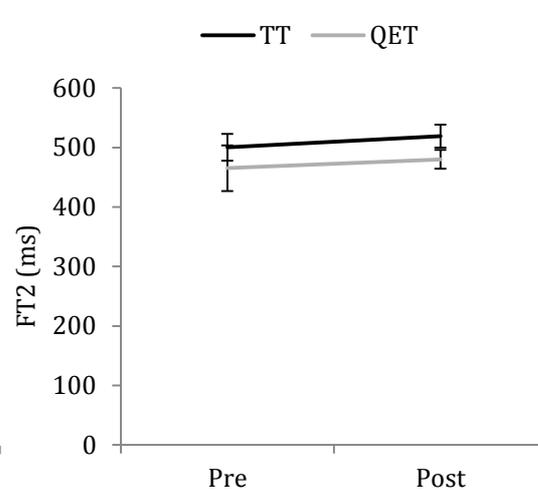


Figure 4.2 (b)

Figure 4.2: Experiment 1 – Flight time 1 (a) and Flight time 2 (b) for QET and TT groups from pre- to post-training. (Error bars are S.E.M).

4.3.4. QE Durations

There were 43 occasions when QE1 could not be computed (QET = 33, TT = 10) and 72 occasions when QE2 could not be computed (QET = 44, TT = 28) across the 320 trials analysed. However for each participant in each condition (pre- and post-test) we were able to determine both a QE1 and QE2 on more than 5 trials, allowing meaningful mean values to be computed.

QE1 (pre-throw). The ANOVA revealed no significant main effect for intervention group, $F_{(1,14)} = 3.13$, $p = .099$, $\eta_p^2 = .18$. There was however a significant main effect for test, $F_{(1,14)} = 16.93$, $p = .001$, $\eta_p^2 = .55$; and a significant interaction effect, $F_{(1,14)} = 39.71$, $p < .001$, $\eta_p^2 = .74$. Follow up comparisons revealed that the QET group significantly lengthened their QE1 duration following training ($p = .001$), whereas the TT group's QE1 duration was shorter ($p = .050$). Follow up tests revealed no significant differences in QE1 duration between the groups at pre-test ($p = .294$), but there was a significant difference between the groups at post-test ($p = .008$). (Figure 4.4. (a)).

QE2 (pre-catch). The ANOVA yielded no main effect for the intervention group, $F(1,14) = 0.01$, $p = .912$, $\eta_p^2 < .01$, however test approached significance, $F(1,14) = 3.99$, $p = .065$, $\eta_p^2 = .11$. There was a significant interaction effect found, $F(1,14) = 7.39$, $p = .017$, $\eta_p^2 = .35$. Follow up comparisons revealed that the QET group significantly lengthened their QE2 duration following training ($p = .004$), whereas there was no change for the TT group ($p = .675$). These tests also revealed marginally significant group differences at pre- ($p = .072$) and post- ($p = .092$) tests.³ (Figure 4.4.b)

³ Computing a relative (%) QE2 duration ((QE2 x 100) / FT2); Causer et al., 2010) made no difference to these findings. The interaction effect still remained significant, $F_{(1,14)} = 6.69$, $p = .022$, $\eta_p^2 = .32$, with the QET group increasing QE2 from 32.9% to 46.2% of FT2 after the intervention, while the TT group's QE2 was 39.2% at pre-test and 34.3% of FT2 at post-test. Relative QE2 did not mediate catching success.

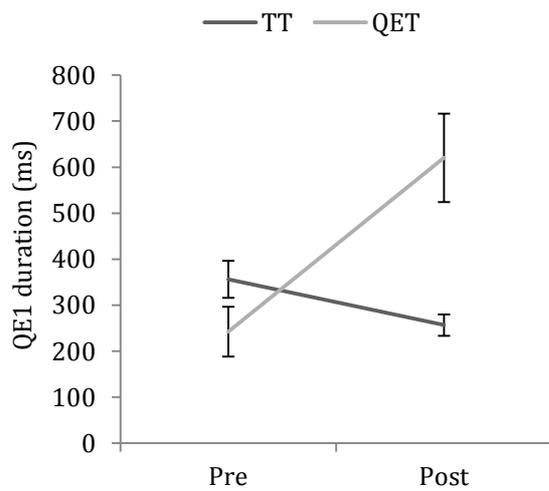


Figure 4.3 (a)

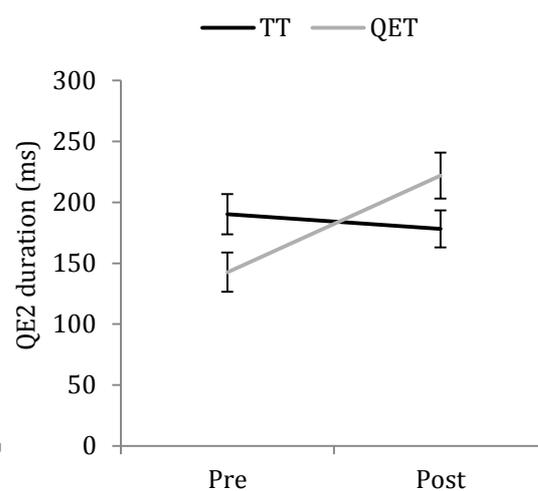


Figure 4.3 (b)

Figure 4.3: Experiment 1 – QE1 (a) and QE2 (b) of QET and TT groups at pre- and post-training. (Error bars are S.E.M).

4.3.5. Mediation Analyses

To establish whether catching performance had been mediated by gaze behaviour, intervention group was entered as the independent variable, post-test catching performance as the dependent variable, and QE1 and QE2 individually entered as mediators. Results from bootstrapping (based on 10,000 sampling rate) indicated that there was only a significant indirect effect for QE1 duration (95% CI = -5.33 to -0.41). QE2 did not mediate the group-based differences in catching performance (95% CI = -3.44 to 1.60).

Table 4.2. Mean (S.D) catching, flight time and quiet eye data for quiet eye trained (QET) and traditionally trained (TT) participants across pre-test and post-test conditions for experiment 1.

	Pre-Test		Post-test	
	QET	TT	QET	TT
Catching Success (%)	47.50 (8.61)	51.25 (8.10)	70.00 (10.35)	55.00 (9.06)
FT1 (hand-wall; ms)	254.28 (19.02)	271.88 (19.98)	298.97 (24.54)	308.95 (20.76)
FT2 (wall-hand; ms)	465.31 (38.27)	500.45 (22.52)	480.08 (15.77)	519.19 (19.20)
QE1 (pre-throw; ms)	242.41 (54.23)	356.00 (40.12)	620.35 (95.98)	256.65 (23.29)
QE2 (pre-catch; ms)	142.66 (16.06)	190.28 (16.45)	222.07 (18.88)	178.15 (15.18)

4.4. Experiment 1: Discussion

4.4.1 Discussion of Key Findings and Implications

This is the first study to explore the efficacy of QET for motor skill learning in typically developing children, although the paradigm has been applied successfully in adults (see Vine et al., 2014). Study 1 (Chapter 3) revealed that highly coordinated children reveal significantly longer targeting and tracking QE durations (QE1 and QE2) in this throw and catch task than less coordinated children. We therefore predicted that QET's focus on optimising

gaze behaviour might produce a larger training effect in the catching performance of a group of children's of moderate catching ability, compared to a TT intervention (as Vine & Wilson, 2011).

The performance results supported our primary hypothesis, with QET children catching 23% more balls after training, compared to a 4% improvement for TT children. Significant interaction effects were also evident for the duration of both the QE1 (targeting fixation on the wall) and QE2 (tracking gaze on the ball). In both cases, the QET group significantly increased their QE durations following training, whereas the TT group revealed no change in QE2 and a reduction in QE1. Both groups significantly increased FT1 after training, but there were no differences in FT2 times across conditions or between groups. Taken together, the ball flight time data would suggest that all participants learned to throw the ball slower and then step in to intercept the ball earlier following training. The training advantage for the QET group over the TT group therefore cannot simply be explained by this strategic change in the way the task was performed. Rather, the additional mediation analyses suggest that improvements in anticipation and focus during the pre-throw phase of the task (QE1) underpinned this performance advantage.

As first highlighted in chapter 3, it appears that the catching component of the task is simplified if a consistent relationship between the throw and the rebound can be established. The QET group's ability to predict the consequences of the ensuing action – the likely path of the ball after it leaves the hand – is assisted by the extended information processing time facilitated by the longer QE durations during both the pre-throw and pre-catch phases of the task. While chapter 3 found that QE2 mediated catching performance differences between groups of children of varying coordination abilities, the

current experiment found that QE1 was more important in mediating between group post-test performance. The lack of a mediating effect for QE2 is likely to be due to the TT group also being given instructions related to tracking the ball as it came towards them (Table 4.1). While we felt it would be inappropriate to omit a 'watch the ball' instruction from the gold standard coaching instructions, it is likely that this reduced the additional impact of the QET instructions relating to tracking the ball (QE2). Future work could perhaps reduce the emphasis on this instruction to help determine the effect of changes in QE2 duration. It should also be noted that in this experiment (with a small sample size) the ball flight time measures taken during this experiment indicate that the children in both QET and TT groups threw the ball faster than those in chapter 3, resulting in a greater time constraint in this experiment on shifting their gaze firstly to the predicted ball-wall bounce location and then onto the tracking QE2 gaze. The QE1 duration would however have remained unaffected by this change.

4.4.2 Limitations and Development of Methodology for Exp. 2

Being the first attempt at transferring a QET intervention into children, there were understandably a number of methodological limitations that were discovered in this first experiment, both by the researchers conducting the study and also from the review process of the resultant published article. Experiment 2 of this study is an extension of experiment 1 that attempts to develop and improve the protocol to become a more reliable and effective measure of the effect of QET in children. These limitations of experiment 1 are discussed below:

First, reviewer feedback proposed that the definitions for QE1 and QE2 would benefit from a more rigorous approach to determining the critical

movement involved. For example, previous research examining throwing tasks (e.g., basketball free-throw shooting) has defined the QE with respect to the forward extension of the arm, rather than ball release (Vickers, 1996; Vine & Wilson, 2011). From a cognitive perspective, the final fixation on the wall is where visual information is gathered to inform the individual of the task parameters. This fixation therefore needs to take place before the targeting movement is initiated to allow for accurate pre-programming. Once the movement (e.g. the forward extension of the arm) is initiated, the motor programme is being executed and so visual information gathered after this point may not be relevant to the task execution. QE research of targeting tasks indicates that the true critical movement occurs prior to the onset of the forward movement in projection, but after a preparation phase when visual information is gathered. In throwing Klostermann, Koedijker and Hossner (2013a) and Klostermann, Kredel and Hossner (2013b), used the foreswing of the arm as the critical movement in their study of the QE.

As the external camera (for the purpose of recording the qualitative performance) used during experiment 1 had a different capture rate to the gaze registration system, such a 'vision-in-action' analysis was not possible, and hence the definitions adopted in chapter 3.2.7 were used. However for experiment 2 it was possible to utilise a 30Hz external motor camera, placed to capture a side-on (sagittal) view of the participant. From this view, the researchers can classify the movement phases of the throwing and catching task, and synchronise this with the gaze registration data allowing them to refine the QE definitions. These are described in chapter 4.5.5. This external camera also would allow the researcher (and a blinded second researcher for inter-rater reliability) to qualitatively analyse each catch from slow-motion video data, and

for the FT data to be analysed without risk of the ball or hands becoming occluded, which occurred on 6 trials of experiment 1.

Second, the review process also highlighted an issue with our intervention instructions. One factor that may have contributed to the performance differences between the intervention groups was the locus of attentional focus. The TT intervention was based on current best practice so as well as a directive to watch the ball, these involved instructions relating to the internal focus of monitoring and controlling limb movement. The QET instructions however direct an individual to use a more external focus of control (Table 4.1), which Wulf and colleagues found to be beneficial to motor learning and performance (see Wulf, 2013) for a review). Indeed previous research has found that a QET group performed better in post-test compared to both a TT and discovery-learning group (Wilson et al., 2011b), suggesting that there are benefits of QET, not just problems associated with TT. Experiment 2 could seek to control for this explanation by also giving the QET group the traditional instructions.

By providing TT instructions to both groups however, this raised another issue of providing the children (especially in the QET group) with too much information, which would hinder their learning, and make the intervention ultimately less transferable to children with DCD who already suffer from deficits in motor learning. Therefore the decision was made to reduce the training points from three used in experiment 1 to just two in the second experiment and introduce a review of these points in the third phase of training. The practice tasks that were completed between the videos therefore also needed to be refined to become more simplistic and specific to the MABC-2 task. Chapter 4.5.3 describes these changes in more detail.

The third limitation relates to the sample size. Although 38 participants were recruited and took part in experiment 1, just 16 of these children were included in the analysis, and thus the pre-training baseline scores for various measures had greater variability. It was therefore important in experiment 2 to screen for and exclude children who had high-level motor coordination to ensure a larger sample size prior to training. To do this all participants in experiment 2 completed the full MABC-2 (as was used in chapter 3) prior to completing the baseline test. This also helped screen for and exclude children with movement disorders such as DCD.

The final limitation of experiment 1 was the lack of consideration for the learning effect. Only a short break separated the final training phase and the post-test, so the long-term impact of the training on the participant's catching ability was not measured. Therefore one further addition made in experiment 2 was the inclusion of a delayed retention test to investigate the longevity of the learning effect over a 6-week period.

4.4.3. Conclusions

To conclude, the primary aim of this experiment was to pilot test a QET intervention for a throw and catch task in typically developing children. While there were some limitations to the findings discussed, QET appears to proffer a learning advantage over traditional training instructions when learning fundamental interception skills that are key building blocks for sport and playground games. What is potentially exciting about this finding is that a meaningful increase in catching performance (from 50% success to 70% success) was achieved following a brief (~45 minute) but unique (gaze-focused) intervention. Therefore providing children with an insight into optimal gaze

control strategies (via QET) is effective in expediting skill acquisition in throwing and catching and is also a technique that children seemed to be able to adopt relatively quickly. Experiment 2 will build on experiment 1, to address some of the methodological limitations and to examine the extent to which these improvements are durable over time.

4.5. Experiment 2: Methods

4.5.1. Participants

35 children aged 8-10yrs (none of who took part in experiment 1) were recruited from primary schools in the South West of England. Ethical approval was obtained from a local ethics committee and full participant and parental consent was obtained prior to commencing the study. All participants individually attended 3 sessions held at the University of Exeter. These sessions were termed the assessment phase, the training phase and the retention phase.

4.5.2. Assessment Phase

In the first session each child completed the MABC-2 to quantify their coordination ability. The 8 standardised tasks of this assessment were carried out as described in chapter 3.2, however no eye tracking was collected at this stage. Children who scored more than 80% on the throwing and catching task were excluded from the study. This resulted in 5 participants being removed from the training protocol. The assessment phase took on average 45 minutes.

4.5.3. Training Phase

As in experiment 1, prior to the training phase the children were randomly allocated to one of two intervention groups: a traditional training group (TT) and a quiet eye training group (QET). There were 15 participants in each group. The training phase started the week after assessment.

Apparatus. The training phase involved first fitting the participant with an Applied Science Laboratories' Mobile Eye gaze registration system (ASL, Bedford, MA), which measures point of gaze at 30Hz. This was the same system used described in chapter 3.2.3 which is very similar to that used in experiment 1. A Digital SLR camera (Finepix S6500fd) was placed on a tripod 3m to the right of the throw line, capturing a side on view (sagittal plane) of the participant's movements at 30Hz.

Task. The throwing and catching task and procedure remained the same (task 4 of the MABC-2) as was used in experiment 1 and chapter 3, with data collected for the 10 baseline trials. Following these trials the eye tracker was removed.

Training protocol. The training protocol had many similarities to experiment 1 however it also incorporated a number of changes to overcome various limitations (chapter 4.4.2) so is described here in some detail: The task was broken down into its two elements which each consisted of a QE period: the throw (QE1) and the catch (QE2). For each element, the participant was shown a video of an expert model performing the specific training point, overlaid with key visual prompts. The child was then asked to summarise this video to demonstrate their understanding. Following this, the participant performed 30 practice attempts of the whole MABC-2 task, with the researcher providing a verbal prompt of the specific training point after every 5 trials. Participants were

allowed to take a break when needed. Once the participant completed the training for the two elements of the task (60 total practice trials), they were then shown a short summary video of the task and completed a final 25 practice attempts of the complete task.

During the training phase, both TT and QET groups viewed the same footage of a highly skilled model performing the throw and catch task and displaying QE1 and QE2 durations representative of past studies. Figure 4.4 demonstrates the use of the synchronised split-screen vision-in-action approach (Vickers, 2007), with the point of gaze on the left of the screen, and the sagittal view of the model's throwing action on the right. The QET video incorporated the TT traditional instructions and additionally included point of gaze for the targeting and tracking QE periods. See Table 4.3 for scripted instructions of the training videos.



Figure 4.4: A screenshot of a QET training video for the catch attempt; showing the gaze video (with circular cursor following the ball) on the left, and the actor's body position on the right, which is dimmed to direct attention to the gaze view.

After the training phase ended, participants were refitted with the gaze registration system and completed ten post-training (immediate retention) trials but without any verbal prompts or guidance (as baseline).

Table 4.3: A summary of the instructions for the adapted QET and TT videos used for experiment 2.

	QET Video 1	TT Video 1
Phase 1: The Throw	<p>[General Introduction] Look at the scene view [highlighted]. See how the girl takes her time to aim at a spot on the wall before she throws?</p> <p>Now look at the side on view [highlighted]. Notice how the girl throws the ball with a smooth arm action.</p> <p>[Scene view highlighted] To make a good throw, focus your eyes on the target and count to two before you start a smooth throwing action</p> <p>Remember, aim at your target, count to two, and then a smooth throw</p> <p>Now its time for you to practice this.</p>	<p>[General Introduction] Look at the scene view [highlighted]. See how the girl takes her time before she throws?</p> <p>Now look at the side on view [highlighted]. Notice how the girl throws the ball with a smooth arm action.</p> <p>[Side-on view highlighted] To make a good throw, take your time, then throw at a target using a smooth throwing action.</p> <p>Remember, take your time, and concentrate on a smooth swing of your throwing arm.</p> <p>Now its time for you to practice this.</p>
Phase 2: The Catch	<p>Look at the scene view [highlighted]. Can you see how the girl watches the ball as soon as it hits the wall and keeps her eye on it all the way back to her outstretched hands?</p> <p>Look at the scene view [highlighted]. Can you see how the girl watches the ball as soon as it hits the wall and keeps her eye on it all the way back to her outstretched hands?</p> <p>Now look at the side on view [highlighted]. Can you see how the girl cups her hands together to catch the ball?</p> <p>[Scene view highlighted] To make a good catch, it's really important that you keep your eye on the ball from as soon as it hits the wall, until it comes back into your cupped hands.</p> <p>Remember, focus on the target when throwing, but this time try really hard to watch the ball bounce, and then watch the ball right back into your hands.</p>	<p>Look at the scene view [highlighted]. Can you see how the girl concentrates on the ball as it flies back to her outstretched hands?</p> <p>Look at the scene view [highlighted]. Can you see how the girl concentrates on the ball as it flies back to her outstretched hands?</p> <p>Now look at the side on view [highlighted]. Can you see how the girl cups her hands together to catch the ball?</p> <p>[Side on view highlighted] To make a good catch, it's really important that you concentrate on the ball and cup your hands together.</p> <p>Remember to throw with a smooth arm action, but this time you need to concentrate really hard on the ball and cup your hands together to make the catch</p>

Phase 3: The Review	<p>OK, so far you have learned two training points.</p> <p>[Scene view highlighted] To throw, you need to take your time to aim at the target, count to two in your head, before smoothly throwing the ball.</p> <p>[Scene view highlighted] To catch, you need to keep your eye on the ball from its bounce on the wall right until it comes back into your cupped hands.</p> <p>Now lets try and put this all together in the final practice session.</p> <p>Remember the two training points: Firstly focus on the target for two seconds and throw smoothly</p> <p>And secondly keep your eye on the ball and cup your hands ready for the catch.</p> <p>Now its time for your last set of practices.</p>	<p>OK, so far you have learned two training points.</p> <p>[Side on view highlighted] To throw, you need to take your time before you smoothly throw the ball at the target.</p> <p>[Side on view highlighted] To catch, you need to concentrate on the ball, and cup your hands together to catch it when it comes back to you.</p> <p>Now lets try and put this all together in the final practice session.</p> <p>Remember the two training points: Firstly, take you time to throw with a smooth arm action.</p> <p>And secondly concentrate on the ball and cup your hands ready for the catch.</p> <p>Now its time for your last set of practices.</p>
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4.5.4. Retention Phase

Participants attended a final session between six and eight weeks after their training session. On arrival at this session participants were again fitted with the gaze registration system and completed 10 final retention trials of the throwing and catching task. Each participant was awarded a £10 shopping voucher (funded by the Waterloo Foundation) for completing the study and along with their parents, were debriefed as to the purpose of the study.

4.5.5. Measures

Flight Time. The same measures of FT1 and FT2 used in experiment 1 were also used in this experiment; therefore refer to chapter 4.2.5 for definitions of these.

Gaze behaviour. Gaze data were analysed as a manipulation check to ensure the QET intervention actually did increase the QE durations of the participants. The gaze data was digitised from digital tapes using Eye Vision Software (ASL) and the sagittal motor videos were downloaded and edited using CyberLink PowerDirector (Version 8, Dolby). The gaze and motor videos were synced using Quiet Eye Solutions vision-in-action software (www.QuietEyeSolutions.com) to enable QE durations to be calculated via frame-by-frame analysis.

QE1 (pre-throw). In chapter 3 and experiment 1, QE1 was defined as the final fixation prior to the ball release. The ball release was chosen as a critical movement as it was the final movement in the throwing task. For this experiment, the QE1 definition is refined to reflect the cognitive pre-programming theory and emerging research that proposes the critical movement of a targeting QE duration such as throwing takes place before the initiation of the ball projection action (Klostermann et al., 2013a; 2013b) as the fixation that occurs immediately prior to this action provides the most salient information to programme the movement execution. QE1 onset in this experiment therefore is defined as the final fixation (within 3° area on a “virtual” location on the wall) for 100ms or more before the onset of the foreswing of the throwing arm. The offset of this fixation occurred when gaze deviated from this location by more than 3° for longer than 100ms. The duration of QE1 was the time between the QE1 onset and offset (ms). QE1 is defined in a similar manner

to other throwing tasks (Vickers, 2007), and has been adapted from the definition operationalised in chapter 3 and experiment 1. In far aiming tasks (e.g., basketball free-throw, darts, golf putting) a longer QE1 duration has been associated with superior performance.

QE2 (pre-catch). The time to QE2 onset was calculated (ms) as the time between the ball contacting the wall to the onset of QE2. QE2 onset is defined as the final tracking gaze on the tennis ball for more than 100ms before the catch was attempted or the trial ended. The offset of QE2 occurred when gaze deviated off the ball for more than 100ms or when the trial ended. QE2 duration was defined as the time between QE2 onset and offset (ms). Thus QE2 duration may be sensitive to changes in ball flight time (FT) – a longer ball flight offers more time to track the ball, so we continued to measure FT1 (release to wall contact) and FT2 (wall contact to end of trial⁴). In interceptive tasks (e.g., goalkeeping, shotgun shooting, service return) an earlier and longer QE duration has been associated with superior performance (Vickers, 2007).

Performance. We assessed performance outcome and a measure of performance quality.

Catching performance. Performance outcome was expressed as the percentage of the 10 trials that were successfully caught at baseline, retention 1 (immediate retention) and retention 2 (delayed retention). The measure of catching quality was adapted from experiment 1 (see footnote 3) to provide more detail and was analysed from the video footage to provide a more sensitive measure of performance (Table 4.3). This measure was based on the qualitative performance scale developed by Przysucha and Maraj (2010), with modifications made to reflect the specific nature of the catching task used in this

⁴ Trial end occurred when the ball contacted the participant's hands, body or another surface or when the ball crossed the throw line. The trial also ended if the ball bounced before reaching the participant.

study (e.g., one handed catching was not rewarded). The first author blindly scored the catch attempt according to this adapted 11-point scale, and a second blinded researcher also scored 10% of the trials to check for inter-rater reliability using the inter-observer agreement method (see chapter 3.3). This analysis revealed a satisfactory amount of agreement of 95%.

Table 4.4: *The qualitative catching performance scale used in experiment 2.*

Outcome	Code	Description
No Reaction	0	Makes no move towards the ball as it comes back
Reaction, no contact	1	Makes some move towards ball, no contact, no attempt at a catch (delayed)
Inaccurate/Delayed reaction, no contact	2	Reacts to ball direction and makes effort to catch the ball. No contact
Delayed Reaction, no contact before bounce	3	Reacts to ball direction and makes effort to catch the ball. Ball bounces/contacts some part of the body
Delayed reaction, limited contact	4	Reacts to the ball, poor throw results in it bouncing/contacting another surface before catch can be made
Ball contacts hands	5	The ball contacts one or both hands but there is no control
Trap ball, no hands	6	Ball hits body and trapped with arms but not hands
Fumble	7	Ball is fumbled and drops to the ground
Trap	8	The ball is grasped by both hands, with the aid of the trunk or other body part.
Fumble but re-grasped	9	Clean catch completed after a fumble without ball hitting another surface
Clean, controlled catch,	10	The catch is made exclusively with the palms and fingers.

4.5.6. Analysis

The performance data (success vs failure) was recorded and scored during the testing sessions, and verified later using the external motor video. The external video was also used for coding the qualitative catching performance of each trial. Mixed design analyses of variance (ANOVA; Statistical Package for Social Sciences, version 20; SPSS Inc., Chicago, IL) with Intervention group (TT vs QET) as the between group variable, and Test (Baseline [BL] vs Retention 1 [R1] vs Retention 2 [R2]) as the repeated measures factor, were computed for each of the dependent variables. If the assumption of sphericity was violated, a Greenhouse-Geisser correction was used. Uncorrected degrees of freedom are reported, along with the corrected probability values and epsilon value.

Estimated effect sizes (η_p^2) were calculated using partial eta squared and LSD *post hoc* tests were used to interrogate significant main and interaction effects. Linear regression analyses were also performed to determine which variables could significantly predict the variance of catching performance at both R1 and R2. Gaze and kinematic variables were individually entered into the regression analysis.

As in experiment 1, mediation analyses were used to determine whether QE1 or QE2 mediated between-group differences in catching performance, using the *MEDIATE* SPSS custom dialog (Hayes, 2013). The mediation analysis requires a good level of statistical power to determine a significant effect of a variable on each of the groups. Therefore, if no significant mediators were found to explain the gaze variables on group effects, a linear regression analysis was conducted to determine whether an individual gaze variable could significantly predict the variance in performance. This regression analysis does not distinguish between the group effects like a mediation analysis, therefore

although it still provides an indication of how much a gaze variable affects performance, the regression cannot provide as strong evidence for QET variable directly affecting performance over the affect of TT. All data was analysed using SPSS (version 20).

4.6. Experiment 2: Results

4.6.1. MABC-2

The participants of this experiment had an average MABC-2 percentile rank score of 42.07, which would place their motor coordination ability as just below average. Any score above the 15th percentile denotes that no movement difficulty is detected (Henderson et al., 2007). The QET group (6 males, 9 females) had a mean percentile rank of 47.27 (SD = 21.28) and the TT group (8 males, 7 females) had a mean percentile rank of 36.87 (SD = 19.60). An independent t-test revealed no significant difference in the MABC-2 percentile rank of the two groups, $t_{(28)} = 1.39$, $p = .175$. There were also no significant differences between the age of the two groups, $t_{(28)} = 1.95$, $p = .061$ and both groups had an identical baseline catching percentage (QET = 51.33, TT = 51.33). The skewness and kurtosis values were checked, revealing normal levels of distribution within the groups (skewness values between -1/+1; and kurtosis values between -1/+2).

There was a significant positive correlation between the MABC-2 percentile score and Baseline catching performance ($r = .37$, $p = .044$), however there was no significant correlation between MABC-2 percentile score and the participant's age ($r = .09$, $p = .640$).

Flight times (ms). For FT1 ANOVA revealed there was no significant main effect for test, $F_{(2,56)} = 0.96$, $p = .391$, $\eta_p^2 = .03$, or for intervention, $F_{(1,28)} = 0.44$, $p = .511$, $\eta_p^2 = .02$. There was also no significant interaction between the variables, $F_{(2,56)} = 0.62$, $p = .544$, $\eta_p^2 = .02$. See Figure 4.4 (a).

For FT2 however there was a significant main effect for test, $F_{(2,56)} = 12.09$, $p < .001$, $\eta_p^2 = .30$ as both groups reduced FT2 from BL to R1 (Mean difference = -34ms, $p = .011$) and R1 to R2 (Mean difference = -32ms, $p = .012$) and a significant main effect for intervention, $F_{(1,28)} = 8.43$, $p = .007$, $\eta_p^2 = .23$, with the QET group having a shorter catch time (Mean Difference = 26ms, $p = .007$) however there was no significant interaction effect, $F_{(2,56)} = 0.08$, $p = .928$, $\eta_p^2 < .01$. See Figure 4.2 (b).

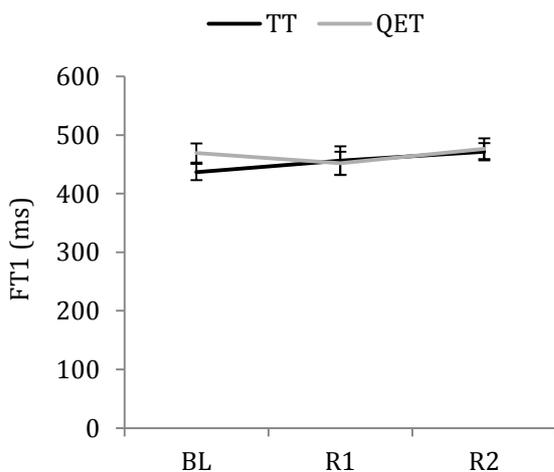


Figure 4.2(a)

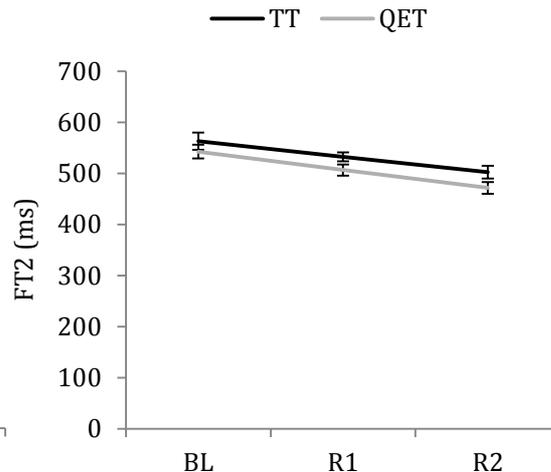


Figure 4.2(b)

Figure 4.5: Experiment 2 – The FT1 (a) and FT2 (b) for the QET and TT groups throughout the tests. (Error bars represent S.E.M).

4.6.2. Gaze Behaviour (Training Manipulation Check)⁵

QE1 duration (ms). ANOVA revealed there was a significant main effect for test, $F_{(2,56)} = 16.11$, $p < .001$, $\epsilon = .77$, $\eta_p^2 = .37$, and for intervention, $F_{(1, 28)} = 2.92$, $p = .100$, $\eta_p^2 = .11$. There was a significant interaction between these variables, $F_{(2,56)} = 8.73$, $p = .002$, $\epsilon = .77$, $\eta_p^2 = .24$. Post hoc analyses of the between group effects revealed there was no significant difference in QE1 duration at BL (Mean Difference = 42ms, $p = .552$), however the QET group had a significantly longer QE1 durations at R1 (Mean Difference = 550ms, $p < .001$), and at R2 (Mean Difference = 234ms, $p = .003$) in comparison to the TT group. Within group post hoc analyses revealed no significant improvements in QE1 duration for the TT group throughout the tests (p 's $> .225$), however the QET group significantly increased their QE1 duration from BL to R1 (Mean Difference = 604ms, $p < .001$). Despite this they were unable to maintain this increase as there was a significant decrease in QE1 duration between R1 and R2 (Mean Difference = -363ms, $p = .002$). Their QE1 duration at R2 however remained significantly longer than their BL score (Mean Difference = 241ms, $p = .001$). Figure 4.6 (a) shows the QE1 duration of the groups.

QE2 onset (ms). ANOVA revealed there was a near significant main effect for test, $F_{(2,56)} = 2.68$, $p = .077$, $\eta_p^2 = .09$, however there was a main effect for intervention, $F_{(1,28)} = 23.80$, $p = .001$, $\eta_p^2 = .31$ with the QET having a significantly earlier QE2 onset. There was a significant interaction between the variables, $F_{(2,56)} = 4.73$, $p = .013$, $\eta_p^2 = .14$. Post hoc analyses revealed no significant differences between the intervention groups at BL (Mean Difference

⁵ Due to technical problems with gaze tracking 364 trials out of 900 could not be analysed and were therefore excluded. For QE1, a total of 160 trials were excluded (TT = 60; QET = 100) and for QE2, a total of 204 trials were excluded (TT = 97; QET = 107). Excluded trials were due to calibration errors or un-codable data, errors in data collection, and data lost due to data storage problems.

= 1ms, $p = .977$) but at R1 the QET group had a significantly earlier QE2 onset than the TT group (Mean Difference = 59ms, $p = .001$) and they were able to maintain this earlier QE2 onset at R2 (Mean Difference = 63ms, $p = .001$). The within group analysis revealed that the QE2 onset of the TT group did not significantly change throughout the tests (p 's > .631). The QET group however significantly reduced the time to QE2 onset from BL to R1 (Mean Difference = -53ms, $p = .001$) and there was no significant difference between R1 and R2 suggesting they maintained this difference (Mean Difference = -3ms, $p = .857$). This is shown in Figure 4.6 (b).

QE2 duration (ms). ANOVA revealed no significant main effect for test, $F_{(2,56)} = 2.35$, $p = .104$, $\epsilon = .80$, $\eta_p^2 = .08$, however there was a significant main effect for intervention, $F_{(1,28)} = 13.11$, $p = .001$, $\eta_p^2 = .32$ with the QET group having a significantly longer QE2 duration. There was also a significant interaction between the variables, $F_{(2,56)} = 3.76$, $p = .040$, $\epsilon = .80$, $\eta_p^2 = .12$. Post hoc analysis revealed no significant difference between the groups at BL (Mean Difference = 12ms, $p = .717$). However the QET group had significantly longer QE2 duration at R1 (Mean Difference = 81ms, $p = .002$) and this difference was maintained at R2 (Mean Difference = 96ms, $p < .001$). The within group analysis revealed the TT group only had a significant decrease in QE2 duration from R1 to R2 (Mean Difference = -38ms, $p = .031$). The QET group however significantly increased QE2 duration from BL to R1 (Mean Difference = 66ms, $p = .020$), and there was no significant difference between R1 and R2 so they were able to maintain this increase (Mean Difference = -22ms, $p = .186$). The QE2 duration is shown in Figure 4.6 (c) along with the relative QE2 duration (Figure 4.6 (d)), which is calculated to compensate for differences in FT2.

Relative QE2 Duration: $(QE * 100)/FT2$. Both groups reduced the catch time (FT2) and the QET had an overall lower FT2. The effect of this on relative QE2 ANOVA was the generation of a main effect for test, $F_{(2,56)} = 3.84$, $p = .027$, $\eta_p^2 = .12$ the main effect for intervention remained similar to absolute QE2 duration, $F_{(1,28)} = 17.44$, $p < .001$, $\eta_p^2 = .38$ but the interaction between the variables became stronger, $F_{(2,56)} = 4.46$, $p = .016$, $\eta_p^2 = .14$. Post hoc analysis revealed similar between group differences to absolute QE2 duration however in the within groups analysis, there were no significant differences for the TT group (p 's $> .241$) and there was a greater margin between BL and R1 for the QET group (Mean difference = 16%, $p = .005$) who also maintained a similar relative QE2 between R1 and R2 (Mean difference = 0%, $p = .919$). Table 4.5 shows the QE mean values for the two groups at each test.

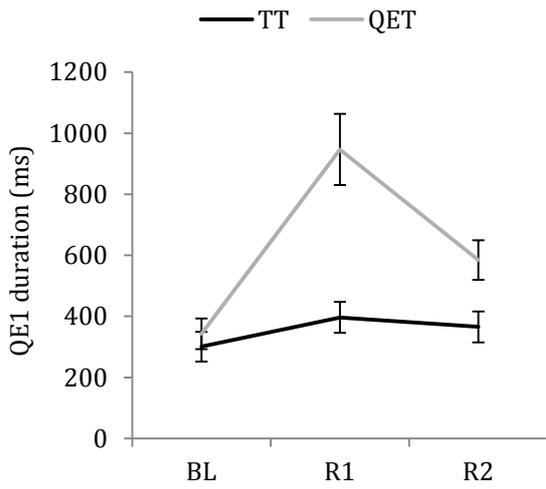


Figure 4.6(a)

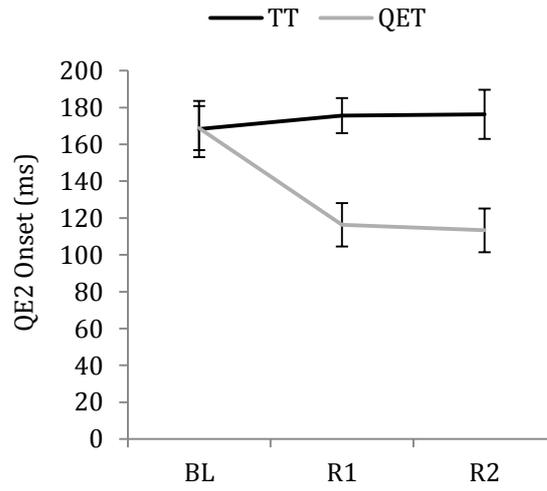


Figure 4.6(b)

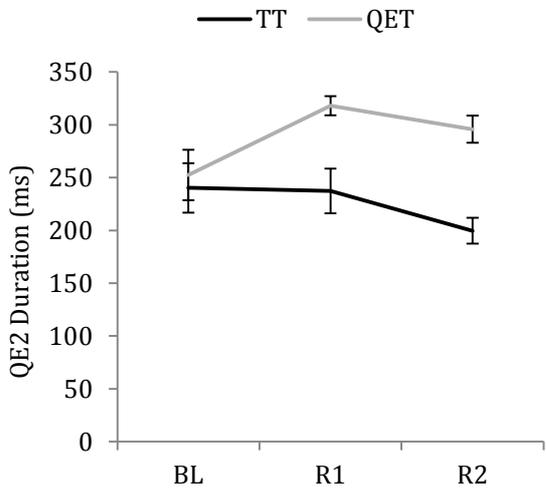


Figure 4.6(c)

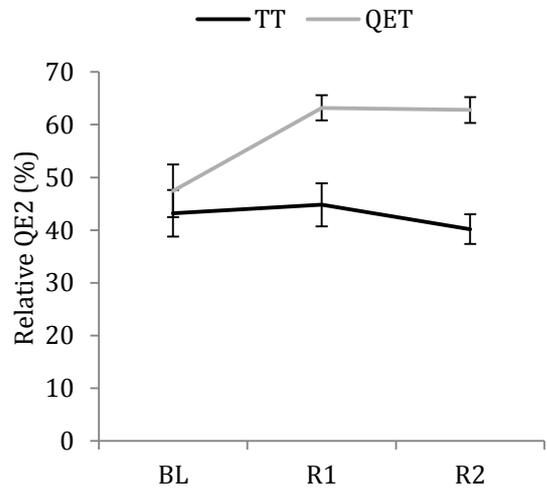


Figure 4.6(d)

Figure 4.6: Experiment 2 – The QE1 duration (a), QE2 onset (b), QE2 duration (c) and Relative QE2 (d) for the QET and TT groups over the tests. Relative QE2 was a calculation of $(QE2 \cdot 100) / FT2$ that determined the effect of ball speed during the catch phase on QE2 duration – see footnote 7. (Error bars represent S.E.M).

4.6.3. Performance

MABC-2 catching performance (%). ANOVA revealed a significant main effect for test, $F_{(2,56)} = 10.79$, $p < .001$, $\eta_p^2 = .28$ but no significant main effect for intervention, $F_{(1,28)} = 3.34$, $p = .078$, $\eta_p^2 = .11$. There was however a significant interaction between these variables, $F_{(2,56)} = 3.64$, $p = .033$, $\eta_p^2 = .12$. Table 4.5 shows the mean scores for catching performance between the groups. Post hoc analysis revealed no significant difference between the groups at BL (Mean Difference = 0%, $p = 1.00$), and the difference between the groups at R1 was not quite significant either (Mean Difference = 16%, $p = .089$). The QET group did however score significantly higher than the TT group at R2 (Mean Difference = 23%, $p = .005$). The within group analysis revealed no significant change in performance for the TT children throughout the tests (p 's $> .181$). The QET group however significantly increased performance from BL to R1 (Mean Difference = 25%, $p = .001$), and there was no significant difference between R1 and R2 so they were able to maintain this increase (Mean Difference = 5%, $p = .394$). This is shown in Figure 4.7 (a).

Qualitative catching score. ANOVA revealed a significant main effect for test, $F_{(2,56)} = 4.74$, $p = .012$, $\eta_p^2 = .15$ and for intervention, $F_{(1,28)} = 5.90$, $p = .022$, $\eta_p^2 = .17$ and a significant interaction between these variables, $F_{(2,56)} = 4.66$, $p = .013$, $\eta_p^2 = .14$ (see Table 4.5 for mean scores). Post hoc analyses revealed that there were no significant differences between the groups at BL (Mean Difference = 0.35, $p = .633$) but the QET group scored higher at R1 (Mean Difference = 1.40, $p = .037$ and at R2 (Mean Difference = 2.20, $p = .001$). There were no significant differences in the qualitative performance of the TT group throughout the tests (p 's $> .542$), however the QET group did significantly improve their performance from BL to R1 (Mean Difference = 1.25,

$p = .004$) and there was no significant difference between R1 and R2 suggesting they were able to maintain this improvement (Mean Difference = .56, $p = .162$), shown in Figure 4.7 (b).

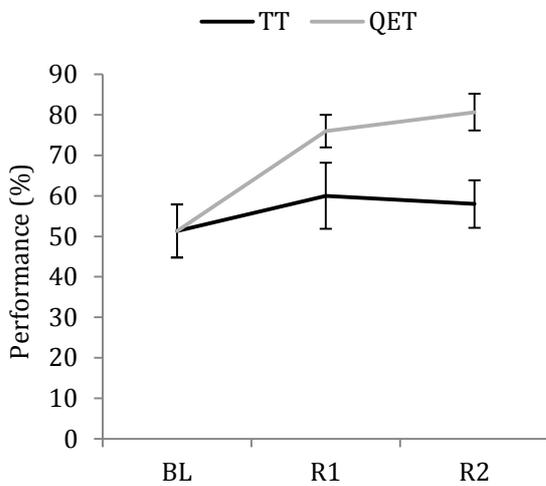


Figure 4.7 (a)

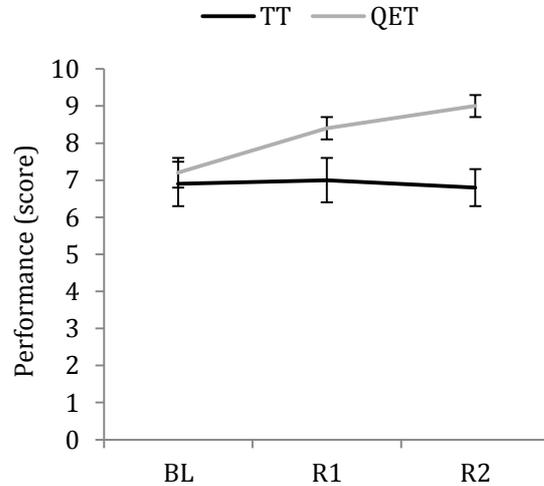


Figure 4.7 (b)

Figure 4.7: The performance % (a) and qualitative performance (b) for the QET and TT groups. (Error bars represent S.E.M).

4.6.4. Mediation Analysis

The mediation analysis revealed none of the gaze variables significantly mediated the effect of intervention on either performance % or qualitative performance at R1 or R2, so this analysis could not establish a direct or indirect effect of the gaze variables on the difference in catching performance between the groups. Therefore a linear regression analysis was conducted to determine the extent to which the QE variables could predict performance.

4.6.5. Regression Analysis

The regression analysis revealed that at R1, none of the gaze variables significantly predicted the variance in performance % (p 's > .130). These findings were not significantly altered when qualitative scores were entered as a dependant variable. For R2, the gaze variables were still unable to individually predict performance % however of these variables relative QE2 was the strongest predictor of performance ($p = .093$), and a significant predictor for qualitative performance ($R^2 = .15$, $p = .037$, $b = .48$).

Table 4.5: Mean (S.E.M) QE1 duration, QE2 onset, Absolute QE2 duration, Relative QE2 duration, Performance (%) and Qualitative Performance data for QET and TT groups at baseline, retention 1 and retention 2 for experiment 2.

	Baseline		Retention 1		Retention 2	
	QET	TT	QET	TT	QET	TT
QE1 Duration (ms)	342.99 (50.33)	300.91 (48.56)	946.73 (116.78)	396.44 (50.81)	584.23 (65.13)	365.52 (50.74)
QE2 Onset (ms)	158.93 (11.95)	158.62 (15.31)	116.34 (11.72)	175.62 (9.57)	113.31 (11.89)	176.33 (13.31)
Absolute QE2 Duration (ms)	252.55 (23.9)	240.28 (23.47)	318.05 (9.07)	237.22 (21.17)	295.71 (12.85)	199.70 (12.34)
Relative QE2 Duration (%)	47.45 (5.00)	43.21 (4.42)	63.20 (2.38)	44.80 (4.08)	62.81 (2.45)	40.19 (2.81)
Performance (%)	51.33 (6.61)	51.33 (6.54)	76.00 (4.00)	60.00 (8.17)	80.67 (4.52)	58.00 (5.87)
Qualitative Performance (0 – 10)	7.20 (0.35)	6.85 (0.62)	8.45 (0.26)	7.05 (0.59)	9.01 (0.26)	6.81 (0.51)

4.7. Experiment 2: Discussion

The second experiment of this study made a number of methodological adaptations to the QET protocol of experiment 1 with the purpose designed to improve the validity and effectiveness of the training interventions for children. Some of the key changes made were to include the TT instructions into the QET intervention, to help reduce the impact of directing attentional focus internally, and reducing the number of training phases from 3 to just 2 with a revision phase. A delayed retention assessment was also used to determine the effects of QET six weeks after training. Changes were also made to the measures for this experiment. The QE definitions were more specific regarding the onset of critical movements and the qualitative scoring system was made more task-specific. Finally the sample size used in experiment 2 was almost double that included in the analysis in experiment 1 due to pre-screening using the MABC-2.

The findings of this experiment further establish that QET for children is an effective strategy for adopting more 'expert-like' gaze strategies. This is demonstrated by evidence of the QET children employing a longer QE1 duration (pre-throw) in comparison to both their own baseline levels and the control group of children who were taught using traditional catching instructions. The QET children were also able to initiate an earlier and longer tracking QE gaze (QE2) on the ball (pre-catch) and this was reflected in the performance findings which indicated that the QET group improved and retained a higher performance level than the TT group and their own baseline scores at both immediate (R1) and delayed retention (R2).

There were however, a few surprising findings in this experiment that need to be considered. Firstly, despite an initial increase in QE1 that was

greater than the QE1 duration of the TT group immediately after training, the QE1 duration of the QET group then significantly decreased from R1 to R2. Chapter 2.2.4 discusses how a longer QE fixation during aiming is a critical time for children to pre-plan and parameterise the movement of the throw and catch, whilst directing attention to critical aspects of the task, however due to little prior research of the QE in throwing and catching, the optimal duration of this QE1 is unknown. Research in adults would suggest that the QE has an optimal duration in aiming tasks of 2 seconds (Vickers, 2007) and indeed this was the basis for recognising this duration as an appropriate QE1 duration, however this duration may be unsuitable for children. In relation to the findings of chapter 3.3.4, the average QE1 duration of the highly coordinated children (who had not received any QET) was 496ms. Therefore it may be pertinent in future studies of QET to target a smaller QE1 improvement to identify with these findings, which children will find easier to retain.

The mediation analysis failed to determine whether any of the measures used in this experiment significantly mediated performance, however the QE2 significantly predicted 15% of qualitative catching performance. This supports the findings of chapter 3, which indicated that QE2 was likely the most important factor in affecting catching performance in children. It was discussed in this chapter (3.4) that the QE2 afforded children more time to gather accurate information about the flight of the ball that would assist them in predicting the optimal interception location and timing.

4.8. General Discussion

The purpose of this study was to pilot test and develop a QET intervention that would be suitable and effective at improving the catching performance of typically developing children. The first experiment performed a basic intervention assessing catching performance and two QE measures pre- and post-intervention. Experiment 2 developed measures such as the process analysis using a qualitative analysis of performance and a number of other methodological adaptations to improve the intervention.

Both experiments found that QET could manipulate the gaze behaviour of children to adopt a more 'expert-like' strategy with longer QE durations both in the aiming phase (QE1) and interceptive phase (QE2) of the task. Experiment 2 also determined that this training induced an earlier QE2 onset. Both experiments also reported similar improvements in catching percentage, particularly for the QET group (exp. 1 = +22%, exp. 2 = +23%), but also the TT group (exp. 1 = +4%, exp. 2 = +9%).

There were however some discrepancies between the findings of the two experiments that are of note. The random allocation of groups meant that the baseline measures for most of the variables, particularly between the TT groups were very similar, however between the QET groups, the baseline measures for QE1 and QE2 duration did differ by more than 100ms between the two experiments. The small sample size of experiment 1 will almost certainly have had a substantial impact on these differences at baseline, but one must also consider that no pre-screening took place in experiment 1 to determine the motor coordination ability of the participants beyond catching percentage score. Indeed, when compared to the findings of chapter 3, the baseline scores of the gaze variables of the QET participants in experiment 1, resemble very closely

those in the low motor coordination group (mean differences of 17ms, and 3ms for QE1 and QE2 duration respectively). However the gaze variables of QET participants in experiment 2, more closely resemble the median group of the study in chapter 3 (84ms and 52ms) and with an average MABC-2 percentile rank just under 50, it would appear that these children are indeed of a higher motor coordination ability than those recruited for experiment 1.

Better skilled children would perhaps have benefitted more from practice effects, as Debrabant et al. (2013) proposed that tasks such as catching remain novel to children with poor motor skills as they fail to effectively use previous experience and memories to inform their movements. This could explain why children in both groups in experiment 2 generally made more improvements in their gaze behaviour. Based on this assumption, it may therefore be unsurprising that this sample of participants in the QET group were able to increase their QE1 durations by 226ms more than the QET group in experiment 1. Studies of children with poor motor coordination abilities (such as DCD) have demonstrated that these children do have difficulties with motor skill learning (Wilson, Maruff, & Lum, 2003) and memory (Chen et al., 2013). However, critically the methodological adaptations brought into experiment 2 would also have had an impact of the findings of these two studies.

The most significant change made in regards to QE1 is the definition of the critical movement from which the QE1 onset was measured. The movement defined in experiment 2 (foreswing of arm) occurs slightly earlier in the movement phases of the throw, so the QE1 fixation for some participants would be different depending on which definition was used. This change in definition could affect the accuracy of the correction fixation, as some participants make online adaptations to their gaze behaviour during the

foreswing of the arm to reflect updated kinaesthetic information from this movement. However these differences were likely to be minimal due to the rapid duration of the foreswing and the findings of experiment 2 indicate that the QE1 period remained important in linking the two phases of the throw and catch task.

Furthermore, the QET instructions incorporated the TT instructions in study 2, thus with more information to process regarding two sets of instructions (use a smooth throw and aim at a virtual target) it may be that the QET children in experiment 2 were simply taking longer to internalise the instructions to develop an internal model to guide the movements (Wilson, Maruff, Ives, & Currie, 2001). The two sets of instructions also require a switch of attentional focus from internal (movements of the arm) to external (aim at target) prior to executing a movement. This effect would also relate to the loss of QE1 duration as a significant predictor or mediator of performance. If the children are processing more information and switching attentional focus during this QE1 fixation (especially if some of this information isn't crucial to the successful performance of the task), the QE1 duration will be extended but to no profit in terms of performance. Furthermore, the extended QE1 is targeted at improving the quality of the throw (as was discussed in chapter 3.4) however the children (possibly of higher motor skill) recruited in experiment 2 generally threw the ball slower, affording themselves more time to initiate the tracking QE2 earlier (a variable not reported in experiment 1). Therefore the mediation effect of QE1 in experiment 1 may have been a result of less skilled throwers gaining more benefit from one clear instruction to aim at a virtual target.

The findings of chapter 3 support the notion that the pre-catch phase of this task is more sensitive to the pick-up of accurate visual information, making

the earlier, and longer QE2 duration critical to task success. Indeed, the regression analyses of experiment 2 support this finding, particularly at retention 2, after a longer period of 'de-training' has taken place. However, despite finding QE durations were good predictors of performance in both experiments, there might be other reasons why the QET intervention was more successful – beyond the improved action planning and sensorimotor mapping explanation discussed in chapter 3.4. For example the QET participants may have simply been more motivated by the novelty of the training instructions, which are likely to be different to those they have received previously. Furthermore, the adaptations of the second experiment also did not fully address the question of whether the lack of external attentional focus used in the TT instructions may be attributable to poorer learning of the training instructions. An inclusion of a discovery-learning group such as that used by (Vine et al., 2013a) and Wilson et al. (2011b) would help determine that the QET effect is more beneficial than the TT effect is detrimental to performance in children.

In summary, this study presents a major step forward in the development of QET and specifically in the successful adaption of this form of intervention for children in a throwing and catching task. The combined effect of these two experiments indicate that children can indeed learn to replicate the gaze behaviours of highly coordinated peers, and this appears to have a substantial influence on their ability to execute a catch successfully. Furthermore this study supports the longevity of QET, indicating that the performance improvement is robust to a period of 'de-training'.

4.9. Future Directions

This study has strongly supported the QET effect and advocated its use in typically developing children, however the question remains to be answered regarding the effect of QET and TT on more homogeneous groups of different ability children; is QET more suitable for typically developing children (of average ability), or children with motor coordination difficulties? The next step of this thesis is to apply the QET intervention to a sample of children diagnosed with DCD. If successful, such interventions may help these children break the negative cycle linking low motor skill competence with low levels of physical activity and cardio-respiratory fitness.

Chapter 5

Study 3: Quiet Eye Training facilitates catching performance in children with Developmental Coordination Disorder

An adaptation of this study has been submitted as Miles, C.A.L., Wood, G., Vine, S. J., Vickers, J. N. and Wilson, M. R. (submitted). Quiet eye training facilitates catching performance in children with Developmental Coordination Disorder, Research in Developmental Disabilities.

5.1 Introduction

Developmental Coordination Disorder (DCD) affects between 1.7-6% of children (depending on the stringency of diagnostic criteria; Hendrix et al., 2014). The condition is characterised by a marked impairment in the performance of motor skills that have a significant, negative impact on daily activities (Sugden et al., 2006). Not only does DCD impact all areas of motor performance (Cantin, Ryan, & Polatajko, 2014), but it can influence academic achievement (Chen et al., 2013; Liberman et al., 2013), social development (Chen et al., 2009; Tseng et al., 2007) and long term physical health (Cairney & Veldhuizen, 2013). Furthermore, DCD is not confined to young children, but can continue into adolescence and adulthood (e.g. Cantell et al., 2003). A longitudinal study by Tal-Saban, Ornoy, and Parush (2014) found young adults with DCD score significantly lower than their typically developing (TD) peers in participation in everyday activities, life satisfaction and quality of life, making early identification and effective intervention a priority for children with DCD.

Whilst uncertainty remains regarding the precise aetiology of DCD (Caravale, Baldi, Gasparini, & Wilson, 2014; Vaivre-Douret, 2014), there is strong evidence to suggest that children with DCD have significant impairments in the processing of visual information relevant to the performance of motor tasks, compared to their typically developing (TD) peers (e.g. Piek & Dyck, 2004; Sigmundsson et al., 2003; Tsai et al., 2008; Wilson & McKenzie, 1998). One view of this visuomotor impairment postulates that children with DCD have fewer resources for the processing of visual information (Smyth, Anderson, & Churchill, 2001). Debrabant et al. (2013) suggested children with DCD are unable to utilise predictive information to assist with mapping of the required movement patterns, resulting in constantly high processing demands and

therefore a task remaining novel to the child despite repeated practice. For example, it has been demonstrated that children with DCD, unlike their TD counterparts, cannot make use of advanced (partial) visual cues to support the efficient planning of subsequent movements (Mon-Williams et al., 2005; Wilmot & Wann, 2008). Additionally, children with DCD (and co-occurring learning difficulties) are unable to shift towards a predictive or feed-forward mode of control on more complex movement tasks, and instead rely on a less efficient strategy, using updated visual information as it becomes available (Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003).

Smits-Engelsman et al. (2003) proposed that feed-forward control may be under-developed or impaired in children with DCD, limiting their ability to utilise sensory information to make pre-emptive or anticipatory responses. These authors found that children with DCD required more target-related feedback during movement execution than TD children. It is well established that predictive eye movements support the planning and control of goal-directed movements in natural environments (see Land, 2009 for a review), and such eye movement analyses can differentiate between children with and without DCD (Langaas et al., 1998; Robert et al., 2014).

The resulting paradox is that, despite having impaired eye movements (e.g. Robert et al., 2014), children with DCD rely more on visually guided online control when responding to stimuli (Debrabant et al., 2013). Visual target perturbation studies have demonstrated the significant difficulties children with DCD experience when making predictive online movement adaptations to movement trajectories (Hyde & Wilson, 2011a; Hyde & Wilson, 2011b). Importantly, the deficits experienced by children with DCD are most pronounced in complex, interceptive tasks (Bairstow & Laszlo, 1989; Mak, 2010; Wilmot &

Wann, 2008), and as such there is a need for research to further examine visuomotor control and motor performance in these less constrained settings and using 'real-world' tasks.

Ball catching is a complex dynamic task that requires modifications to planned movement responses based on visual information about the flight of the ball (Olivier, Ripoll, & Audiffren, 1997; Williams, 1992). Children with DCD find this task difficult (e.g. Przysucha & Maraj, 2013; Utley et al., 2007; Van Waelvelde et al., 2004) and use a different technique to TD children; extending their arms out in front of them and 'freezing' their elbow angles in this position throughout the catch in an attempt to reduce the degrees of freedom they have to coordinate in the movement (Astill, 2007; Utley et al., 2007). While this freezing strategy is likely driven by deficits in perception of ball flight characteristics - making online corrections of movement difficult - current methods and analysis procedures are unable to test this objectively.

The departure point for the current study is the examination of the visuomotor processes underpinning throwing and catching in children performed in the first two studies of this thesis (chapters 3 and 4). Chapter 3 found a specific gaze behaviour termed the QE could distinguish between the motor coordination skill and throwing and catching performance of children. The QE has been found to be a key predictor of perceptual-cognitive skill in a wide range of movement tasks (see review by Vine et al., 2014). QE durations of experts in a wide range of motor tasks are typically longer suggesting additional time is needed to organise the neural networks underlying the planning and control of motor skills.

The study in chapter 3 was the first to examine the QE in children, and found that those with low motor coordination ability (< 20th percentile of MABC-

2) had significantly shorter QE durations during both the throwing (QE1) and catching (QE2) phase of the task compared to highly coordinated children (> 70th percentile of MABC-2). It was suggested that the longer QE fixation prior to the throw (held on a virtual target on the wall; QE1) of the more skilled children helped to guide a more accurate throw which in turn helped them to locate the ball more quickly as it bounced off the wall. This subsequently helped them to initiate an earlier onset of a QE prior to the catch (the tracking gaze on the ball; QE2), providing earlier information about the ball flight, which could be used to plan and control the catch attempt.

As well as being a key marker of proficient performance, the QE has been shown to be trainable (chapter 2.1.5; chapter 4; Vine et al., 2014). The objective of QET is to guide a performer's judgement as to where and when to fixate their gaze when executing a motor skill in order to process the most relevant information guiding the planning and control of the action (Vine et al., 2014). Initial studies of QET in the sporting domain have been successful in accelerating the skill acquisition of novice performers when compared to traditional training instructions (e.g. Vine & Wilson, 2010, 2011). Chapter 4 described the first QET study in children, assessing the effectiveness of a QET intervention in improving performance in a throwing and catching task. This study found that the video-based QET intervention significantly increased the duration of QE1 and QE2, and improved catching performance by over 20% in comparison to traditional training instructions, which produced no significant training effects. These findings represent a step forward in determining the transferability of QET to children suffering from DCD in complex, real-world movement skills that underpin many sport and playground games.

The aim of the current study was to extend the work of chapter 4 to assess the effectiveness of a QET intervention for a throw and catch task in children with DCD. We propose that such a study has both a strong scientific and practical rationale. First, based on Land's (2007) model of predictive eye movements and Vickers' (1996) conceptualisation of the QE, it is important to understand how training children with DCD to adopt the gaze and attention of experts can improve their ability to make accurate online predictions to guide and adapt movement patterns, in real-world tasks. Second, not only do children with DCD struggle with this task, but impairments in catching can also lead to significant health implications. Indeed, Magalhaes, Cardoso, and Missiuna (2011) identified poor ball skills as an important limiting factor in activity participation for children with DCD, and longitudinal work by Barnett and colleagues (Barnett et al., 2008b, 2009) linked childhood object control proficiency with adolescent physical activity levels and fitness.

It is hypothesised that QET, compared to a traditional training (TT) method will: (1) lengthen QE1 duration on a "virtual" target on the wall prior to the throw and QE2 on the ball prior to catch, (2) improve prediction capability that will reveal itself in a more expert-like movement patterns, and finally (3) improve catching technique and performance.

5.2 Methods

This study was conducted alongside experiment 2 of chapter 4; therefore this study shares very similar methodology with that experiment. To reduce repetition in this chapter, there are several references to the methods of chapter 4.5.

5.2.1 Participants

30 children aged 8-10yrs who were diagnosed with DCD by an occupational therapist (DCD; 19 male, 11 female; 9.07yrs \pm 0.87) were recruited for this study. This diagnosis was confirmed by an MABC-2 score at or below the 5th percentile. The children were recruited from primary schools in the South West of England, through Vbranch House Clinic in Exeter and the UK Dyspraxia Foundation (www.dyspraxiafoundation.org.uk).

Ethical approval was obtained from a local ethics committee and full participant and parental consent was obtained prior to commencing the study. All participants individually attended 3 sessions held at the University of Exeter. These sessions were termed the assessment phase, the training phase and the retention phase.

5.2.2. Experiment Protocol

The protocol for this study followed the same process through the assessment, training and retention phases as chapters 4.5.2 – 5.5.4 and also used the same MABC-2 throwing and catching task. In the first phase of this procedure the children completed the MABC-2 and were excluded from the study if they scored above the 5th percentile. In addition, whilst the children were completing this assessment, their parents also filled out the Attention Deficit/Hyperactivity Disorder (ADHD) Rating Scale-VI (Parent Version) which asks parents to assess their child's behaviour over the previous 6 months. This scale takes around five minutes to complete and has been verified as a suitable tool for screening for ADHD in relation to the DSM-IV conceptualisation of this disorder. As such the ADHD Rating Scale-IV has been extensively used in academic research exploring DCD and ADHD in children (DuPaul et al., 1998).

In the present study, this scale identified 8 of the 30 participants as likely to have co-occurring ADHD. The children were randomly assigned into the QET and TT groups and the training phase took place approximately 1 week following assessment.

The training protocol was identical to that described in chapter 4.5.3. The baseline (BL) measure of the MABC-2 catching task was conducted using the same gaze registration equipment, and marker placement. Then the groups were shown the QET or TT instructional videos described in chapter 4.5.3 before they completed the stated set of practices. The children were then re-fitted with the gaze registration system and performed the 10 immediate retention trials (R1).

The delayed retention (R2) took place 6-8 weeks after the completion of training, and again followed the same protocol of chapter 4.5.4. The children in this study were also given a £10 shopping voucher on completion of the testing (funded by the Waterloo Foundation) and debriefed along with their parents.

5.2.3. Measures

The measures used in this study are again very similar to those described in chapter 4.5.5, however in this study the reporting of ball flight times have been omitted as this factor is incorporated in the relative QE2 measure. An additional measure of elbow angle was also included. The measures used in this study are briefly described below:

QE1 duration (pre-throw), is defined as the final fixation of more than 100ms within 3° of visual angle on the wall before the onset of the foreswing of the throw.

QE2 onset (pre-throw) is defined as the time from the ball contacting the wall, to the onset of the QE2 tracking gaze.

Absolute QE2 duration (pre-catch), is defined as the final tracking gaze of more than 100ms within 3° of visual angle on the ball before the catch or trial ended.

Relative QE2 duration (pre-throw) is computed as such $(QE2 \text{ duration} \times 100) / FT2$. FT2 relates to the time from the ball contacting the wall to the end of the trial (defined as when the ball contacts a surface or participant or crosses the throw line).

EA, (at catch attempt) is a process measure defined as the elbow angle at the point the ball contacts the hands (regardless of the result of the trial). Markers were placed on the acromion process of the shoulder, lateral epicondyle of the elbow and styloid process of the ulna of the participant's dominant hand. EA data was collected from an external camera (Finepix S6500fd) recording at 30Hz. The camera was placed on a tripod at the participants shoulder height, 3m from the throw line on the side of their dominant hand to record the participant's movements in the sagittal plane. This data was analysed using Dartfish (version 5.5) video analysis software to calculate the EA on a single frame extracted from the video at the point the ball contacted the participant's hands.

Catching performance (quantitative) is scored by the guidelines of the MABC-2 that requires the ball to be cleanly caught in the hands without the assistance of any other part of the body. The performance is scored (catch = 1, no-catch = 0) out of the 10 trials and converted to a percentage (x10).

Catching performance (qualitative) is scored using the performance scale shown in Table 4.4. This measure rewards participants for making better

attempts at catching the ball, even if that attempt is deemed unsuccessful in the quantitative scoring measure.

5.2.4. Analysis

For the method of analysing the results, see chapter 4.5.6. In this study the reporting of the mediation analysis was removed, as this again yielded no significant findings due to the lack of statistical power of the findings. The linear regression analysis therefore was used to determine which QE variables most significantly predicted performance. Furthermore, if more than one variable was found to be a significant predictor of performance, a multiple hierarchical regression analysis was used to determine which of these variables were most critical in the prediction of performance variables.

5.3. Results

After random allocation, the 8 children diagnosed as likely having co-occurring ADHD via the ADHD Rating Scale-IV had been divided equally into the two groups (QET = 4; TT = 4). Adding ADHD status as a co-variant in subsequent analyses did not significantly influence results.

5.3.1. MABC-2

The MABC-2 percentile rank scores were used to confirm the diagnosis of DCD. Skewness and kurtosis values were checked, revealing normal levels of distribution (skewness values between -1/+1; and kurtosis values between -1/+2). The DCD group all scored at or below the 5th percentile, which is described by Henderson et al. (2007) as “denotes a significant movement

difficulty". There was no significant difference between the MABC-2 percentile scores of the TT (Mean Difference = 1.95, SD 0.51) and QET (Mean Difference = 2.21, SD 0.46) intervention groups, $t_{(28)} = 0.37$, $p = .713$. There was a significant positive correlation between the MABC-2 percentile score and Baseline catching performance ($r = .43$, $p = .019$), however there was no significant correlation between MABC-2 percentile score and the participant's age ($r = .17$, $p = .383$).

5.3.2. Gaze Behaviour (Training Manipulation Check)⁶

QE1 duration (ms). ANOVA revealed there was a significant main effect for test, $F_{(2,48)} = 5.46$, $p = .007$, $\eta_p^2 = .19$, but not for intervention, $F_{(1, 24)} = 2.92$, $p = .100$, $\eta_p^2 = .11$. There was a significant interaction between these variables, $F_{(2,48)} = 5.37$, $p = .008$, $\eta_p^2 = .18$. Post hoc analyses of the between group effects revealed there was no significant difference in QE1 duration at BL (Mean Difference = 86ms, $p = .134$), or at R1 (Mean Difference = 121ms, $p = .237$), however the QET group had significantly longer QE1 durations at R2 (Mean Difference = 234ms, $p = .003$) in comparison to the TT group. Within group post hoc analyses revealed no significant improvements in QE1 duration for the TT group throughout the tests (p 's > .059), however the QET group significantly increased their QE1 duration from BL to R1 (Mean Difference = 267ms, $p = .001$) and they were able to maintain this increase as there was no significant difference between R1 and R2 (Mean Difference = -20ms, $p = .765$). These findings are shown in Figure 5.1 (a) (see also Table 5.1).

⁶ Due to technical problems with gaze tracking 392 trials out of 900 could not be analysed and were therefore excluded. For QE1, a total of 215 trials were excluded (TT = 96; QET = 119) and for QE2, a total of 177 trials were excluded (TT = 71; QET = 106). Excluded trials were due to calibration errors or un-codable data, errors in data collection, and data lost due to data storage problems.

QE2 onset (ms). ANOVA revealed there was no significant main effect for test, $F_{(2,46)} = 0.35$, $p = .707$, $\eta_p^2 = .02$, but there was a main effect for intervention, $F_{(1,23)} = 23.39$, $p < .001$, $\eta_p^2 = .50$ with the QET having a significantly earlier QE2 onset. There was a significant interaction between the variables, $F_{(2,46)} = 6.79$, $p = .003$, $\eta_p^2 = .23$. Post hoc analyses revealed no significant differences between the intervention groups at BL (Mean Difference = 11ms, $p = .629$) however at R1 the QET group had a significantly earlier QE2 onset than the TT group (Mean Difference = 94ms, $p < .001$) and they were able to maintain this earlier QE2 onset at R2 (Mean Difference = 86ms, $p = .001$). The within group analysis revealed the TT group initiated a significantly later QE2 onset from BL to R1 (Mean Difference = 36ms, $p = .016$), and there was no significant difference between R1 and R2 suggesting they maintained this difference (Mean Difference = 6ms, $p = .734$). The QET group however significantly reduced the time to QE2 onset from BL to R1 (Mean Difference = -47ms, $p = .002$) and there was no significant difference between R1 and R2 suggesting they maintained this difference (Mean Difference = 15ms, $p = .411$). This is shown in Figure 5.1 (b) (see also Table 5.1).

Absolute QE2 Duration (ms). ANOVA revealed no significant main effect for test, $F_{(2,46)} = 1.71$, $p = .192$, $\eta_p^2 = .07$, but there was a significant main effect for intervention, $F_{(1,23)} = 6.38$, $p = .019$, $\eta_p^2 = .22$, with the QET group having a significantly longer QE2 duration compared to the TT group. There was a significant interaction between these variables, $F_{(2,46)} = 3.39$, $p = .042$, $\eta_p^2 = .13$. Post hoc analyses revealed no significant difference between the intervention groups at BL (Mean Difference = 13ms, $p = .674$) however the QET group had significantly longer QE2 durations at R1 (Mean Difference = 62ms, $p = .003$) and this difference was maintained at R2 (Mean Difference = 63ms, $p =$

.009). The within group analysis revealed no significant increases in QE2 duration for the TT children throughout the tests (p 's > .649). The QET group however significantly increased QE2 duration from BL to R1 (Mean Difference = 66ms, $p = .013$), and there was no significant difference between R1 and R2 so they were able to maintain this increase (Mean Difference = -3ms, $p = .851$). These findings are shown in Figure 5.1 (c) (see also Table 5.1).

Relative QE2 Duration (%) (QE * 100) / FT2. ANOVA revealed no significant main effect for test, $F_{(2,46)} = 2.20$, $p = .122$, $\eta_p^2 = .09$ however there was a significant main effect for intervention, $F_{(1,23)} = 4.41$, $p = .047$, $\eta_p^2 = .16$ with the QET group having a significantly longer relative QE2 duration. There was also a significant interaction between the variables, $F_{(2,46)} = 4.34$, $p = .019$, $\eta_p^2 = .16$. Post hoc analysis revealed no significant difference between the groups at BL (Mean Difference = 5%, $p = .444$), however the QET group had significantly longer relative QE2 at R1 (Mean Difference = 14%, $p = .027$) and this difference was maintained at R2 (Mean Difference = 16%, $p = .008$). The within group analysis revealed no significant increases in relative QE2 duration for the TT children throughout the tests (p 's > .574). The QET group however significantly increased relative QE2 duration from BL to R1 (Mean Difference = 17%, $p = .006$), and there was no significant difference between R1 and R2 so they were able to maintain this increase (Mean Difference = 0%, $p = .943$). Relative QE2 duration for both groups is shown in Figure 5.1 (d) (see also Table 5.1).

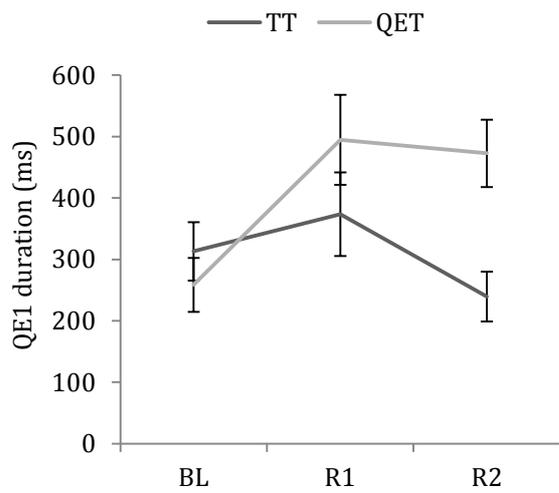


Figure 5.1 (a)

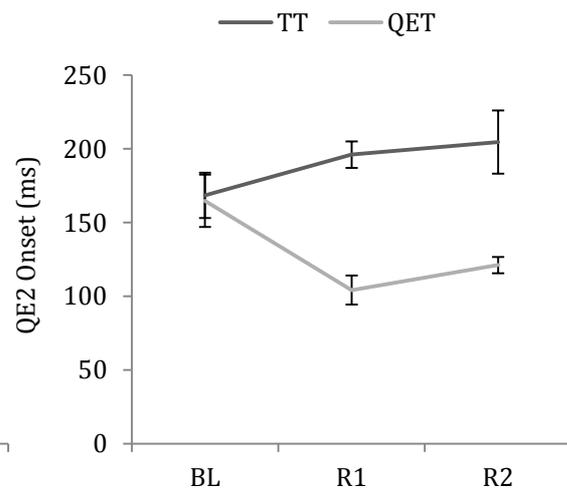


Figure 5.1 (b)

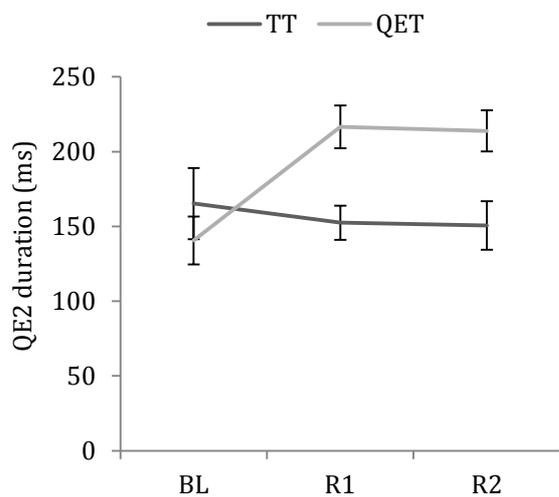


Figure 5.1 (c)

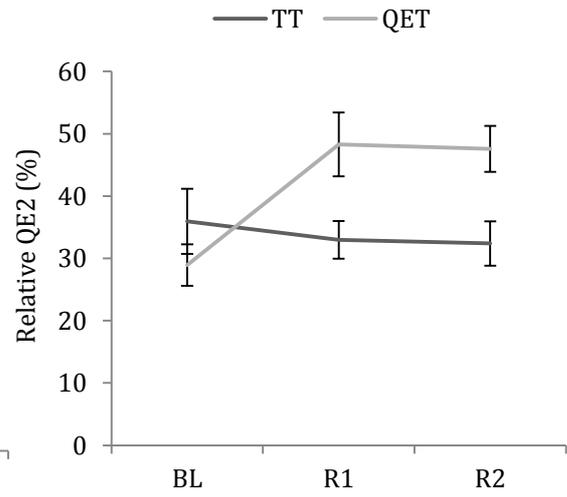


Figure 5.1 (d)

Figure 5.1: The QE1 duration (a), QE2 onset (b), QE2 Absolute duration (c), QE2 Relative duration (d) of the QET and TT groups throughout the tests. (Error bars represent S.E.M).

5.3.3. Performance

Elbow angle at catch (EA). As EA was measured at the point that the ball contacted the hands, trials that ended with the ball not contacting the participant's hands were excluded from the analysis (e.g. trials when the ball was missed, hit the participant's body, or bounced off a surface prior to hand contact). This resulted in 430 trials being included (TT = 212, QET = 218). Of these, 133 were from BL (TT = 66, QET = 67), 162 from R1 (TT = 79, QET = 83) and 135 from R2 (TT = 67, QET = 68). Of the total 30 participants, four had all trials excluded because the ball did not contact their hands.

ANOVA revealed significant main effects for test, $F_{(2,54)} = 28.38, p < .001, \eta_p^2 = .51$, and intervention, $F_{(1,27)} = 9.36, p = .005, \eta_p^2 = .26$. There was also a significant interaction between test and intervention, $F_{(2,54)} = 14.42, p < .001, \eta_p^2 = .35$. Post hoc analyses revealed no significant differences between the groups at BL (Mean Difference = $5^\circ, p = .465$) however the QET group had significantly smaller elbow angles at R1 (Mean Difference = $26^\circ, p = .001$) and at R2 (Mean Difference = $24^\circ, p = .001$). The within group analysis revealed the TT group significantly reduced their elbow angle (increased elbow flexion) from BL to R1 (Mean Difference = $-9^\circ, p = .030$) but there was a near significant difference between R1 and R2 suggesting they were only marginally able to maintain this increase in flexion (Mean Difference = $9^\circ, p = .067$). The QET group however had a larger decrease in their elbow angle from BL to R1 (Mean Difference = $-40^\circ, p < .001$) and although elbow angle difference significantly increased between R1 and R2 (Mean difference = $11^\circ, p = .021$), the amount of elbow flexion for the QET group at R2 was still greater than the TT group in all the tests. These findings are represented in Figure 5.2 (a).

MABC-2 catching performance (%). ANOVA revealed a significant main effect for test, $F_{(2,56)} = 4.65$, $p = .023$, $\epsilon = .748$, $\eta_p^2 = .14$ with significant improvements in performance between BL and R1 (Mean Difference = 14%, $p < .001$) but not between the other tests (p 's $> .122$). There was no significant main effect for intervention, $F_{(1,28)} = 1.28$, $p = .268$, $\eta_p^2 = .04$ and no significant interaction between these variables, $F_{(2,56)} = 0.21$, $p = .746$, $\epsilon = .748$, $\eta_p^2 = .01$. These findings are shown in Figure 5.2 (b).

Qualitative catching score. ANOVA revealed a significant main effect for test, $F_{(2,56)} = 3.21$, $p = .048$, $\eta_p^2 = .10$, but no significant main effect for intervention, $F_{(1,28)} = 1.17$, $p = .289$, $\eta_p^2 < .04$. There was a significant interaction between test and intervention, $F_{(2,56)} = 3.35$, $p = .042$, $\eta_p^2 = .11$. Post hoc analyses revealed that there were no significant differences between the groups at BL (Mean Difference = 0.13, $p = .884$) or at R1 (Mean Difference = 0.99, $p = .347$) but there was a near significant difference at R2 with the QET group scoring higher (Mean Difference = 1.69, $p = .068$). There were no significant differences in the qualitative performance of the TT group throughout the tests (p 's $> .090$), however the QET group did significantly improve their performance from BL to R1 (Mean Difference = 1.19, $p = .001$) and there was no significant difference between R1 and R2 suggesting they were able to maintain this improvement (Mean Difference = -.13, $p = .790$). These findings are shown in Figure 5.2 (c).

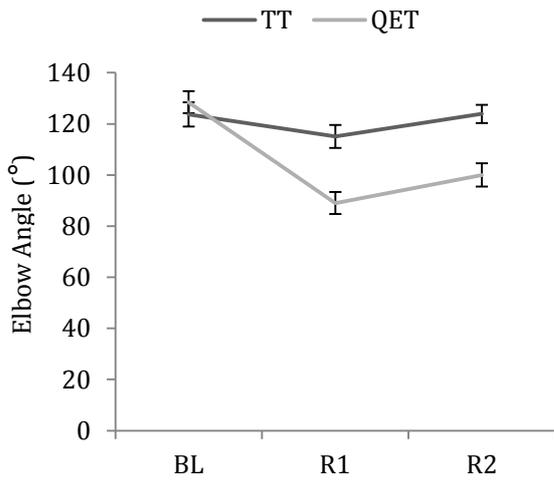


Figure 5.2 (a)

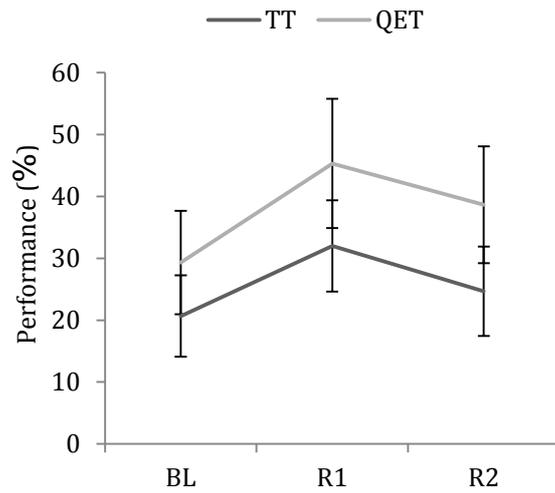


Figure 5.2 (b)

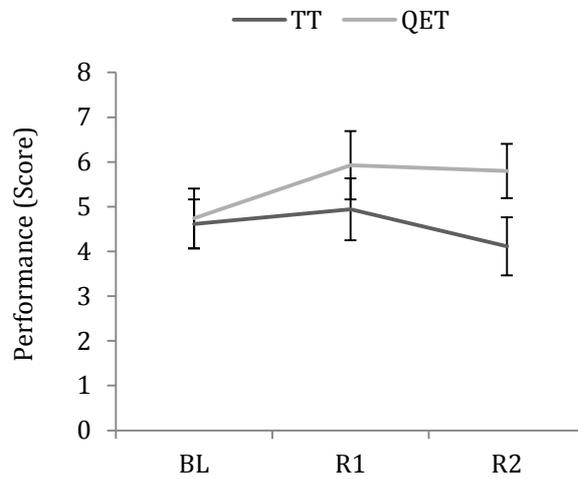


Figure 5.2 (c)

Figure 5.2: The EA (a), quantitative performance (b), and qualitative performance (c) scores for each group over the three tests. (Error bars represent S.E.M).

Table 5.1: Mean (S.E.M) QE1 duration, QE2 onset, Absolute QE2 duration, Relative QE2 duration, Elbow Angle, Performance (%) and Qualitative Performance data for QET and TT groups at baseline, retention 1 and retention 2.

	Baseline		Retention 1		Retention 2	
	QET	TT	QET	TT	QET	TT
QE1 Duration (ms)	258.60 (43.98)	313.17 (47.64)	494.70 (75.15)	373.51 (68.00)	472.69 (54.84)	239.47 (40.45)
QE2 Onset (ms)	164.79 (17.73)	168.43 (15.34)	104.24 (9.87)	196.11 (9.00)	121.14 (5.53)	204.54 (21.45)
Absolute QE2 Duration (ms)	150.76 (21.07)	163.72 (21.93)	216.48 (13.12)	154.65 (13.65)	213.37 (15.21)	150.63 (15.84)
Relative QE2 Duration (%)	28.92 (3.33)	35.93 (5.23)	48.28 (5.11)	32.98 (3.03)	47.59 (3.69)	32.38 (3.57)
Elbow Angle (°)	128.49 (4.34)	123.74 (4.74)	89.02 (4.35)	115.13 (4.50)	99.98 (4.55)	123.92 (3.55)
Performance (%)	29.33 (8.37)	20.67 (6.58)	45.33 (10.46)	32.00 (7.38)	38.67 (9.46)	24.67 (7.23)
Qualitative Performance (0 – 10)	4.74 (0.67)	4.61 (0.55)	5.93 (0.76)	4.94 (0.69)	5.80 (0.61)	4.11 (0.65)

5.3.4. Regression Analysis

As intervention had a greater effect on qualitative catching performance, over that of the percentage catching performance, qualitative catching was entered into the regression analysis as the dependant variable.

Linear regression analysis revealed that at R1, QE2 duration was the only variable to significantly predict performance ($R^2 = .17$, $p = .035$, $b = .22$).

Multiple hierarchical regression analysis revealed that QE2 duration was nearly a significant predictor of performance over and above the effects of QE1 and QE2 onset ($\Delta R^2 = .14$, $p = .066$, $b = .23$). EA did not significantly predict qualitative performance at R1 ($p = .156$). At R2, QE2 onset significantly predicted qualitative performance ($R^2 = .35$, $p = .002$, $b = -.23$) and QE2 duration was also a significant predictor ($R^2 = .18$, $p = .030$, $b = .18$). A multiple hierarchical regression revealed that QE2 duration was a significant predictor of qualitative performance over and above the effect of QE1 ($\Delta R^2 = .19$, $p = .021$, $b = .19$), and furthermore, QE2 onset significantly predicted performance over and above the effects of both QE1 and QE2 durations ($\Delta R^2 = .18$, $p = .019$, $b = -.19$). EA however was not a significant predictor of qualitative performance ($p = .147$)

5.4. Discussion

The purpose of this study was to determine the effectiveness of QET and TT for improving the throwing and catching skill of children diagnosed with DCD. Results revealed that children who received QET were able to respond to the training instructions. They significantly increased QE1 (pre-throw) and QE2 (pre-catch) durations. Importantly, not only were the QET group able to make immediate changes to their gaze behaviour and arm mechanics after one hour of training (retention 1), but this effect was durable after a 6 week de-training period (retention 2). These findings therefore add further support for the efficacy of video-based, gaze behaviour interventions in general (Vine et al., 2014), and also suggest that QET is effective for children with DCD. To our knowledge this is one of the first training studies of this nature to show significant improvements in cognitive function and motor behaviour of DCD children. Experiencing

deficits related to visual processing and motor planning appears to be no barrier to being able to model the optimal gaze behaviours of high performing individuals for many of the children in this study. Indeed children with DCD were able to adopt focused QE durations that were of a similar magnitude (within 45ms in QE2) to those used by highly coordinated children in chapter 3 and experience similar improvements in focus as TD children (e.g., within 6ms in QE2) shown in chapter 4, experiment 1.

Having identified that QET successfully brings about the changes in gaze behaviour that were hypothesised, it is important to determine whether such modifications drive subsequent changes in task performance. We predicted that the elbow angle at catch attempt (EA) would be a relevant process measure that would reflect a change in technique to a more efficient visuomotor strategy (e.g., Astill, 2007; Utley et al., 2007). In order to have greater elbow flexion at the catch attempt, the catcher needs to have anticipated the speed and flight of the ball to be closer to this interception point at that moment. The QET group learned to increase the amount of elbow flexion at the point of ball-hand contact immediately after training and this was maintained after 6 weeks. The TT group did have some initial increases in flexion at EA however this was much smaller than that of the QET group and this improvement was not durable after training. It is evident that QET contributes to changes in the way in which the body self-organises to reach a movement goal. This result is all the more intriguing, as the QET group received no additional explicit instructions to change the elbow angle. Previous research has also revealed that QET individuals reveal greater improvements in mechanics reflective of expert performance (e.g. a longer preparation phase in the basketball free throw, (Harle & Vickers, 2001) and basketball shooting, (Oudejans et al., 2005); improved putter kinematics in golf

putting, (Moore et al., 2012); reduced tool path length in simulated laparoscopic surgery, (Wilson et al., 2011b) than those following a TT intervention. These results not only suggest that children with DCD have the capacity to comprehend the significance of QE related gaze data, but also the ability to translate this into positive changes in their arm mechanics.

These findings are in line with those of chapters 3 and 4, the studies of which are based on the premise first outlined by Vickers (1996) that the QE reflects the time required to pre-programme movement control. In this task, the QE1 duration gave the children a longer time to parameterise the motor action of the throw in order to project the ball in a more optimal direction and speed to assist the catch. A consequence of this is likely to be a more accurate throw to the QE1 fixation location and therefore smaller shifts of visual gaze are required to fixate the ball during its bounce (an accurate correction fixation) and a quicker QE2 onset. The regression analyses would indicate that longer QE2 durations afford children more time to gather and process relevant visual information regarding the ball flight, which guides the timing and location of the movements required to complete a catch.

It is well established that children with DCD are poor at making online adaptations to movements based on dynamic visual stimuli (e.g. Mon-Williams et al., 2005; Wilmot & Wann, 2008). One could argue that in its simplest form, QET 'chunks' together the visual, perceptual and kinematic information required for these online adjustments, by directing an individual's attention to one or two critical visual cues (Vine et al., 2013b). For example in this current study, QET had the effect of implicitly increasing elbow flexion, which was not overtly taught in the intervention. By implicitly chunking together these aspects of a motor skill, we may also circumvent the impact of potential deficiencies identified in

children with DCD, such as everyday memory (Chen et al., 2013) and selective attention (Tsai, Pan, Cherng, Hsu, & Chiu, 2009), which interfere with the learning and execution of motor skills (Smits-Engelsman et al., 2003).

Interestingly, the regression analysis found the timing of the QE2 became more important to catching technique after the 6-week de-training phase. One explanation of this would be that the children experienced a learning effect during training that provided task-relevant information they could use to predict and pre-programme a movement response. However after a substantial period of no practice, memory of the task parameters had diminished, leading to a renewed reliance on the rapid pick-up of information that could only be gathered from an earlier QE2 onset. The TT group did also develop this skill after training, but the QET group were able to initiate a QE2 tracking gaze 83ms earlier than the TT group at this stage, providing additional critical information to guide their response.

Despite the significant gaze and technique alterations, this study found no significant performance advantage (% catches) for QET over TT children, as measured by MABC-2 catching performance. Both experiments in chapter 4 demonstrated that QET was superior to TT in improving catching performance in TD children of the same age, performing the same task as used in this current study. It is possible that two factors; random selection procedures, and the length of training contributed to this result. The random selection procedures we used inadvertently ended in the QET being 10% better in catching at baseline than the TT. In future research, we recommend a screening test be given first and two groups formed with high, medium and low scoring children being equally represented in each group. Second, it is also likely that the QET intervention period was too short for significant

improvements in overall performance to be observed. The time frame for this training intervention (approximately one hour) was based on previous QET literature (see Vine et al., 2014 for a review) performed almost exclusively with typically developing (or expert) adult participants. Intervention studies involving children with DCD typically run for significantly longer periods and are more intensive in their nature (review by Smits-Engelsman et al., 2013). While it is noted that durable improvements in catching technique appear possible for DCD children after such a short period of training, future research should aim to test the efficacy of repeated QET run over a number of sessions and weeks. A final consideration for QET in a population of children with DCD is the heterogeneous nature of this condition. It was possible to observe during this study that some children experienced greater benefits from this type of visuomotor training compared to others, and this could be an important factor for future work.

In conclusion, the QET intervention proved to be an effective strategy for teaching children with DCD to change their gaze behaviour, adopting extended QE1 and QE2 periods, which in turn led to more optimal technique when catching a ball that they had thrown against a wall. It is recommended that QET instruction be added to traditional instructions, for teachers, therapists and parents teaching visuomotor skills to children with DCD.

Chapter 6

General Discussion

6.1. Summary of Key Findings

The purpose of this thesis was to conduct the first examination of the role of the QE in supporting visuomotor performance in children and the potential benefits of QE training for improving the motor skills of those both with and without Developmental Coordination Disorder. The QE has never before been studied in children or in a clinical population, so its application to children with DCD provides a significant contribution to our understanding of the mechanisms of this gaze strategy, and also to our understanding of the visuomotor impairments of children diagnosed with this condition.

The literature (synthesised in chapter 2.1.3 and 2.1.4) reveals the QE to be a characteristic of proficiency and outcome related differences in adult visuomotor control (Mann et al., 2007). However prior to this series of experiments, there was little indication as to whether these comparisons would transfer to children. Children develop perceptual skills (such as reading and internal imagery) at different rates (Johnson, 2003; Johnson & Mareschal, 2001) with factors such as age and experience playing a significant role in when a child will reach the equivalent skill level of an adult (Deutsch & Newell, 2005).

For this reason, it was pertinent to study the QE in a task that would challenge the perceptual and motor skills of children of a narrow age bracket (8-10 years). A combined skill of throwing and catching is used in a number of standardised motor skill assessments for children of this age (chapter 2.2.2) and is an important task underpinning many sports and playground games. In the experimental studies of this thesis, the typically developing groups of children averaged around the 50th percentile in this skill in comparison to the MABC-2 norms, indicating that this was an appropriate task for 8-10 year old children from Exeter-based primary schools.

Although visuomotor aspects of adult catching skill have been studied in some detail, the QE strategy has never before been examined in this skill. Some comparisons can be made to the distinct aspects of this task (e.g. the QE has been investigated in aiming skills; basketball and darts throwing, and in interceptive skills; volleyball, table tennis and ice hockey), however to date no research has attempted to examine the QE strategies for two distinct skills performed in sequence such as the throwing and catching task studied in this thesis.

Chapter 3 addressed the first hypothesis of this thesis, which predicted that the QE could predict the throwing and catching performance of children. The experiment in chapter 3 was the first published work studying the QE in children, and found that, as in adults, the QE could differentiate the throw and catch performance of children of different motor abilities (Low, Median and High). The higher skilled children caught on average 92% of their throws and had an earlier and longer QE fixation on a virtual target during the pre-throw phase of the task (QE1) and an earlier and longer QE tracking gaze on the ball during the pre-catch phase (QE2). In comparison, the children with the lowest motor skills caught only 35% of the throws and had much later and shorter QE durations on the virtual target and on the ball. More detailed mediation analysis revealed that the QE2 duration had a significant influence on the catching performance of the children. Specifically the QE2 duration mediated the catching success of the different groups of children, indicating that longer QE2 durations underpinned more expert catching performance.

The second hypothesis of this thesis (chapter 4) postulated that QET instructions would be more effective for improving the throwing and catching skill of children in comparison to traditional training instructions (TT). Both

experiments in this chapter found that QET was indeed able to teach typically developing children with a low-to-moderate motor coordination ability to use earlier and longer QE durations. Additionally, not only did this group of children also achieve a higher skill performance level after training compared to the TT group (experiment 1 & 2), but this difference was maintained after a 6 week de-training period (experiment 2). Interestingly there were conflicting findings regarding the respective influence of QE1 and QE2 durations on performance, which may have been influenced by the differing motor abilities of the children, or the changes made to the instructions to limit any effects caused by an external attentional focus (chapter 4.8).

The final hypothesis of this study was to determine the 'clinical utility' of this specific QET intervention; by applying it to children diagnosed with DCD (chapter 5). While the positive effects of QET were not as strong as those observed in chapter 4, this study also demonstrated that children with DCD who were given QET were able to change the timing of their QE periods to emulate the earlier and longer QE of the highly skilled children in chapter 3, and that this appeared to contribute to improvements in their throwing and catching technique.

6.2. Theoretical implications

6.2.1. QE Mechanisms

6.2.1.1. Attentional control. The findings of these studies make significant contributions to our knowledge of the theory surrounding the QE and the visuomotor abilities of children, particularly those diagnosed with DCD. In

chapter 2 (section 2.1) I describe and discuss three mechanisms that have been proposed to explain why the QE is related to proficient and successful performance in adults (Vine et al., 2014).

The first of these mechanisms postulates that the QE directs attentional resources to task-relevant stimuli and limits unwanted interruption from the stimulus-driven attentional system. Chapter 3 found that LMC children were significantly later in initiating both their QE1 fixation and their QE2 tracking gaze than the other groups. In the language of Corbetta and Shulman (2002), top down attentional control is impaired in these children, as they are not directing visual attention to the critical stimuli that support performance. The transfer from the throw into the catch phase of the task appears to be particularly relevant in terms of attentional control, as it requires a switch in the location of visual attention from a static target (on the wall) onto a different dynamic target (the ball). Children with MMC and HMC are quicker at completing this attentional switch, perhaps due to more accurate throws and therefore a reduced reliance on correction fixations, however those with LMC maintain their attention on the now irrelevant target on the wall for longer. It would appear that this latency in shifting visual attention to task relevant stimuli is a function of poor skill level (Williams & Davids, 1998) and slower shifting of selective attention has also been associated with DCD (Tallet, Albaret, & Barral, 2013; Tsai et al., 2009).

The LMC children also disengage from the tracking gaze earlier than the MMC and HMC children (an effect also shown in children with DCD). In relation to Corbetta and Shulman's (2002) theory, it would appear that the bottom-up attentional system is diverting the visual attention of these children away from the ball earlier than the other groups of typically developing children.

Distractors such as worry about performance or the conscious control of movements may be significant concerns for children with DCD, whom studies have shown are aware and often concerned about their movement difficulties (Cairney et al., 2007; Cairney et al., 2005b; Cairney, Rigoli, & Piek, 2013). The Attentional Control Theory (ACT; Eysenck, Derakshan, Santos, & Calvo, 2007) postulates that anxiety (caused by internal worry or physical threat) is one example of a factor that will increase the prominence of the bottom-up driven system, causing an individual to attend to more task-irrelevant stimuli such as how to respond to the source of anxiety or circumstance it creates. This finding along with that of Nieuwenhuys and Oudejans (2012) who apply the ACT in the perceptual motor domain would indicate that LMC children have impairments in their ocular inhibitory control that would otherwise 'buffer' them from attentional shifts demonstrated through involuntary saccades towards distracting stimuli (Miyake et al., 2000).

Critically, QET has consistently been shown to protect an individual from the negative effects of anxiety on performance (e.g. Vine et al., 2013b; Vine et al., 2011; Vine & Wilson, 2010, 2011). This would indicate that the maintenance of longer QE durations in the throwing and catching task is likely increasing the attentional control of children, by retaining the allocation of their attentional resources on task-relevant cues. As such it was shown in chapter 4 that QET improves the attentional control of these children, directing overt attention to the target earlier and for longer prior to the throw, more rapid shifting of their attention between the stimuli during the transition into the throw, and promoting the inhibitory control by maintaining the QE2 on the ball for longer. Future work needs to further understand the mechanisms of attentional control in children by incorporating a pressurised condition into this task. This

would manipulate their attentional focus and additionally determine whether QET can protect children from the effects of performance anxiety as Vine and Wilson have shown in adult participants (Vine & Wilson, 2010, 2011).

6.2.1.2 Pre-programming movement. The second mechanism proposed by Vine et al. (2014) is the proposition that the QE affords an individual with a critical period of motor programming prior to (and during) the execution of a response. In order to produce accurate goal-directed movements, the motor system requires accurate and timely visual information about targets critical to task completion. Research has demonstrated that gaze is tightly coupled, temporally and spatially, to the motor actions of the task (see Ballard & Hayhoe, 2009 and Land, 2009 for reviews). Specifically, gaze tends to move to the target in advance of movement initiation and remains stable ('gaze anchoring'; Neggers & Bekkering, 2001) as the movement unfolds. Longer and earlier QE durations may therefore provide a period to efficiently pass visually acquired goal position information to the motor control systems, which should therefore result in movement kinematics and patterns of muscle activation that are more effective for successful skill performance. This is supported by the fact that differences in QE have been linked to differences in movement kinematics, (e.g. Moore et al., 2012; Vickers, 2011). QET studies have revealed that the training induces changes in movement mechanics, even when limb movements are not mentioned in the instructions (e.g., Chapter 4). Furthermore, the significantly earlier QE periods of elite performers and the highly coordinated children in chapter 3 would indicate that important processes are taking place prior to the onset of the movement, indicating that the QE represents a critical period of pre-programming, rather than simply the allocation of visual attention on relevant stimuli to guide and update movements.

Indeed, Williams et al. (2002a) suggested that the QE reflects a period of cognitive processing during which predictions are made regarding the parameters of the required movement that are then programmed. This explanation was supported by the fact that more complicated shots in billiards required longer QE durations (Williams et al., 2002a). The findings of this thesis would indicate that by extending the QE durations, the children's predictions about the catch location and resultant movements became more accurate and so reduced their reliance on making large shifts in gaze for accurate correction fixations. During QE1 task-relevant visual information is gathered for the pre-planning of the entire skill, and therefore the formulation of an internal model to guide the movements (Wolpert et al., 1995). A more complete and accurate internal model will result in a faster, more precise movement response, which would explain why a longer QE1 and QE2 would lead to more efficient movements and improvements in performance accuracy. However the predictive element in the formulation of an internal model appears to be impaired or under developed in children with LMC and DCD (Smits-Engelsman et al., 2003) forcing them to rely on slower sensorimotor feedback (Williams et al., 2011).

By extending processing time in QE1, the child has longer to parameterise the required movement pattern, leading to a more accurate throw (and therefore a more accurate correction fixation) to the selected target. Studies of the QE in aiming tasks have indeed determined in adults that longer QE durations lead to more accurate throws in tasks such as basketball (Harle & Vickers, 2001; Vickers, 1996; Vine & Wilson, 2011; Wilson et al., 2009) and darts (Horn, Okumura, Alexander, Gardin, & Sylvester, 2012; Rienhoff, Baker, Fischer, Strauss, & Schorer, 2012). A more accurate throw will mean better

predictions about the location of the bounce point on the wall resulting in fewer and more accurate gaze shifts, so the child should be able to transfer into an early tracking gaze on the ball – providing more time to predict where it should be intercepted in space and time. The additional elbow angle measure in chapter 5 provides more evidence of QET improving temporal and spatial prediction in DCD. This measure shows that after QET, children with DCD utilise a technique to move their hands into a more optimal position to catch that was similar to the typically developing children, rather than simply extended their limbs towards the ball (Utley et al. 2007). This is reinforced by a significant improvement in the measure of qualitative catching performance, indicating that QET promotes a more expert-like technique, with a greater range of controlled movement around the elbow.

6.2.1.3. External focus of attention. The final mechanism to explain QE benefits, provided by Vine et al. (2014) was that it affords an external focus of attention. As we took no physiological measures during this work we cannot determine the influence of psychomotor quieting on performance. However, Wulf's constrained action hypothesis, proposes that an external focus of attention (as provided in a QE period) crucially avoids an internal attentional focus that can lead to conscious processing of a movement that interferes with automatic processes (Wulf, 2013; chapter 2.1.4). This theory was largely addressed in chapter 4, where the second experiment of QET incorporated internally focused instructions as well as the external QE instructions to determine whether the positive effects of QET could be attributed to an external locus of attention. This study found that QET remained equally, if not more effective in improving catching performance even when internally focused

instructions were provided, therefore supporting the proposition that the QE provides a child with more than simply avoidance of an internal focus.

This study however did not demonstrate the effect of externally focused instructions over the effect of QET. In other words, chapter 4 demonstrates that a combination of internal and external QE instructions were not detrimental to performance, however future work could consider investigating the difference between QET and TT when purely externally focused instructions are provided for both groups. There have been few examples of this in the QE literature as traditional coaching instructions generally take on an internal attentional focus at some point throughout performance of the skill (such as those used by Vine & Wilson, 2011 for learning the basketball free-throw). Klostermann, Kredel, and Hossner (2014) postulate that the efficacy of the QE is varied in its manifestation under movement focused instructions.

Masters and colleagues' theory of reinvestment also outlines the dangers of focusing on movement mechanics during the learning of a motor skill (Masters & Maxwell, 2008). However, they have tended to limit the accrual of rules related to the performance of a motor skill via implicit motor learning techniques (e.g., errorless learning, analogy learning), rather than attentional focus instructions. While QET instructions are explicitly provided they do not refer to step-by-step movement control and may therefore provide a way to chunk information about movement. Vine et al. (2013b) found that QET participants were able to report fewer rules than an explicitly trained group and similar numbers of rules as an analogy learning group. The benefits of QET in terms of limiting an internal focus on movement mechanics may therefore be explained by both attentional focus and implicit motor learning explanations.

6.2.2. Task-specific Targeting and Tracking QE

The throwing and catching task used throughout the experimental chapters of this thesis is fairly distinct from the rest of the QE literature, as it requires the sequential amalgamation of two quite different skills for effective performance. The first of these is the throw, where a static QE1 fixation is used to guide accurate projection of the ball. The second skill is the catch, for which a tracking QE2 gaze on the ball is employed prior to the interception attempt.

Although both of these QE periods were shown to be beneficial to the children's catching performance throughout the studies, there appeared to be a disparity in their relative contribution to the overall performance of the task; with three of the four experiments indicating a greater importance for a longer tracking QE (QE2) on the ball during the catch phase of the task. Building on the QE mechanisms previously discussed, QE2 is largely responsible for completing the internal predictive model in order to guide the online movements and ultimately improve the anticipated location and timing of the catch. As an earlier, longer QE2 will provide more visual information to improve this prediction, it may not be surprising that the results indicate this is the most important element for successful performance in children with and without DCD. However, as the task rewards catch success (rather than throw accuracy) it is expected that the element preceding the catch will explain most of the variance in task performance. Furthermore, the experiment that provided the exception to this finding (chapter 4, experiment 1) had the least statistical power that was greatly affected by the small sample size.

The importance of different gaze strategies in a 'combination' task such as this have not been previously studied, so few comparisons can be made to the literature. However work by Panchuk and Vickers (2009) has investigated

the use of a predictive gaze strategy in elite ice hockey goaltenders. They used an occlusion paradigm to study the goaltender's reliance on a predictive (static fixations) or prospective (tracking gaze) strategy. Although these authors acknowledge that the prospective strategy of tracking the puck provides important late information used for updating and adjusting movements, the goaltenders were more successful (and had shorter reaction times) when they could gather early predictive information about the shooter's posture through a long static QE fixation prior to (and throughout) projection. The authors postulated that the QE fixation in this study anchored the gaze on a pertinent cue in the visual workspace (the stick-puck contact point), while other information regarding the shooter's posture and movements was picked up from the periphery. This would indicate that the QE was allowing the performer to process this information to pre-plan (feed-forward) their response, allowing them to respond quickly after the puck had been struck, so they were likely relying on accurate predictions formulated from a forward internal model of the movement. In relation to the throw and catch task, this finding of Panchuk and Vickers would indicate that although QE2 duration appeared to be most critical to task success, a longer QE1 duration may also be critical in setting up the earlier and therefore longer QE2 period.

While Panchuk and Vickers' results might suggest that QE1 alone might be enough for accurate prediction, there are important differences between the studies described in this thesis and that of Panchuk and Vickers, which make comparisons of gaze strategies difficult. Not only did Panchuk and Vickers test elite goaltenders with well-developed perceptual skill and experience, but also the available flight times were much less in the ice hockey task (250ms) in comparison to this catching task (500ms). The goalkeepers may not have used

a tracking gaze, simply because it exceeded the capabilities of the smooth pursuit system. In our catching task, smooth pursuit tracking of the target was possible and this late information provides the most recent, up-to-date information that can be used to fine-tune the movement (Oudejans et al., 2002). The findings of this series of studies would suggest that, as predicted by Oudejans, late visual information during the shooting movement is important, for informing the timing and accuracy of a movement being produced.

Mazyn et al. (2007) used a protocol where during a catching task the room lights were extinguished on the onset of a movement. The effect of this constraint was that participants were able to compromise their movement response in order to visually track the ball for longer, as perhaps significantly, they required visual information later into the ball flight in order to successfully catch the ball. The QE typically suggests that the information gathered prior to the onset of a movement is critical for performance success. However, De Oliveira, Oudejans and colleagues proposed that late visual information gathered after the movement onset maybe just as, if not more important. This was demonstrated with a basketball shooting task, where the performer's vision was occluded at various time points (de Oliveira et al., 2006; Oudejans et al., 2002) or their movement timing was constrained (de Oliveira, Huys, Oudejans, van de Langenberg, & Beek, 2007). They found that shooters preferred to pick-up visual information as late as possible and although these findings don't rule out the significance of pre-programming, they would indicate that online control and adjustments are perhaps most important for movement accuracy. These studies used an aiming task, however Regan (1997) discusses the visual strategies of batting in cricket. Specifically Regan postulates that a bowler will attempt to force a batsman to make decisions about their response early (in the

ball's flight), which will reduce their response timing and accuracy. Therefore batters who can visually track the ball for longer and adapt their movements accordingly will be at an advantage. This theory would perhaps suggest that QE2 is not a QE period in the traditional sense (a gaze initiated prior to the onset of a critical movement), as the participants continue to track as they move towards the ball, continually updating their movement strategy.

Overall, it would appear that in samples of typically developing children, an extended QE period is beneficial for directing their visual attention to task relevant stimuli to formulate internal models, and buffering them from the stimulus-driven system. Indeed, children with DCD also benefited from this attentional control mechanism, as studies have proposed that they have attentional deficits, which may be overcome by extended processing of task relevant information. The studies described in this thesis would therefore most strongly support the suggestion that the extended QE periods are providing children more, better quality visual information from increased attentional control from which they can formulate more complete and accurate predictions about the parameters of the task and required movement patterns.

6.2.3 Theoretical Implications for DCD

These studies also explore the nature of the visuomotor impairment experienced by children with DCD, adding to the view that children with DCD are unable to efficiently pick-up and process visual information. The study of typically developing children in the second experiment of chapter 4 and the study of DCD children in chapter 5 used the same methodology as they were conducted simultaneously. This allows us to draw direct comparisons between these two groups of children to help develop our understanding of the

visuomotor impairments of children with DCD and how QET affects this in comparison to a typically developing group.

First, both the DCD and typically developing children used a targeting QE fixation (QE1) to enable them to pre-plan and organise their movements. Gabbard (2009) found that typically developing children are able to create a mental image of a movement by ages 5-6 years and can produce the resulting movement with some degree of accuracy by age 7. However studies of the internal modelling deficit hypothesis indicate that this is not the case for children with DCD as old as 12 years (Hyde & Wilson, 2011a; Hyde & Wilson, 2011b; Williams et al., 2011). The children with DCD had shorter QE durations at baseline compared to the typically developing group, despite suggestions that this group require a longer visual information processing time (Wilmot & Wann, 2008) indicating that perhaps they are not forming a complete internal model prior to movement. When QET increased the QE durations of the typically developing group, these children also significantly improved their catching performance, suggesting the increased processing time allowed for better formulation of internal models, aiding the prediction of the location and timing of the interception point and the movement parameters required to complete a catch. The DCD group however did not experience such significant improvements in performance outcome from QET, supporting the conclusion of an internal modelling deficit that was improved but not entirely overcome by increasing the processing time.

To investigate this pre-programming difference between typically developing and those with DCD further, we completed an unpublished experiment examining the link between the QE1 and QE2 phase of this throwing and catching task. This experiment used a reaction ball (Figure 6.1)

for the throwing and catching task. This is a 'misshapen' ball with the same diameter of a tennis ball, but will bounce in an unpredictable direction and speed off the wall. With the reaction ball condition, the location and timing of the interception point will be unpredictable prior to the throw, therefore the internal model of the catch formed at this stage will be incomplete (i.e. it cannot be predicted from the early information of ball flight *towards* the bounce point). Only once the bounce on the wall has taken place and QE2 is initiated, can the participant update the model with visual information and the resultant online adjustments to their movements. The critical phase of this task therefore, becomes the rapid pick-up and recognition of the ball flight direction and speed after the bounce, or in other words, the time to QE2 onset.



Figure 6.1: *A reaction ball that bounces off a surface in a relatively random direction and speed. It is constructed of rubber and is the same diameter as a tennis ball (6.7cm).*

Preliminary findings ($n = 14$) suggest that the QE2 onset is indeed a critical factor for performance in typically developing children. It would appear that with a round tennis ball these children are able to formulate internal (forward) models to accurately guide their movements, and as a result are able

to locate and initiate an earlier QE2 fixation (within 156ms – similar to the median and BL of typically developing groups in chapters 3 and 4 – Table 6.1) and they are able to catch 51% of the throws (also see Table 6.1 for comparisons). However, when the internal model is incomplete (i.e. when using the reaction ball), it would appear that these children are reduced to a performance level that was not much better than the baseline tennis ball scores of children with DCD prior to any training (Table 6.1). The incomplete model was compounded by comparatively slow QE2 onset times, with the TD children taking 54ms longer to locate the ball than the DCD participants in chapter 5 and, unsurprisingly, this reduced their QE2 durations. Therefore in the reaction ball condition, not only do the typically developing children have an incomplete pre-programmed response, but the longer lag before QE2 is initiated will delay their ability to make online corrections to their predicted movement.

The children with DCD do not have such a decrease in their QE2 duration when using the reaction ball (Table 6.1). This is possibly due to their impairments in feed-forward prediction (Smits-Engelsman et al., 2003) that cause incomplete or ineffective internal modelling with both types of ball. Instead these children appear to rely on a somewhat random search for the ball as it comes back towards them, providing them with little time to prepare the catch attempt. While the DCD group also performed worse in this task than in the tennis ball task, the percentage impairment (14%) is less than that for the typically developing children (18%).

In addition to the findings from the earlier QET studies, these preliminary findings support the postulation that the QE provides an extended period for the pre-programming of task parameters and formulation of a forward internal model (QE1) that is updated to make online adjustments (QE2). Children with

DCD however have shorter QE1 and QE2 durations with both the tennis ball and reaction ball, indicating they are perhaps not taking the time to effectively plan their movements. It is reasonable to conclude from this experiment that the extended QE1 duration learnt from QET affords children more time to formulate or improve the predictive accuracy of an internal model. Furthermore, an earlier and longer QE2 duration helps them to get earlier and more complete visual information necessary for adjusting their movements online.

Table 6.1: A comparison of the QE1 duration, QE2 onset, QE2 duration and performance % from chapter 3, chapter 4 (experiments 1

and 2), chapter 5 (DCD children) and the reaction ball trials of typically developing children and those with DCD.

	Chapter 3, Median (MMC) Group	Chapter 4 (TD), experiment 1	Chapter 4 (TD), experiment 2	Chapter 5 (DCD)	Reaction Ball trials (TD) (N = 14)	Reaction Ball Trials (DCD) (N = 14)
QE1 Duration (ms)	558.99	299.21	321.95	285.89	337.14	249.40
QE2 Onset (ms)	172.88	(Not reported)	156.78	166.61	220.8	227.68
QE2 Duration (ms)	200.50	166.47	246.42	157.24	162.63	149.88
Performance (%)	62	49	51	25	33	11

Studies of smooth pursuit tracking in children with DCD have proposed that these children also have deficits in their eye movements that may impair their ability to pick-up visual information (Langaas et al., 1998; Roberts et al., 2014). Indeed, our studies would indicate impairment in the pursuit tracking of children with DCD as these children had much shorter QE2 durations (-89ms) at baseline in comparison to typically developing children. However, although still slower in initiating a QE2 gaze in comparison to typically developing children, the DCD children did not demonstrate as much of a timing lag prior to pursuit tracking (-10ms) as was seen in the LMC children of the first study (-34ms). It must be noted that the children with DCD had more experience of the task by the point of data collection as they completed it during the assessment phase prior to baseline measures being taken, exposing them to a further 15 trials (including practices). This finding would perhaps indicate a more significant impairment in their ability to retain the ball on the fovea for as long as typically developing children.

In section 6.2.1.1 of this chapter, I discussed the possibility that this impairment in QE2 duration could be related to poor visual attentional control, where the locus of attention for children with DCD is taken from the task-driven stimulus (ball) and relocated on a behavioural or environmental stimulus that is irrelevant to the execution of the catch or interferes with autonomous processes. For example, if a child with DCD is concerned about their movement coordination skills, they may redirect their attentional focus internally, trying to consciously control movements that are more autonomous in typically developing children.

The implications of an internal focus on a movement such as catching have already been discussed, but essentially this increases the risk of an

individual attempting to consciously control their movements and as a result, constraining automatic processes. Furthermore, the conscious control of movements will also increase the processing demands of a movement. Children with DCD have been shown to perceive tasks to be more difficult than typically developing controls (Chen & Wu, 2013) and Mon-Williams et al. (2005) postulated that children with DCD choose to adapt their movements to compensate for motor impairments. Przysucha and Maraj (2013) and Utley et al. (2007) found that one compensatory solution used by children with DCD when catching was to couple the movements of limbs and freeze the degrees of freedom around the elbow joint. Based on these findings, it is likely when performing complex tasks such as catching, children with DCD do indeed have an internal attentional focus on their movements, and it is possible they are consciously trying to constrain these movements to improve their perceptions of control.

QET however redirects an individual's focus of attention to a relevant external target. Rather than consciously constraining limb movements, they are free to self-organise unconsciously while attention is taken up with providing the relevant visual information to support this process. Indeed, after receiving QET the children demonstrated significantly more elbow flexion, without receiving instructions relating to the explicit control and coordination of these limb movements.

Additionally, by gathering more (and later) visual information about the ball during flight, more accurate predictions for guiding the location and timing of the grasping action take place, which are indicated in these studies by better qualitative performance scores. Visual information gained from longer pursuit tracking has previously been associated with performance advantages in

various interceptive tasks such as baseball batting, cricket batting and catching (Fogt & Zimmerman, 2014; Land & McLeod, 2000; Millslagle, Hines, & Smith, 2013; Panchuk et al., 2013).

In order to increase the QE2 and indeed QE1 durations, our QET intervention used a set of fairly explicit training instructions for both the QET and TT groups. However, theories such as the constrained action hypothesis would suggest that a more implicit set of instructions would help an individual to maintain attentional focus on the performance effect and reduce the interruption to autonomous movements caused by explicit movement rules. Indeed, Wilson et al. (2003) found that children with DCD could learn to sequence together aspects of a movement at a similar rate to typically developing children in an implicit learning task. Therefore, although our findings indicate that the children with DCD were able to increase their QE durations with explicit instruction, it is possible that implicit learning of QET may improve the retention and particularly the execution of these instructions.

Therefore I have completed a follow-up study of the throwing and catching task using a ball that lights up when it contacts the wall and flashes throughout the flight back towards the participant. It is hypothesised that the flashing ball will provide an implicit cue to draw the visual attention of the child onto the ball earlier and encourage them to track the ball for longer through its flight. Early findings indicate that the performance of children with DCD ($n = 10$) is significantly better ($p = .032$) when catching with the light-up ball (mean 45%, $SD = 30.31$), compared to normal ball (mean 25%, $SD = 24.61$). However this effect cannot yet be attributed to an earlier and longer QE2 gaze as this analysis has yet to be conducted and is outside the scope of this thesis.

Overall, we can conclude that a longer processing time of visual information during pursuit tracking (QE2) that included late visual information prior to the grasping motion was critical to the catching performance of these children. The longer QE2 enabled them to make better judgements about the trajectory of the ball that would inform online adjustment to their movements and to adapt to better predictions about the catch location and timing. Many studies of children with DCD suggest children with DCD are unable or unwilling to adapt their movements once initiated (e.g. Hyde & Wilson, 2011a; Hyde & Wilson, 2011b; Mon-Williams et al., 2005; Wilmut & Wann, 2008), therefore QET appears to produce an interesting development in the technique of these children that affords them the resources to make these adjustments. Furthermore, an extended QE2 gaze could also have afforded these children with an external attentional focus on the movement effect rather than the execution, and this appeared to alter their technique to become more similar to that used by typically developing children and adults.

6.3. Practical Implications for Children with DCD

QET is a task-specific intervention so more research is required to determine the effect of this training for children with and without DCD on other tasks, and to investigate the transferability of these findings to other motor skills. However as chapter 2.3.1 identifies, improvements in catching skill may alone have a significant impact on children's mental, physical and social wellbeing by encouraging them to take part in more physical and group activities such as sport and playground games. The longitudinal work by Barnett and colleagues (Barnett et al., 2008b, 2009) indicates that better object control skill during childhood years is likely to have a significant effect on children's

cardiorespiratory fitness and physical activity participation levels as adolescents. It is therefore imperative that effective motor skill interventions are explored to interrupt this vicious cycle.

Current approaches to intervention for children with DCD are generally intensive and span over a period of 8 or more weeks (review by Smits-Engelsman et al., 2013; chapter 2.2.6). However the QET intervention used in chapter 5 produced 'long term' (durable over 6 weeks) changes to performance technique in just a brief 1 hour training session. Vine et al. (2011) also found a positive effect of a short QET protocol for elite golf putting. They found that after a short training session consisting of just 20 putts, a group that had received QE-related feedback via video increased their QE durations and holed more putts than the control group who received no instructional feedback with the videos. This improvement immediately after training was not statistically significant, however when transferred into a pressured test, the QET group were able to maintain their QE durations and performance levels, whereas the control group decreased in both these measures. Interestingly this study also assessed the performance of the golfers in an ecologically valid competitive environment that took place over several months following training. They found the QET group significantly reduced the number of putts they took per round, indicating an increase in performance over a longer period of time.

Developing quick, effective strategies for improving children's long-term performance of motor skills such as catching could have significant implications for children with movement difficulties that cause them to withdraw from physical and social activities. The findings of this thesis indicate that a short QET intervention that can be performed at home or in school could help these children improve their performance of a skill to a level that may change their

attitude towards participating in a sport or activity. Furthermore, although the competitive performance of the children was not measured during these studies, based on the similarities of this training interventions with other studies of QET and pressure (e.g. Vickers & Williams, 2007; Vine et al., 2011; Vine & Wilson, 2010, 2011), one could postulate that the QET may also 'buffer' these children from the negative effects of competitive anxiety that come with performing the skill in front of significant others, or in the competitive environment of sports and playground games. Future studies of QET in children could include a competitive test to determine if these buffering effects are indeed transferable to this population.

Despite the overall positive outlook of the findings for QET, the diminished effect of QET on performance percentage of the DCD children in comparison to the typically developing children cannot be ignored (Table 6.2). The QET groups showed larger improvements than the TT groups in both the R1 tests, and these differences between the groups were extended in the typically developing children and maintained for the DCD children after 6 weeks. However as Table 6.2 shows, the DCD children in chapter 5 have smaller increases in their catching performance and are poorer in maintaining this over 6 weeks, despite identical methodology to experiment 2 of chapter 4 using typically developing children. The DCD literature does indicate that children with this condition have difficulties with motor learning (e.g. Debrabant et al., 2013; Gheysen, Van Waelvelde, & Fias, 2011), which would explain smaller improvements compared to typically developing children. Within the DCD group, those with the lowest overall MABC-2 scores (< 1st percentile rank, QET = 3, TT = 6) scored below average at baseline in the catching task (10%) and experienced smaller improvements in their catching performance at R1 (QET

=+10%, TT = +6%), whereas the 8 children (QET = 4, TT = 4) scoring the highest in the DCD group (5th percentile) scored on average 55% at baseline and the QET children were able to make much larger improvements over the TT group (QET = +20%, TT = +5%). This would indicate that the children with the lowest overall coordination levels were perhaps less able to retain the gaze strategies taught during such a short training session.

Table 6.2: *The improvement in performance % of the QET and TT groups in experiment 2 in chapter 4 and the DCD children in chapter 5. These studies used almost identical methodology for both training groups.*

	Chapter 4 (TD)		Chapter 5 (DCD)	
	QET	TT	QET	TT
BL to R1 performance improvement (%)	+25	+9	+16	+11
R1 to R2 performance improvement (%)	+5	-2	-6	-7

Another possible explanation is in the sampling of children with a DCD diagnosis used in this study. Although co-occurring ADHD was identified and co-variant analysis checked, there was no control over other co-occurring disorders and no consideration was made for DCD subtype. The heterogeneous nature of DCD is well established and research has suggested that distinct groups of children with DCD can be formulated based on aspects of their coordination skill such as fine motor impairments overriding gross or complex motor skills or vice versa (Piek, Baynam, & Barrett, 2006) or by neurological function (e.g. Bo & Lee, 2013; Zwicker, Missiuna, Harris, & Boyd, 2011) or by perceptual abilities (e.g. Wilson et al., 2004; Wilson et al., 2002).

Visser (2003) argues that DCD subtype will have differing causes, treatment requirements and outcomes, and Bo and Lee (2013) speculate that effective intervention strategies should reflect DCD subtype. However despite many studies attempting to define these subtypes, no distinct categories have yet been established, beyond the severity of motor impairment (Green et al., 2008).

The children recruited for chapter 5 may have varying symptoms of DCD such as sequential or sensorimotor motor learning abilities that would affect their ability to learn and perform the catching skill. The MABC-2 quantifies three aspects of motor skill performance: manual dexterity skills, aiming and catching skills and dynamic and static balance. The children who scored below the 1st percentile on just the aiming and catching skills (QET = 2, TT = 6) had an average baseline score of 6% and made very small improvements at R1 (QET = 0%, TT = +7%) and at R2 (QET = +5%, TT = -5%). These observations support the suggestion that children with very low aiming and catching ability may have affected the overall group effect for improving catching performance.

It cannot be determined from the present studies why children with low overall motor coordination ability and low baseline catching performance were particularly poor at improving their catching ability in either intervention. It is possible that these children experience other symptoms of DCD more severely, such as sequential motor learning (Bo & Lee, 2013); the ability to formulate internal models (Deconinck, Spitaels, Fias, & Lenoir, 2009; Hyde & Wilson, 2011a; Hyde & Wilson, 2011b; Williams et al., 2013); or the ability to retain everyday information (Chen et al., 2013) that would reduce their ability to apply and practice the instructions. In terms of the practical implications, this would indicate that an intervention such as QET may not be appropriate for children with more severe forms of DCD.

6.4. Limitations and Directions for Future Research

The process of recruiting participants for this work was singularly the biggest challenge of this project, particularly in recruiting adequate numbers of children diagnosed with DCD. The initial aim for the study described in chapter 5 was to recruit 60 children diagnosed with DCD, which would have enabled us to separate children with 'pure' DCD and those with co-occurring disorders into two separate groups. These children were all to be recruited through Vbranch House Clinic in Exeter, however this clinic was only able to provide 15 participants with DCD over an 18month period. Therefore the inclusion criteria for this study had to be relaxed, and children from further afield were recruited through schools, social media and the UK Dyspraxia Foundation. In total the recruitment and testing procedure of the 30 DCD participants for chapter 5 took 18 months, leaving no option to expand this sample size any further or include additional experimental groups such as a discovery learning group.

The relaxed inclusion criteria meant we had less knowledge of, and consistency in the DCD diagnosis of the children recruited from other sources. Therefore it is possible that our sample was more varied in their motor skill impairment. We had little control over other interventions children had or were currently participating in during the testing period. Furthermore we were unable to control for co-occurring disorders outside of ADHD such as autism spectrum disorders (ASD) and learning disabilities. Although this group therefore represented a more ecologically valid representation of children with DCD in the UK population, these factors may have led to more variability in the motor function and processing resources of children in our sample, as children with ASD for example have a high occurrence of uneven cognitive development (Joseph, Tager-Flusberg, & Lord, 2002).

The recruitment and testing of the typically developing children also represented a challenge, as much of the data collection (studies 1 and 2) took place in schools during the school day (over a 6-8 week period) so the availability of empty classrooms, school lessons and events and holidays had to be structured into the timetabling of the data collection. These factors significantly slowed the process, again limiting the sample sizes and number of training groups used for the studies.

The QE definitions for the throwing and catching task had to be developed based on previous studies of other aiming and interceptive skills. These definitions (particularly QE1) did therefore evolve throughout the studies based on our learning about the skill and the critical movements and gaze strategies involved in its performance. This meant study 1 (chapter 3) and the first experiment of chapter 4 used a different definition of the QE relating to the onset of a critical movement. For QE1, the critical movement from which the onset of the QE was initiated was redefined from the release of the ball to the start of the foreswing of the arm. The critical movement for QE2 was somewhat more challenging to define due to the sequential nature of the whole task meaning the movements of the throw follow-through flow directly into the movements of the catch. Throughout this project, several movements were considered as potential critical movements of the catch by which QE2 could be defined, such as the first foot movement (as used by Vickers & Adolphe, 1997); and the first observable movement of the non-throwing and throwing arm in the direction of the ball, however these movements were not consistently performed within or between the participants. Furthermore, as the QE2 was most likely responsible for predicting the location and timing of the final interception point of the ball, the critical movement of this phase of the task was deemed to be the

onset of the grasping action that signifies the attempt at a catch. This movement of the fingers flexing around the ball indicates the participant's final prediction of the timing and location of the interception point based on the QE2, and therefore is the critical movement that will distinguish between failed and successful attempts. This definition of the critical movement for QE2 was ultimately used consistently throughout the studies of this thesis.

The three experimental chapters of this thesis all used the MABC-2 throwing and catching task and therefore adhered to the specific instructions of the task as prescribed by Henderson et al. (2007). This decision meant the task remained consistent and therefore comparable across the studies and samples of children used throughout the thesis, however a significant drawback of this task was the small number of trials that the testing conditions were restricted to. The MABC-2 dictates that a participant should complete 5 practices followed by 10 assessed trials. It is important to conduct a suitable number of trials to obtain stable data that is representative of the sample's population, particularly for children with DCD, as their movements are likely to be variable due to the nature of the condition. Future work may consider including more trials in a task such as this, although a balance needs to be struck between a representative number of trials and time for which a child can remain concentrated and motivated on the task. Children and particularly those with poor motor skills tend to have a lower attentional threshold, which drove the decision for this thesis to retain the recommended number of trials prescribed in the MABC-2.

The training protocol used in this study, whilst typical for QET studies, was undoubtedly brief compared to previous intervention studies for children with DCD. Whilst this carries the advantage for teachers, parents and therapists to use a QET method to quickly improve movement technique of

children with DCD, future work should perhaps consider how a longer, more focused QET intervention might induce better and longer performance improvements. This could better prepare QET as a more suitable therapeutic intervention that could be used to improve the motor skill performance of children with more severe movement difficulties, as the studies in this thesis would indicate that this intervention is perhaps more suited to children of a higher overall movement coordination level (as indexed by the MABC-2).

The nature of the QET instructions may have evoked an external attentional focus, which Wulf (2013) has linked with better motor learning and performance. However, the training video instructions were explicit, instructing and demonstrating the skill adjustment that was required. Explicit instructions such as these provide a participant with conscious 'rules' about the skill and the effect of a movement upon the outcome that they will attempt to control. This may lead to what is known as reinvestment (Poolton, Maxwell, & Masters, 2004) where autonomous movements are interrupted by conscious processes. Table 6.2 indicates that the DCD children in both training interventions were poorer at retaining their performance improvements in comparison to typically developing children, and Wilson et al. (2003) found that when children with DCD learnt a simple task implicitly they were able to improve their motor response accuracy and timing to a similar degree to typically developing children. Future development of QET could therefore investigate the effects of implicit learning of the QE techniques for these children, which will reduce the child's dependence on cognitive processes for learning.

Capio, Poolton, Sit, Holmstrom, and Masters (2013) found that children made better improvements in a fundamental movement skill (throwing) using an implicit errorless learning technique. The theory of errorless learning suggests

that feedback obtained from outcome errors causes a performer to attempt to consciously correct a movement, so reducing these errors will limit the conscious processes involved with performing the task (Capio et al., 2013). This method is based around practice rather than instruction, where the task is constrained to limit the number of outcome errors, such as catching a larger ball or throwing from a shorter distance before progressing to the full MABC-2 skill, similar to the methods of NTT (chapter 2.2.5).

The light ball study described earlier in this chapter is also an attempt to develop more implicit learning and implicit gaze training for the children with DCD, by subconsciously directing their attention to the ball at the bounce, and therefore attempting to prolong QE2. The gaze data has not been analysed for this work, however it would appear from preliminary results that children with DCD were more successful catching with this ball in comparison to a tennis ball. These implicit learning protocols are likely to make significant improvements to how we teach children with DCD motor skills, therefore future work is needed to develop this technique to encourage longer, earlier QE durations during this catching task.

One final consideration is how QET might affect other psychological factors critical for performance. In chapter 6.2.1.1, the perceived difficulty of a task is discussed in relation to a child's attentional control. The findings of Wood, Vine, and Wilson (2013) and Chen and Wu (2013) would indicate that the QE is affected by perceived task difficulty, so one might postulate that QET may reduce this effect in children with DCD. The Children's Self-Perceptions of Adequacy in and Predilection for Physical Activity (CSAPPA) questionnaire has been proposed as a suitable screening tool for children with DCD (Hay, Hawes, & Faught, 2004). This tool has three sub-scales: perceived adequacy,

enjoyment and predilection towards physical activity, so it would appear children with DCD consistently score lower in all of these factors. Interestingly, Cairney et al. (2007) found that children with DCD perceive themselves to have a particularly low adequacy in physical activity. Future research therefore should look to determine how QET might affect psychological factors such as perceived task difficulty and physical activity adequacy in children with DCD.

6.5. Final Conclusions

Children's fundamental movement skills, and particularly ball control skills such as catching are highly associated with better mental, physical and social wellbeing. Children with DCD are particularly prone to health problems such as obesity due to low participation in physical activity, and the associated side effects such as social isolation and low self-efficacy. The QE is a gaze behaviour that has been extensively researched in adults. Successful performance outcomes are characterised by earlier and longer QE durations, a finding which has led to QET being developed. Again, studies of adults have demonstrated that this training technique is effective in fine-tuning expert skill performance, but crucially it has also been shown that increasing the QE durations of adult performers expedites skill learning, leading to faster and more robust skill acquisition.

The QE has not yet been studied in children, therefore the work in this thesis was the first to determine that highly skilled children also exhibit earlier and longer QE fixations when performing a throwing and catching task in comparison to median and low skilled children. Specifically, chapter 3 identified two QE periods in this task; the first taking place during the aiming phase of the throw (QE1), and the second took place as the child visually tracked the ball

prior to the catch. The second phase of this project described in chapter 4 determined that children could be trained to increase their QE durations in this task and this was shown to improve their catching performance over and above the effect of standard training methods (experiment 1). This first attempt at QET in children was based on previous QET in adults, so there were numerous adaptations that were identified to develop this intervention, which were studied in experiment 2 of this chapter. This experiment performed a more substantial investigation of QET in children and also determined that training was relatively robust; increasing both the QE durations and catching performance of children over a six-week period.

With evidence that QET significantly improves the performance of typically developing children to a greater degree than standardised coaching techniques, the third phase of this project applied this intervention to a sample of children diagnosed with DCD (chapter 5). This study followed the same methodology of the second experiment of typically developing children, and although the QET intervention again significantly increased the children's QE1 and QE2 durations, the higher performance outcome of the QET group did not reach significant levels over that of the traditionally trained group. Despite this, a qualitative measure of performance found that the children with DCD who received QET were indeed using a more expert-like technique, and a kinematic measure demonstrated they were using more flexion in their elbow joint at the point of the catch, in comparison to their baseline performance and the group receiving traditional training instructions.

Therefore, we can conclude from this work that increasing the QE durations of children will improve their performance in a throwing and catching task, although this effect is not as strong for children with DCD, instead

improving their technique rather than quantitative performance. It may be that these children were unable to cognitively internalise the training instructions as well as typically developing children, or that they were unable to retain the information they had learned. Therefore future research should investigate the optimal QE duration for this task and determine whether a longer, more focused QET intervention is an appropriate solution for children with DCD. Alternatively the use of implicit training techniques to reduce the cognitive processes involved with the skill learning could help develop QET as a suitable therapeutic intervention for children with DCD.

7. References

- Abercrombie, M. L. J. (1964). *Perceptual and visuo-motor disorders in cerebral palsy: a survey of the literature*. London: Heinemann.
- Adolphe, R. A., Vickers, J. N., & Laplante, G. (1997). The Effects of Training Visual Attention on Gaze Behaviour and Accuracy: A pilot Study. *International Journal of Sports Vision*, 4(1), 28-33.
- Allard, F., & Starkes, J. L. (1980). Perception in sport: Volleyball. *Journal of Sport Psychology*, 2, 22-23.
- Asmussen, M. J., Przysucha, E. P., & Dounskaia, N. (2014). Intersegmental dynamics shape joint coordination during catching in typically developing children but not in children with developmental coordination disorder. *Journal of Neurophysiology*, 111(7), 1417-1428. doi: 10.1152/jn.00672.2013
- Asonitou, K., Koutsouki, D., Kourtessis, T., & Charitou, S. (2012). Motor and cognitive performance differences between children with and without developmental coordination disorder (DCD). *Research in Developmental Disabilities*, 33(4), 996-1005. doi: 10.1016/j.ridd.2012.01.008
- American Psychiatric Association. (2000). *Diagnostic and Statistical Manual of Mental Disorders (4th Revised Ed.)*. Washington DC: American Psychiatric Association.
- Astill, S. (2007). Can children with developmental coordination disorder adapt to task constraints when catching two-handed? *Disability and Rehabilitation*, 29(1), 57-67. doi: 10.1080/09638280600947856
- Astill, S., & Utley, A. (2006). Two-handed catching in children with developmental coordination disorder. *Motor Control*, 10(2), 109-124.

- Astill, S., & Utley, A. (2008). Coupling of the reach and grasp phase during catching in children with developmental coordination disorder. *Journal of Motor Behavior, 40*(4), 315-323. doi: 10.3200/jmbr.40.4.315-324
- Bairstow, P. J., & Laszlo, J. I. (1989). Deficits in the planning, control and recall of hand movements, in children with perceptuo-motor dysfunction. *British Journal of Developmental Psychology, 7*, 251-273.
- Ballard, D. H., & Hayhoe, M. M. (2009). Modelling the role of task in the control of gaze. *Visual Cognition, 17*(6-7), 1185-1204. doi: 10.1080/13506280902978477
- Barnett, L., van Beurden, E., Morgan, P., Brooks, L., & Beard, J. (2008a). Do Skilled Children Become Active Adolescents? *Medicine and Science in Sports and Exercise, 40*(5), S96-S96. doi: 10.1249/01.mss.0000321868.26713.44
- Barnett, L. M., Van Beurden, E., Morgan, P. J., Brooks, L. O., & Beard, J. R. (2008b). Does Childhood Motor Skill Proficiency Predict Adolescent Fitness? *Medicine and Science in Sports and Exercise, 40*(12), 2137-2144. doi: 10.1249/MSS.0b013e31818160d3
- Barnett, L. M., Van Beurden, E., Morgan, P. J., Brooks, L. O., & Beard, J. R. (2009). Childhood Motor Skill Proficiency as a Predictor of Adolescent Physical Activity. *Journal of Adolescent Health, 44*(3), 252-259. doi: 10.1016/j.jadohealth.2008.07.004
- Bart, O., Jarus, T., Erez, Y., & Rosenberg, L. (2011). How do young children with DCD participate and enjoy daily activities? *Research in Developmental Disabilities, 32*(4), 1317-1322. doi: 10.1016/j.ridd.2011.01.039

- Beutum, M. N., Cordier, R., & Bundy, A. (2013). Comparing Activity Patterns, Biological, and Family Factors in Children with and Without Developmental Coordination Disorder. *Physical and Occupational Therapy in Pediatrics*, 33(2), 174-185. doi: 10.3109/01942638.2012.747585
- Blank, R., Smits-Engelsman, B., Polatajko, H., & Wilson, P. (2012). European Academy for Childhood Disability (EACD): Recommendations on the definition, diagnosis and intervention of developmental coordination disorder (long version). *Developmental Medicine and Child Neurology*, 54(1), 54-93. doi: 10.1111/j.1469-8749.2011.04171.x
- Bo, J., & Lee, C. M. (2013). Motor skill learning in children with Developmental Coordination Disorder. *Research in Developmental Disabilities*, 34(6), 2047-2055. doi: 10.1016/j.ridd.2013.03.012
- Bonifacci, P. (2004). Children with low motor ability have lower visual-motor integration ability but unaffected perceptual skills. *Human Movement Science*, 23(2), 157-168. doi: 10.1016/j.humov.2004.08.002
- Bootsma, R. J. (1991). Predictive information and the control of action - What you see is what you get. *International Journal of Sport Psychology*, 22(3-4), 271-278.
- Bootsma, R. J., & Van Wieringen, P. C. W. (1988). Timing an attacking forehand drive in table tennis. *Journal of Experimental Psychology*, 16(1), 21-29.
- Braddick, O., & Atkinson, J. (2013). Visual control of manual actions: brain mechanisms in typical development and developmental disorders. *Developmental Medicine and Child Neurology*, 55, 13-18. doi: 10.1111/dmcn.12300

- Bruininks, R. H. (1978). *Bruininks-Oseretsky Test of Motor Proficiency: Examiner's Manual*. Circle Pines, Minnesota: American Guidance Services.
- Bruininks, R. H., & Bruininks, B. (2005). *Bruininks-Oseretsky test of motor proficiency (2nd ed.)*. Minneapolis: NCS Pearson.
- Bunker, D., Hardy, C., Smith, B., & Almond, L. (1994). *Primary physical education: Implementing the national curriculum*. Cambridge: Cambridge University Press.
- Cairney, J., Hay, J., Mandigo, J., Wade, T., Faught, B. E., & Flouris, A. (2007). Developmental coordination disorder and reported enjoyment of physical education in children. *European Physical Education Review*, 13(1), 81-98. doi: 10.1177/1356336x07072678
- Cairney, J., Hay, J., Veldhuizen, S., Missiuna, C., Mahlberg, N., & Faught, B. E. (2010). Trajectories of relative weight and waist circumference among children with and without developmental coordination disorder. *Canadian Medical Association Journal*, 182(11), 1167-1172. doi: 10.1503/cmaj.091454
- Cairney, J., Hay, J. A., Faught, B. E., & Hawes, R. (2005a). Developmental coordination disorder and overweight and obesity in children aged 9-14 y. *International Journal of Obesity*, 29(4), 369-372. doi: 10.1038/sj.ijo.0802893
- Cairney, J., Hay, J. A., Faught, B. E., Wade, T. J., Corna, L., & Flouris, A. (2005b). Developmental coordination disorder, generalized self-efficacy toward physical activity, and participation in organized and free play activities. *The Journal of pediatrics*, 147(4), 515-520. doi: 10.1016/j.jpeds.2005.05.013

- Cairney, J., Rigoli, D., & Piek, J. (2013). Developmental coordination disorder and internalizing problems in children: The environmental stress hypothesis elaborated. *Developmental Review, 33*(3), 224-238. doi: 10.1016/j.dr.2013.07.002
- Cairney, J., & Veldhuizen, S. (2013). Is developmental coordination disorder a fundamental cause of inactivity and poor health-related fitness in children? *Developmental Medicine and Child Neurology, 55*, 55-58. doi: 10.1111/dmcn.12308
- Cantell, M. H., Smyth, M. M., & Ahonen, T. P. (2003). Two distinct pathways for developmental coordination disorder: Persistence and resolution. *Human Movement Science, 22*(4-5), 413-431. doi: 10.1016/j.humov.2003.09.002
- Cantin, N., Ryan, J., & Polatajko, H. J. (2014). Impact of task difficulty and motor ability on visual-motor task performance of children with and without developmental coordination disorder. *Human Movement Science, 34*, 217-232. doi: 10.1016/j.humov.2014.02.006
- Capio, C. M., Poolton, J. M., Sit, C. H. P., Holmstrom, M., & Masters, R. S. W. (2013). Reducing errors benefits the field-based learning of a fundamental movement skill in children. *Scandinavian Journal of Medicine and Science in Sports, 23*(2), 181-188. doi: 10.1111/j.1600-0838.2011.01368.x
- Caravale, B., Baldi, S., Gasparini, C., & Wilson, B. N. (2014). Cross-cultural adaptation, reliability and predictive validity of the Italian version of Developmental Coordination Disorder Questionnaire (DCDQ). *European Journal of Paediatric Neurology, 18*(3), 267-272. doi: 10.1016/j.ejpn.2013.11.009

- Causer, J., Bennett, S. J., Holmes, P. S., Janelle, C. M., & Williams, A. M. (2010). Quiet Eye Duration and Gun Motion in Elite Shotgun Shooting. *Medicine and Science in Sports and Exercise*, 42(8), 1599-1608. doi: 10.1249/MSS.0b013e3181d1b059
- Causer, J., Holmes, P. S., & Williams, A. M. (2011). Quiet Eye Training in a Visuomotor Control Task. *Medicine and Science in Sports and Exercise*, 43(6), 1042-1049. doi: 10.1249/MSS.0b013e3182035de6
- Cermak, S. A., & Larkin, D. (2002). *Developmental Coordination Disorder*. Brooklyn, NY: Singular Press.
- Chen, F. C., & Wu, S. K. (2013). Perceived Hole Size, Performance, and Body Movement During Putting in Children With and Without Probable Developmental Coordination Disorder. *Motor Control*, 17(4), 382-398.
- Chen, I. C., Tsai, P. L., Hsu, Y. W., Ma, H. I., & Lai, H. A. (2013). Everyday memory in children with developmental coordination disorder. *Research in Developmental Disabilities*, 34(1), 687-694. doi: 10.1016/j.ridd.2012.09.012
- Chen, Y. W., Tseng, M. H., Hu, F. C., & Cermak, S. A. (2009). Psychosocial adjustment and attention in children with developmental coordination disorder using different motor tests. *Research in Developmental Disabilities*, 30(6), 1367-1377. doi: 10.1016/j.ridd.2009.06.004
- Cheng, C. H., Ju, Y. Y., Chang, H. W., Chen, C. L., Pei, Y. C., Tseng, K. C., & Cheng, H. Y. K. (2014). Motor impairments screened by the Movement Assessment Battery for Children-2 are related to the visual-perceptual deficits in children with Developmental Coordination Disorder. *Research in Developmental Disabilities*, 35(9), 2172-2179. doi: 10.1016/j.ridd.2014.05.009

- Chia, L. C., Reid, S. L., Licari, M. K., & Guelfi, K. J. (2013). A comparison of the oxygen cost and physiological responses to running in children with and without Developmental Coordination Disorder. *Research in Developmental Disabilities, 34*(7), 2098-2106. doi: 10.1016/j.ridd.2013.03.023
- Corbetta, M. (1998). Frontoparietal cortical networks for directing attention and the eye to visual locations: Identical, independent, or overlapping. *Proceedings of the National Academy of Sciences of the United States of America, 95*, 831-838.
- Corbetta, M., Patel, G., & Schilman, G. L. (2008). The reorienting system of the human brain: From environment to theory of mind. *Neuron, 58*(306-324).
- Crawford, S. G., & Dewey, D. (2008). Co-occurring disorders: A possible key to visual perceptual deficits in children with developmental coordination disorder? *Human Movement Science, 27*(1), 154-169. doi: 10.1016/j.humov.2007.09.002
- D'Hondt, E., Deforche, B., Gentier, I., De Bourdeaudhuij, I., Vaeyens, R., Philippaerts, R., & Lenoir, M. (2013). A longitudinal analysis of gross motor coordination in overweight and obese children versus normal-weight peers. *International Journal of Obesity, 37*(1), 61-67. doi: 10.1038/ijo.2012.55
- de Oliveira, R. F., Huys, R., Oudejans, R. R. D., van de Langenberg, R., & Beek, P. J. (2007). Basketball jump shooting is controlled online by vision. *Experimental Psychology, 54*(3), 180-186. doi: 10.1027/1618-3169.54.3.180

- de Oliveira, R. F., Oudejans, R. R. D., & Beek, P. J. (2006). Late information pick-up is preferred in basketball jump shooting. *Journal of Sports Sciences, 24*(9), 933-940. doi: 10.1080/02640410500357101
- Debrabant, J., Gheysen, F., Caeyenberghs, K., Van Waelvelde, H., & Vingerhoets, G. (2013). Neural underpinnings of impaired predictive motor timing in children with Developmental Coordination Disorder. *Research in Developmental Disabilities, 34*(5), 1478-1487. doi: 10.1016/j.ridd.2013.02.008
- Deconinck, F. J. A., De Clercq, D., Savelsbergh, G. J. P., Van Coster, R., Oostra, A., Dewitte, G., & Lenoir, M. (2006). Adaptations to task constraints in catching by boys with DCD. *Adapted Physical Activity Quarterly, 23*(1), 14-30.
- Deconinck, F. J. A., Spitaels, L., Fias, W., & Lenoir, M. (2009). Is developmental coordination disorder a motor imagery deficit? *Journal of Clinical and Experimental Neuropsychology, 31*(6), 720-730. doi: 10.1080/13803390802484805
- Deutsch, K. M., & Newell, K. M. (2005). Noise, variability, and the development of children's perceptual-motor skills. *Developmental Review, 25*(2), 155-180. doi: 10.1016/j.dr.2004.09.001
- Dicks, M., Button, C., & Davids, K. (2010). Examination of gaze behaviors under in situ and video simulation task constraints reveals differences in information pickup for perception and action. *Attention Perception and Psychophysics, 72*(3), 706-720. doi: 10.3758/app.72.3.706
- DuPaul, G. J., Anastopoulos, A. D., Power, T. J., Reid, R., Ikeda, M. J., & McGoey, K. E. (1998). Parent ratings of attention-deficit/hyperactivity disorder symptoms: Factor structure and normative data. *Journal of*

- Psychopathology and Behavioral Assessment*, 20(1), 83-102. doi:
10.1023/a:1023087410712
- Ellinoudis, T., Evaggelinou, C., Kourtessis, T., Konstantinidou, Z., Venetsanou, F., & Kambas, A. (2011). Reliability and validity of age band 1 of the Movement Assessment Battery for Children - Second Edition. *Research in Developmental Disabilities*, 32(3), 1046-1051. doi:
10.1016/j.ridd.2011.01.035
- Emes, C. G., Vickers, J. N., & Livingston, L. F. (1994). Gaze control of children with high versus low motor proficiency. In K. Yabe, K. Kusano & H. Nakata (Eds.), *Adapted Physical Activity* (pp. 147-154). Tokyo: Springer-Verlag.
- Estil, L. B., Ingvaldsen, R. P., & Whiting, H. T. A. (2002). Spatial and temporal constraints on performance in children with movement co-ordination problems. *Experimental Brain Research*, 147(2), 153-161. doi:
10.1007/s00221-002-1193-7
- Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion*, 7(2), 336-353. doi: 10.1037/1528-3542.7.2.336
- Faught, B. E., Rivilis, I., Klentrou, P., Cairney, J., Hay, J., & Liu, J. (2013). Submaximal oxygen cost during incremental exercise in children with developmental coordination disorder. *Research in Developmental Disabilities*, 34(12), 4439-4446. doi: 10.1016/j.ridd.2013.09.024
- Ferguson, G. D., Aertssen, W. F. M., Rameckers, E. A. A., Jelsma, J., & Smits-Engelsman, B. C. M. (2014). Physical fitness in children with Developmental Coordination Disorder: Measurement matters. *Research*

in Developmental Disabilities, 35(5), 1087-1097. doi:

10.1016/j.ridd.2014.01.031

Ferguson, G. D., Jelsma, D., Jelsma, J., & Smits-Engelsman, B. C. M. (2013).

The efficacy of two task-orientated interventions for children with Developmental Coordination Disorder: Neuromotor Task Training and Nintendo Wii Fit training. *Research in Developmental Disabilities*, 34(9), 2449-2461. doi: 10.1016/j.ridd.2013.05.007

Fitts, P. M., & Posner, M. I. (1967). *Human performance*. Belmont: Brooke/Cole.

Flanagan, J. R., Bowman, M. C., & Johansson, R. S. (2006). Control strategies in object manipulation tasks. *Current Opinion in Neurobiology*, 16(6), 650-659. doi: 10.1016/j.conb.2006.10.005

Flanagan, J. R., Vetter, P., Johansson, R. S., & Wolpert, D. M. (2003).

Prediction precedes control in motor learning. *Current Biology*, 13(2), 146-150. doi: 10.1016/s0960-9822(03)00007-1

Flanagan, J. R., & Wing, A. M. (1997). The role of internal models in motion planning and control: Evidence from grip force adjustments during movements of hand-held loads. *Journal of Neuroscience*, 17(4), 1519-1528.

Fogt, N. F., & Zimmerman, A. B. (2014). A Method to Monitor Eye and Head Tracking Movements in College Baseball Players. *Optometry and Vision Science*, 91(2), 200-211. doi: 10.1097/OPX.0000000000000148

Gabbard, C. (2009). Studying action representation in children via motor imagery. *Brain and Cognition*, 71(3), 234-239. doi: 10.1016/j.bandc.2009.08.011

Gheysen, F., Van Waelvelde, H., & Fias, W. (2011). Impaired visuo-motor sequence learning in Developmental Coordination Disorder. *Research in*

- Developmental Disabilities*, 32(2), 749-756. doi:
10.1016/j.ridd.2010.11.005
- Green, D., Chambers, M. E., & Sugden, D. A. (2008). Does subtype of developmental coordination disorder count: Is there a differential effect on outcome following intervention? *Human Movement Science*, 27(2), 363-382. doi: 10.1016/j.humov.2008.02.009
- Green, D., Lingam, R., Mattocks, C., Riddoch, C., Ness, A., & Emond, A. (2011). The risk of reduced physical activity in children with probable Developmental Coordination Disorder: A prospective longitudinal study. *Research in Developmental Disabilities*, 32(4), 1332-1342. doi: 10.1016/j.ridd.2011.01.040
- Haga, M. (2008). The relationship between physical fitness and motor competence in children. *Child Care Health and Development*, 34(3), 329-334. doi: 10.1111/j.1365-2214.2008.00814.x
- Hands, B. (2008). Changes in motor skill and fitness measures among children with high and low motor competence: A five-year longitudinal study. *Journal of Science and Medicine in Sport*, 11(2), 155-162. doi: 10.1016/j.jsams.2007.02.012
- Hands, B., & Larkin, D. (2002). Physical fitness and developmental coordination disorder. In S. A. Cermak & D. Larkin (Eds.), *Developmental coordination disorder* (pp. 172-184). Albany, NY: Thompson Learning.
- Harle, S. K., & Vickers, J. N. (2001). Training quiet eye improves accuracy in the basketball free throw. *Sport Psychologist*, 15(3), 289-305.
- Hay, D., & Missiuna, C. (1998). Motor Proficiency in Children Reporting Low Levels of Participation in Physical Activity. *Canadian Journal of Occupational Therapy*, 65(2), 64-71.

- Hay, J. A., Hawes, R., & Faught, B. E. (2004). Evaluation of a screening instrument for developmental coordination disorder. *Journal of Adolescent Health, 34*(4), 308-313. doi: 10.1016/j.jadohealth.2003.07.004
- Hayes, A. F. (2013). *Mediation, moderation and conditional process analysis: A regression-based approach*. New York: The Guilford Press.
- Hayes, A. F., & Preacher, K. J. (2012). Statistical mediation analysis with a multicategorical independent variable. Retrieved Dec 2012, from <http://www.afhayes.com/public/mediate.pdf>
- Hayhoe, M., Mennie, N., Sullivan, B., & Gorgos, K. (2005). *The Role of Internal Models and Prediction in Catching Balls*. Paper presented at the AAAI Fall Symposium Series.
- Hayhoe, M. M., McKinney, T., Chajka, K., & Pelz, J. B. (2012). Predictive eye movements in natural vision. *Experimental Brain Research, 217*(1), 125-136. doi: 10.1007/s00221-011-2979-2
- Helsen, W. F., & Pauwels, J. M. (1993). A cognitive approach to visual search in sport *Visual Search II* (pp. 379-388). London: Taylor and Francis.
- Helsen, W. F., & Starkes, J. L. (1999). A multidimensional approach to skills perception and performance in sport. *Applied Cognitive Psychology, 13*, 1-27.
- Henderson, J. M. (2003). Human gaze control during real-world scene perception. *Trends in Cognitive Sciences, 7*(11), 498-504. doi: 10.1016/j.tics.2003.09.006
- Henderson, S. E., & Sugden, D. (1992). *Movement assessment battery for children*. London: Psychological Corporation.

- Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2007). *The Movement Assessment Battery for Children - 2nd Edition (Movement ABC-2)*. London (UK): Pearson Education Inc.
- Hendrix, C. G., Prins, M. R., & Dekkers, H. (2014). Developmental coordination disorder and overweight and obesity in children: a systematic review. *Obesity Reviews*, *15*(5), 408-423. doi: 10.1111/obr.12137
- Hillier, S. (2007). Intervention for Children with Developmental Coordination Disorder: A Systematic Review. *The Internet Journal of Allied Health Sciences and Practice*, *5*(3), 1-11.
- Holm, I., Tveter, A. T., Aulie, V. S., & Stuge, B. (2013). High intra- and inter-rater chance variation of the movement assessment battery for children 2, ageband 2. *Research in Developmental Disabilities*, *34*(2), 795-800. doi: 10.1016/j.ridd.2012.11.002
- Horn, R. R., Okumura, M. S., Alexander, M. G. F., Gardin, F. A., & Sylvester, C. T. (2012). Quiet Eye Duration Is Responsive to Variability of Practice and to the Axis of Target Changes. *Research Quarterly for Exercise and Sport*, *83*(2), 204-211.
- Hua, J., Gu, G. X., Meng, W., & Wu, Z. C. (2013). Age band 1 of the Movement Assessment Battery for Children-Second Edition: Exploring its usefulness in mainland China. *Research in Developmental Disabilities*, *34*(2), 801-808. doi: 10.1016/j.ridd.2012.10.012
- Hyde, C., & Wilson, P. (2011a). Online motor control in children with developmental coordination disorder: chronometric analysis of double-step reaching performance. *Child Care Health and Development*, *37*(1), 111-122. doi: 10.1111/j.1365-2214.2010.01131.x

- Hyde, C., & Wilson, P. H. (2011b). Dissecting online control in Developmental Coordination Disorder: A kinematic analysis of double-step reaching. *Brain and Cognition, 75*(3), 232-241. doi: 10.1016/j.bandc.2010.12.004
- Janelle, C. M., Hillman, C. H., Apparies, R. J., Murray, N. P., Meili, L., Fallon, E. A., & Hatfield, B. D. (2000). Expertise differences in cortical activation and gaze behavior during rifle shooting. *Journal of Sport and Exercise Psychology, 22*(2), 167-182.
- Johnson, M. H. (2003). Development of human brain functions. *Biological Psychiatry, 54*(12), 1312-1316. doi: 10.1016/s0006-3223(03)00426-8
- Johnson, M. H., & Mareschal, D. (2001). Cognitive and perceptual development during infancy. *Current Opinion in Neurobiology, 11*(2), 213-218. doi: 10.1016/s0959-4388(00)00199-9
- Jongmans, M. J., Smits-Engelsman, B. C. M., & Schoemaker, M. M. (2003). Consequences of comorbidity of developmental coordination disorders and learning disabilities for severity and pattern of perceptual-motor dysfunction. *Journal of Learning Disabilities, 36*(6), 528-537. doi: 10.1177/00222194030360060401
- Joseph, R. M., Tager-Flusberg, H., & Lord, C. (2002). Cognitive profiles and social-communicative functioning in children with autism spectrum disorder. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 43*(6), 807-821. doi: 10.1111/1469-7610.00092
- Kirby, A., Sugden, D., & Purcell, C. (2014). Diagnosing developmental coordination disorders. *Archives of Disease in Childhood, 99*(3), 292-296. doi: 10.1136/archdischild-2012-303569
- Klapp, S. T. (1980). The memory drum theory after 20 years - Comments on Henrys note. *Journal of Motor Behavior, 12*(2), 169-171.

- Klostermann, A., Koedijker, J., & Hossner, E. J. (2013). Task aims, quiet eye location and movement parameterization: Indications of a causal mechanism. *Zeitschrift Fur Sportpsychologie*, *20*(2), 59-64. doi: 10.1026/1612-5010/a000094
- Klostermann, A., Kredel, R., & Hossner, E. J. (2013). The "Quiet Eye" and Motor Performance: Task Demands Matter! *Journal of Experimental Psychology-Human Perception and Performance*, *39*(5), 1270-1278. doi: 10.1037/a0031499
- Klostermann, A., Kredel, R., & Hossner, E. J. (2014). On the Interaction of Attentional Focus and Gaze: The Quiet Eye Inhibits Focus-Related Performance Decrements. *Journal of Sport and Exercise Psychology*, *36*(4), 392-400.
- Kwan, M. Y. W., Cairney, J., Hay, J. A., & Faught, B. E. (2013). Understanding physical activity and motivations for children with Developmental Coordination Disorder: An investigation using the Theory of Planned Behavior. *Research in Developmental Disabilities*, *34*(11), 3691-3698. doi: 10.1016/j.ridd.2013.08.020
- Land, M. F. (2009). Vision, eye movements, and natural behavior. *Visual Neuroscience*, *26*(1), 51-62. doi: 10.1017/s0952523808080899
- Land, M. F., & McLeod, P. (2000). From eye movements to actions: how batsmen hit the ball. *Nature Neuroscience*, *3*(12), 1340-1345. doi: 10.1038/81887
- Langaas, T., Mon-Williams, M., Wann, J. P., Pascal, E., & Thompson, C. (1998). Eye movements, prematurity and developmental co-ordination disorder. *Vision Research*, *38*(12), 1817-1826. doi: 10.1016/s0042-6989(97)00399-4

- Lefebvre, C., & Reid, G. (1998). Prediction in ball catching by children with and without a developmental coordination disorder. *Adapted Physical Activity Quarterly*, 15(4), 299-315.
- Liberman, L., Ratzon, N., & Bart, O. (2013). The profile of performance skills and emotional factors in the context of participation among young children with Developmental Coordination Disorder. *Research in Developmental Disabilities*, 34(1), 87-94. doi: 10.1016/j.ridd.2012.07.019
- Lingam, R., Hunt, L., Golding, J., Jongmans, M., & Emond, A. (2009). Prevalence of Developmental Coordination Disorder Using the DSM-IV at 7 Years of Age: A UK Population-Based Study. *Pediatrics*, 123(4), E693-E700. doi: 10.1542/peds.2008-1770
- Losse, A., Henderson, S. E., Elliman, D., Hall, D., Knight, E., & Jongmans, M. (1991). Clumsiness in children - Do they grow out of it - A 10-year follow-up-study. *Developmental Medicine and Child Neurology*, 33(1), 55-68.
- Lubans, D. R., Morgan, P. J., Cliff, D. P., Barnett, L. M., & Okely, A. D. (2010). Fundamental Movement Skills in Children and Adolescents Review of Associated Health Benefits. *Sports Medicine*, 40(12), 1019-1035. doi: 10.2165/11536850-000000000-00000
- Magalhaes, L. C., Cardoso, A. A., & Missiuna, C. (2011). Activities and participation in children with developmental coordination disorder: A systematic review. *Research in Developmental Disabilities*, 32(4), 1309-1316. doi: 10.1016/j.ridd.2011.01.029
- Mak, M. K. Y. (2010). Reaching and Grasping a Moving Target Is Impaired in Children With Developmental Coordination Disorder. *Pediatric Physical Therapy*, 22(4), 384-U131. doi: 10.1097/PEP.0b013e3181f9d885

- Mann, D. T. Y., Williams, A. M., Ward, P., & Janelle, C. M. (2007). Perceptual-cognitive expertise in sport: A meta-analysis. *Journal of Sport and Exercise Psychology, 29*(4), 457-478.
- Martell, S. G., & Vickers, J. N. (2004). Gaze characteristics of elite and near-elite athletes in ice hockey defensive tactics. *Human Movement Science, 22*(6), 689-712. doi: 10.1016/j.humov.2004.02.004
- Martin, N. C., Piek, J. P., & Hay, D. (2006). DCD and ADHD: A genetic study of their shared aetiology. *Human Movement Science, 25*(1), 110-124. doi: 10.1016/j.humov.2005.10.006
- Mazyn, L. I. N., Savelsbergh, G. J. P., Montagne, G., & Lenoir, M. (2007). Planning and on-line control of catching as a function of perceptual-motor constraints. *Acta Psychologica, 126*(1), 59-78. doi: 10.1016/j.actpsy.2006.10.001
- McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research-Psychologische Forschung, 67*(1), 22-29. doi: 10.1007/s00426-002-0093-6
- Millsagle, D. G., Hines, B. B., & Smith, M. S. (2013). Quiet eye gaze behaviour of expert, and near-expert, baseball plate umpires. *Perceptual and Motor Skills, 116*(1), 69-77. doi: 10.2466/24.22.27.pms.116.1.69-77
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49-100. doi: 10.1006/cogp.1999.0734

- Mon-Williams, M., Tresilian, J. R., Bell, V. E., Coppard, V. L., Nixdorf, M., & Carson, R. G. (2005). The preparation of reach-to-grasp movements in adults, children, and children with movement problems. *Quarterly Journal of Experimental Psychology Section a-Human Experimental Psychology*, *58*(7), 1249-1263. doi: 10.1080/02724980443000575
- Moore, L. J., Vine, S. J., Cooke, A., Ring, C., & Wilson, M. R. (2012). Quiet eye training expedites motor learning and aids performance under heightened anxiety: The roles of response programming and external attention. *Psychophysiology*, *49*(7), 1005-1015. doi: 10.1111/j.1469-8986.2012.01379.x
- Moore, L.J., Vine, S.J., Smith, A., Smith, S.J., & Wilson, M.R. (2014). Quiet eye training improves small arms maritime marksmanship. *Military Psychology*, doi: 10.1037/mil0000039
- Moran, A. (2009). Cognitive psychology in sport: Progress and prospects. *Psychology of Sport and Exercise*, *10*(4), 420-426. doi: 10.1016/j.psychsport.2009.02.010
- Moran, A., Byrne, A., & McGlade, N. (2002). The effects of anxiety and strategic planning on visual search behaviour. *Journal of Sports Sciences*, *20*(3), 225-236. doi: 10.1080/026404102317284781
- Neggers, S. F. W., & Bekkering, H. (2001). Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. *Journal of Neurophysiology*, *86*(2), 961-970.
- Niemeijer, A. S., Smits-Engelsman, B. C. M., & Schoemaker, M. M. (2007). Neuromotor task training for children with developmental coordination disorder: a controlled trial. *Developmental Medicine and Child Neurology*, *49*(6), 406-411.

- Nieuwenhuys, A. & Oudejans, R.R.D. (2012). Anxiety and perceptual-motor performance: toward an intergrated model of concepts, mechanisms, and processes. *Psychological Research*, 76, 747-759. 10.1007/s00426-011-0384-x
- Okely, A. D., & Booth, M. L. (2004). Mastery of fundamental movement skills among children in New South Wales: prevalence and sociodemographic distribution. *Journal of Science and Medicine in Sport*, 7(3), 358-372. doi: 10.1016/s1440-2440(04)80031-8
- Olivier, I., Ripoll, H., & Audiffren, M. (1997). Age differences in using precued information to preprogram interception of a ball. *Perceptual and Motor Skills*, 85(1), 123-127.
- Oudejans, R. R. D., Bakker, F. C., Verheijen, R., Gerrits, J. C., Steinbruckner, M., & Beek, P. J. (2005). How position and motion of expert assistant referees in soccer relate to the quality of their offside judgements during actual match play. *International Journal of Sport Psychology*, 36(1), 3-21.
- Oudejans, R. R. D., Michaels, C. F., Bakker, F. C., & Davids, K. (1999). Shedding some light on catching in the dark: Perceptual mechanisms for catching fly balls. *Journal of Experimental Psychology-Human Perception and Performance*, 25(2), 531-542. doi: 10.1037/0096-1523.25.2.531
- Oudejans, R. R. D., van de Langenberg, R. W., & Hutter, R. I. (2002). Aiming at a far target under different viewing conditions: Visual control in basketball jump shooting. *Human Movement Science*, 21(4), 457-480. doi: 10.1016/s0167-9457(02)00116-1
- Panchuk, D., Davids, K., Sakadjian, A., MacMahon, C., & Parrington, L. (2013). Did you see that? Dissociating advanced visual information and ball flight

- constrains perception and action processes during one-handed catching. *Acta Psychologica*, 142(3), 394-401. doi: 10.1016/j.actpsy.2013.01.014
- Panchuk, D., & Vickers, J. N. (2006). Gaze behaviors of goaltenders under spatial-temporal constraints. *Human Movement Science*, 25(6), 733-752. doi: 10.1016/j.humov.2006.07.001
- Panchuk, D., & Vickers, J. N. (2009). Using spatial occlusion to explore the control strategies used in rapid interceptive actions: Predictive or prospective control? *Journal of Sports Sciences*, 27(12), 1249-1260. doi: 10.1080/02640410903156449
- Panchuk, D., & Vickers, J. N. (2011). Effect of narrowing the base of support on the gait, gaze and quiet eye of elite ballet dancers and controls. *Cognitive Processing*, 12(3), 267-276. doi: 10.1007/s10339-011-0395-y
- Perez, L. M. R., Mendez, R. P., Manzano, J. A. N., & Collado, N. R. (2013). Analysis of the visual behavior of taekwondists of different skills level. *Revista Mexicana De Psicología*, 30(1), 32-40.
- Pettit, L., Charles, J., Wilson, A. D., Plumb, M. S., Brockman, A., Williams, J. H. G., & Mon-Williams, M. (2008). Constrained action selection in children with developmental coordination disorder. *Human Movement Science*, 27(2), 286-295. doi: 10.1016/j.humov.2008.02.014
- Piek, J. P., Baynam, G. B., & Barrett, N. C. (2006). The relationship between fine and gross motor ability, self-perceptions and self-worth in children and adolescents. *Human Movement Science*, 25(1), 65-75. doi: 10.1016/j.humov.2005.10.011
- Piek, J. P., & Dyck, M. J. (2004). Sensory-motor deficits in children with developmental coordination disorder, attention deficit hyperactivity

- disorder and autistic disorder. *Human Movement Science*, 23(3-4), 475-488. doi: 10.1016/j.humov.2004.08.019
- Piras, A., Lobietti, R., & Squatrito, S. (2014a). Response Time, Visual Search Strategy, and Anticipatory Skills in Volleyball Players. *Journal of Ophthalmology*. doi: 10.1155/2014/189268
- Piras, A., Pierantozzi, E., & Squatrito, S. (2014b). Visual Search Strategy in Judo Fighters During the Execution of the First Grip. *International Journal of Sports Science and Coaching*, 9(1), 185-197.
- Pless, M., & Carlsson, M. (2000). Effects of motor skill intervention on developmental coordination disorder: A meta-analysis. *Adapted Physical Activity Quarterly*, 17(4), 381-401.
- Polatajko, H., & Cantin, N. (2006). Developmental coordination disorder (dyspraxia): An overview of the state of the art. *Seminars in Pediatric Neurology*, 12(4), 250-258.
- Poolton, J., Maxwell, J., & Masters, R. (2004). Rules for reinvestment. *Perceptual and Motor Skills*, 99(3), 771-774. doi: 10.2466/pms.99.3.771-774
- Posner, M. I. (1980). Orienting Attention. *Quarterly Journal of Experimental Psychology*, 32, 3-25.
- Posner, M. I., & Raichle, M. E. (1994). *Images of mind*. New York: Scientific American Books.
- Poulsen, A. A., Ziviani, J. M., & Cuskelly, M. (2008). Leisure time physical activity energy expenditure in boys with developmental coordination disorder: The role of peer relations self-concept perceptions. *Otjir-Occupation Participation and Health*, 28(1), 30-39. doi: 10.3928/15394492-20080101-05

- Przysucha, E. P., & Maraj, B. K. V. (2010). Movement Coordination in Ball Catching: Comparison Between Boys With and Without Developmental Coordination Disorder. *Research Quarterly for Exercise and Sport*, 81(2), 152-161.
- Przysucha, E. P., & Maraj, B. K. V. (2013). Nature of Spatial Coupling in Children With and Without Developmental Coordination Disorder in Ball Catching. *Adapted Physical Activity Quarterly*, 30(3), 213-234.
- Radlo, S. J., Steinberg, G. M., Singer, R. N., Barba, D. A., & Melnikov, A. (2002). The influence of attentional focus strategy on alpha brain wave activity, heart rate and dart-throwing performance. *International Journal of Sport Psychology*, 33, 205-217.
- Ramalho, M. H. D., Valentini, N. C., Muraro, C. F., Gadens, R., & Nobre, G. C. (2013). Validation for portuguese language: Movement Assessment Battery for Children Checklist. *Motriz-Revista De Educacao Fisica*, 19(2), 423-431.
- Regan, D. (1997). Visual factors in hitting and catching. *Journal of Sports Sciences*, 15(6), 533-558. doi: 10.1080/026404197366985
- Reina, R., Moreno, F. J., & Sanz, D. (2007). Visual behavior and motor responses of novice and experienced wheelchair tennis players relative to the service return. *Adapted Physical Activity Quarterly*, 24(3), 254-271.
- Rienhoff, R., Baker, J., Fischer, L., Strauss, B., & Schorer, J. (2012). Field of vision influences sensory-motor control of skilled and less-skilled dart players. *Journal of Sports Science and Medicine*, 11(3), 542-550.
- Rivilis, I., Hay, J., Cairney, J., Klentrou, P., Liu, J. A., & Faught, B. E. (2011). Physical activity and fitness in children with developmental coordination

- disorder: A systematic review. *Research in Developmental Disabilities*, 32(3), 894-910. doi: 10.1016/j.ridd.2011.01.017
- Robert, M. P., Ingster-Moati, I., Albuissou, E., Cabrol, D., Golse, B., & Vaivre-Douret, L. (2014). Vertical and horizontal smooth pursuit eye movements in children with developmental coordination disorder. *Developmental Medicine and Child Neurology*, 56(6), 595-600. doi: 10.1111/dmcn.12384
- Rodrigues, S. T., Vickers, J. N., & Williams, A. M. (2002). Head, eye and arm coordination in table tennis. *Journal of Sports Sciences*, 20(3), 187-200. doi: 10.1080/026404102317284754
- Saemi, E., Porter, J., Wulf, G., Ghotbi-Varzaneh, A., & Bakhtiari, S. (2013). Adopting an external focus of attention facilitates motor learning in children with attention deficit hyperactivity disorder. *Kinesiology*, 45(2), 179-185.
- Sailer, U., Flanagan, J. R., & Johansson, R. S. (2005). Eye-hand coordination during learning of a novel visuomotor task. *Journal of Neuroscience*, 25(39), 8833-8842. doi: 10.1523/jneurosci.2658-05.2005
- Santos, M. M. D., Ribeiro, S. M. L., Pellegrini, A. M., Rocha, P. R. H., & Hiraga, C. Y. (2012). Do children with motor difficulties show low levels of physical fitness? *Motriz-Revista De Educacao Fisica*, 18(4), 748-756.
- Savelsbergh, G. J. P., Van der Kamp, J., Williams, A. M., & Ward, P. (2005). Anticipation and visual search behaviour in expert soccer goalkeepers. *Ergonomics*, 48(11-14), 1686-1697. doi: 10.1080/00140130500101346
- Savelsbergh, G. J. P., Williams, A. M., Van der Kamp, J., & Ward, P. (2002). Visual search, anticipation and expertise in soccer goalkeepers. *Journal of Sports Sciences*, 20(3), 279-287. doi: 10.1080/026404102317284826

- Schoemaker, M. M., Niemeijer, A. S., Flapper, B. C. T., & Smits-Engelsman, B. C. M. (2012). Validity and reliability of the Movement Assessment Battery for Children-2 Checklist for children with and without motor impairments. *Developmental Medicine and Child Neurology*, *54*(4), 368-375. doi: 10.1111/j.1469-8749.2012.04226.x
- Schulz, J., Henderson, S. E., Sugden, D. A., & Barnett, A. L. (2011). Structural validity of the Movement ABC-2 test: Factor structure comparisons across three age groups. *Research in Developmental Disabilities*, *32*(4), 1361-1369. doi: 10.1016/j.ridd.2011.01.032
- Sekaran, S. N., Reid, S. L., Chin, A. W., Ndiaye, S., & Licari, M. K. (2012). Catch! Movement kinematics of two-handed catching in boys with Developmental Coordination Disorder. *Gait and Posture*, *36*(1), 27-32. doi: 10.1016/j.gaitpost.2011.12.010
- Sharp, R. H., & Whiting, H. T. A. (1974). Exposure and occluded duration effects in a ball catching skill. *Journal of Human Movement Studies*, *6*(3), 139-147.
- Sharp, R. H., & Whiting, H. T. A. (1975). Information processing and eye movement behaviour in ball catching skill. *Journal of Motor Behavior*, *1*(124-131).
- Shim, J., Carlton, L. G., Chow, J. W., & Chae, W. S. (2005). The use of anticipatory visual cues by highly skilled tennis players. *Journal of Motor Behavior*, *37*(2), 164-175. doi: 10.3200/jmbr.37.2.164-175
- Sigmundsson, H., Hansen, P. C., & Talcott, J. B. (2003). Do 'clumsy' children have visual deficits. *Behavioural Brain Research*, *139*(1-2), 123-129. doi: 10.1016/s0166-4328(02)00110-9

- Silman, A., Cairney, J., Hay, J., Klentrou, P., & Faught, B. E. (2011). Role of physical activity and perceived adequacy on peak aerobic power in children with developmental coordination disorder. *Human Movement Science, 30*(3), 672-681. doi: 10.1016/j.humov.2010.08.005
- Smits-Engelsman, B. C. M., Blank, R., Van der Kaay, A. C., Mosterd-Van der Meijs, R., Vlugt-Van den Brand, E., Polatajko, H. J., & Wilson, P. H. (2013). Efficacy of interventions to improve motor performance in children with developmental coordination disorder: a combined systematic review and meta-analysis. *Developmental Medicine and Child Neurology, 55*(3), 229-237. doi: 10.1111/dmcn.12008
- Smits-Engelsman, B. C. M., Niemeijer, A. S., & van Waelvelde, H. (2011). Is the Movement Assessment Battery for Children-2nd edition a reliable instrument to measure motor performance in 3 year old children? *Research in Developmental Disabilities, 32*(4), 1370-1377. doi: 10.1016/j.ridd.2011.01.031
- Smits-Engelsman, B. C. M., Wilson, P. H., Westenberg, Y., & Duysens, J. (2003). Fine motor deficiencies in children with developmental coordination disorder and learning disabilities: An underlying open-loop control deficit. *Human Movement Science, 22*(4-5), 495-513. doi: 10.1016/j.humov.2003.09.006
- Smyth, M. M., Anderson, H. I., & Churchill, A. (2001). Visual information and the control of reaching in children: A comparison between children with and without developmental coordination disorder. *Journal of Motor Behavior, 33*(3), 306-320.
- Snapp-Childs, W., Mon-Williams, M., & Bingham, G. P. (2013). A Sensorimotor Approach to the Training of Manual Actions in Children With

- Developmental Coordination Disorder. *Journal of Child Neurology*, 28(2), 204-212. doi: 10.1177/0883073812461945
- Starkes, J. L. (1987). Skill in field hockey: The nature of cognitive advantage. *Journal of Sport Psychology*, 9, 146-160.
- Strohmeyer, H. S., Williams, K., & Schaubgeorge, D. (1991). Developmental sequences for catching a small ball - A prelongitudinal screening. *Research Quarterly for Exercise and Sport*, 62(3), 257-266.
- Sugden, D. (2007). Current approaches to intervention in children with developmental coordination disorder. *Developmental Medicine and Child Neurology*, 49(6), 467-471.
- Sugden, D. A., Chambers, M., & Utley, A. (2006). Leeds Consensus Statement 2006. Retrieved 2nd July, 2014, from <http://www.dcd-uk.org/consensus.html>
- Sugden, D. A., & Chambers, M. E. (2003). Intervention in children with Developmental Coordination Disorder: The role of parents and teachers. *British Journal of Educational Psychology*, 73, 545-561. doi: 10.1348/000709903322591235
- Takeuchi, T., & Inomata, K. (2009). Visual search strategies and decision making in baseball batting. *Perceptual and Motor Skills*, 108(3), 971-980. doi: 10.2466/pms.108.3.971-980
- Tal-Saban, M., Ornoy, A., & Parush, S. (2014). Young Adults With Developmental Coordination Disorder: A Longitudinal Study. *American Journal of Occupational Therapy*, 68(3), 307-316. doi: 10.5014/ajot.2014.009563
- Tallet, J., Albaret, J. M., & Barral, J. (2013). Developmental changes in lateralized inhibition of symmetric movements in children with and

- without Developmental Coordination Disorder. *Research in Developmental Disabilities*, 34(9), 2523-2532. doi: 10.1016/j.ridd.2013.05.020
- Thomas, J. R., Nelson, J. K., & Silverman, S. (2011). *Research Methods in Physical Activity*. Champaign, IL: Human Kinetics.
- Tsai, C. L. (2009). The effectiveness of exercise intervention on inhibitory control in children with developmental coordination disorder: Using a visuospatial attention paradigm as a model. *Research in Developmental Disabilities*, 30(6), 1268-1280. doi: 10.1016/j.ridd.2009.05.001
- Tsai, C. L., Chang, Y. K., Chen, F. C., Hung, T. M., Pan, C. Y., & Wang, C. H. (2014). Effects of Cardiorespiratory Fitness Enhancement on Deficits in Visuospatial Working Memory in Children with Developmental Coordination Disorder: A Cognitive Electrophysiological Study. *Archives of Clinical Neuropsychology*, 29(2), 173-185. doi: 10.1093/arclin/act081
- Tsai, C. L., Chang, Y. K., Hung, T. M., Tseng, Y. T., & Chen, T. C. (2012). The neurophysiological performance of visuospatial working memory in children with developmental coordination disorder. *Developmental Medicine and Child Neurology*, 54(12), 1114-1120. doi: 10.1111/j.1469-8749.2012.04408.x
- Tsai, C. L., Pan, C. Y., Chang, Y. K., Wang, C. H., & Tseng, K. D. (2010). Deficits of visuospatial attention with reflexive orienting induced by eye-gazed cues in children with developmental coordination disorder in the lower extremities: An event-related potential study. *Research in Developmental Disabilities*, 31(3), 642-655. doi: 10.1016/j.ridd.2010.01.003

- Tsai, C. L., Pan, C. Y., Cherng, R. J., Hsu, Y. W., & Chiu, H. H. (2009). Mechanisms of deficit of visuospatial attention shift in children with developmental coordination disorder: A neurophysiological measure of the endogenous Posner paradigm. *Brain and Cognition*, *71*(3), 246-258. doi: 10.1016/j.bandc.2009.08.006
- Tsai, C. L., Wilson, P. H., & Wu, S. K. (2008). Role of visual-perceptual skills (non-motor) in children with developmental coordination disorder. *Human Movement Science*, *27*(4), 649-664. doi: 10.1016/j.humov.2007.10.002
- Tsai, C. L., & Wu, S. K. (2008). Relationship of visual perceptual deficit and motor impairment in children with developmental coordination disorder. *Perceptual and Motor Skills*, *107*(2), 457-472. doi: 10.2466/pms.107.2.457-472
- Tseng, M. H., Howe, T. H., Chuang, I. C., & Hsieh, C. L. (2007). Cooccurrence of problems in activity level, attention, psychosocial adjustment, reading and writing in children with developmental coordination disorder. *International Journal of Rehabilitation Research*, *30*(4), 327-332.
- Turrell, Y., Bard, C., Fleury, M., Teasdale, N., & Martin, O. (1998). Corrective loops involved in fast aiming movements: effect of task and environment. *Experimental Brain Research*, *120*(1), 41-51. doi: 10.1007/s002210050376
- Ulrich, D. A. (2000). *Test of Gross Motor Development -2*. Austin, TX: Pro-Ed.
- Utley, A., Steenbergen, B., & Astill, S. L. (2007). Ball catching in children with developmental coordination disorder: control of degrees of freedom. *Developmental Medicine and Child Neurology*, *49*(1), 34-38.

- Vaivre-Douret, L. (2014). Developmental coordination disorders: State of art. *Neurophysiologie Clinique-Clinical Neurophysiology*, *44*(1), 13-23. doi: 10.1016/j.neucli.2013.10.133
- Valentini, N. C., Ramalho, M. N., & Oliveira, M. A. (2014). Movement Assessment Battery for Children-2: Translation, reliability, and validity for Brazilian children. *Research in Developmental Disabilities*, *35*(3), 733-740. doi: 10.1016/j.ridd.2013.10.028
- Van der Kamp, J., Rivas, F., Van Doorn, H., & Savelsbergh, G. (2008). Ventral and dorsal system contributions to visual anticipation in fast ball sports. *International Journal of Sport Psychology*, *39*(2), 100-130.
- Van der Molen, M. W., Bashore, T. R., Halliday, R., & Callaway, E. (1991). Chronopsychophysiology: Mental chronometry augmented with physiological measures. In J. R. Jennings & M. G. J. H. Coles (Eds.), *Handbook of cognitive psychophysiology* (pp. 9-178). Chichester: Wiley.
- Van Waelvelde, H., De Weerd, W., De Cock, P., Smits-Engelsman, B. C. M., & Peersman, W. (2004). Ball catching performance in children with developmental coordination disorder. *Adapted Physical Activity Quarterly*, *21*(4), 348-363.
- Venetsanou, F., Kambas, A., Ellinoudis, T., Fatouros, I., Giannakidou, D., & Kourtessis, T. (2011). Can the Movement Assessment Battery for Children-Test be the "gold standard" for the motor assessment of children with Developmental Coordination Disorder? *Research in Developmental Disabilities*, *32*(1), 1-10. doi: 10.1016/j.ridd.2010.09.006
- Vickers, J. N. (1996). Visual control when aiming at a far target. *Journal of Experimental Psychology-Human Perception and Performance*, *22*(2), 342-354. doi: 10.1037/0096-1523.22.2.342

- Vickers, J. N. (2007). *Perception, Cognition and Decision Making: The Quiet Eye in Action*. Champaign: Human Kinetics.
- Vickers, J. N. (2011). Mind over muscle: the role of gaze control, spatial cognition, and the quiet eye in motor expertise. *Cognitive Processing*, 12(3), 219-222. doi: 10.1007/s10339-011-0411-2
- Vickers, J. N., & Adolphe, R. A. (1997). Gaze behaviour during a ball tracking and aiming skill. *International Journal of Sports Vision*, 4(1), 18-27.
- Vickers, J. N., & Lewinski, W. (2012). Performing under pressure: Gaze control, decision making and shooting performance of elite and rookie police officers. *Human Movement Science*, 31, 101-117. doi: 10.1016/j.humov.2011.04.004
- Vickers, J. N., & Williams, A. M. (2007). Performing under pressure: The effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. *Journal of Motor Behavior*, 39(5), 381-394. doi: 10.3200/jmbr.39.5.381-394
- Vine, S. J., Chaytor, R. J., McGrath, J. S., Masters, R. S. W., & Wilson, M. R. (2013a). Gaze training improves the retention and transfer of laparoscopic technical skills in novices. *Surgical Endoscopy and Other Interventional Techniques*, 27(9), 3205-3213. doi: 10.1007/s00464-013-2893-8
- Vine, S. J., Moore, L. J., Cooke, A., Ring, C., & Wilson, M. R. (2013b). Quiet eye training: A means to implicit motor learning. *International Journal of Sport Psychology*, 44(4), 367-386. doi: 10.7352/ijsp2013.44.367
- Vine, S. J., Moore, L. J., & Wilson, M. R. (2011). Quiet eye training facilitates competitive putting performance in elite golfers. *Frontiers in Psychology*, 2. doi: 10.3389/fpsyg.2011.00008

- Vine, S. J., Moore, L. J., & Wilson, M. R. (2014). Quiet eye training: The acquisition, refinement and resilient performance of targeting skills. *European Journal of Sport Science*, 14, S235-S242. doi: 10.1080/17461391.2012.683815
- Vine, S. J., & Wilson, M. R. (2010). Quiet Eye Training: Effects on Learning and Performance Under Pressure. *Journal of Applied Sport Psychology*, 22(4), 361-376. doi: 10.1080/10413200.2010.495106
- Vine, S. J., & Wilson, M. R. (2011). The influence of quiet eye training and pressure on attention and visuo-motor control. *Acta Psychologica*, 136(3), 340-346. doi: 10.1016/j.actpsy.2010.12.008
- Visser, J. (2003). Developmental coordination disorder: a review of research on subtypes and comorbidities. *Human Movement Science*, 22(4-5), 479-493. doi: 10.1016/j.humov.2003.09.005
- Wagner, M. O., Kastner, J., Petermann, F., & Bos, K. (2011). Factorial validity of the Movement Assessment Battery for Children-2 (age band 2). *Research in Developmental Disabilities*, 32(2), 674-680. doi: 10.1016/j.ridd.2010.11.016
- Williams, A. M., & Davids, K. (1995). Declarative knowledge in sport: A by-product of experience or a characteristic of expertise. *Journal of Sport and Exercise Psychology*, 17(3), 259-275.
- Williams, A. M., & Davids, K. (1998). Visual search strategy, selective attention, and expertise in soccer. *Research Quarterly for Exercise and Sport*, 69(2), 111-128.
- Williams, A. M., Davids, K., Burwitz, L., & Williams, J. G. (1994). Visual-search strategies in experienced and inexperienced soccer players. *Research Quarterly for Exercise and Sport*, 65(2), 127-135.

- Williams, A. M., Singer, R. N., & Frehlich, S. G. (2002a). Quiet eye duration, expertise, and task complexity in near and far aiming tasks. *Journal of Motor Behavior*, 34(2), 197-207.
- Williams, A. M., Ward, P., Knowles, J. M., & Smeeton, N. J. (2002b). Anticipation skill in a real-world task: Measurement, training, and transfer in tennis. *Journal of Experimental Psychology-Applied*, 8(4), 259-270. doi: 10.1037/1076-898x.8.4.259
- Williams, J., Anderson, V., Reddihough, D. S., Reid, S. M., Vijayakumar, N., & Wilson, P. H. (2011). A comparison of motor imagery performance in children with spastic hemiplegia and developmental coordination disorder. *Journal of Clinical and Experimental Neuropsychology*, 33(3), 273-282. doi: 10.1080/13803395.2010.509714
- Williams, J., Omizzolo, C., Galea, M. P., & Vance, A. (2013). Motor imagery skills of children with Attention Deficit Hyperactivity Disorder and Developmental Coordination Disorder. *Human Movement Science*, 32(1), 121-135. doi: 10.1016/j.humov.2012.08.003
- Williams, J. G. (1992). Effects of instruction and practice on ball catching skill - Single subject study of an 8-year-old. *Perceptual and Motor Skills*, 75(2), 392-394. doi: 10.2466/pms.75.5.392-394
- Wilmut, K., & Wann, J. (2008). The use of predictive information is impaired in the actions of children and young adults with Developmental Coordination Disorder. *Experimental Brain Research*, 191(4), 403-418. doi: 10.1007/s00221-008-1532-4
- Wilson, M. R., McGrath, J. S., Vine, S. J., Brewer, J., Defriend, D., & Masters, R. S. W. (2011a). Perceptual impairment and psychomotor control in virtual laparoscopic surgery. *Surgical Endoscopy and Other*

- Interventional Techniques*, 25(7), 2268-2274. doi: 10.1007/s00464-010-1546-4
- Wilson, M. R., & Pearcy, R. C. (2009). Visuomotor control of straight and breaking golf putts. *Perceptual and Motor Skills*, 109(2), 555-562. doi: 10.2466/pms.109.2.555-562
- Wilson, M. R., Vine, S. J., Bright, E., Masters, R. S. W., Defriend, D., & McGrath, J. S. (2011b). Gaze training enhances laparoscopic technical skill acquisition and multi-tasking performance: a randomized, controlled study. *Surgical Endoscopy and Other Interventional Techniques*, 25(12), 3731-3739. doi: 10.1007/s00464-011-1802-2
- Wilson, M. R., Vine, S. J., & Wood, G. (2009). The Influence of Anxiety on Visual Attentional Control in Basketball Free Throw Shooting. *Journal of Sport and Exercise Psychology*, 31(2), 152-168.
- Wilson, P. H., Maruff, P., Butson, M., Williams, J., Lum, J., & Thomas, P. R. (2004). Internal representation of movement in children with developmental coordination disorder: a mental rotation task. *Developmental Medicine and Child Neurology*, 46(11), 754-759. doi: 10.1017/s001216220400129x
- Wilson, P. H., Maruff, P., Ives, S., & Currie, J. (2001). Abnormalities of motor and praxis imagery in children with DCD. *Human Movement Science*, 20(1-2), 135-159.
- Wilson, P. H., Maruff, P., & Lum, J. (2003). Procedural learning in children with developmental coordination disorder. *Human Movement Science*, 22(4-5), 515-526. doi: 10.1016/j.humov.2003.09.007
- Wilson, P. H., & McKenzie, B. E. (1998). Information processing deficits associated with developmental coordination disorder: A meta-analysis of

- research findings. *Journal of Child Psychology and Psychiatry*, 39(6), 829-840.
- Wilson, P. H., Ruddock, S., Smits-Engelsman, B., Polatajko, H., & Blank, R. (2013). Understanding performance deficits in developmental coordination disorder: a meta-analysis of recent research. *Developmental Medicine and Child Neurology*, 55(3), 217-228. doi: 10.1111/j.1469-8749.2012.04436.x
- Wilson, P. H., Thomas, P. R., & Maruff, P. (2002). Motor imagery training ameliorates motor clumsiness in children. *Journal of Child Neurology*, 17(7), 491-498. doi: 10.1177/088307380201700704
- Wolpert, D. M., Ghahramani, Z., & Jordan, M. I. (1995). An internal model for sensorimotor integration. *Science*, 269(5232), 1880-1882. doi: 10.1126/science.7569931
- Wood, G., Vine, S. J., & Wilson, M. R. (2013). The impact of visual illusions on perception, action planning, and motor performance. *Attention Perception and Psychophysics*, 75(5), 830-834. doi: 10.3758/s13414-013-0489-y
- Wood, G., & Wilson, M. R. (2012). Quiet-eye training, perceived control and performing under pressure. *Psychology of Sport and Exercise*, 13(6), 721-728. doi: 10.1016/j.psychsport.2012.05.003
- Wuang, Y. P., Su, J. H., & Su, C. Y. (2012). Reliability and responsiveness of the Movement Assessment Battery for Children-Second Edition Test in children with developmental coordination disorder. *Developmental Medicine and Child Neurology*, 54(2), 160-165. doi: 10.1111/j.1469-8749.2011.04177.x

- Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology*, 6(1), 77-104. doi: 10.1080/1750984x.2012.723728
- Zachry, T., Wulf, G., Mercer, J., & Bezodis, N. (2005). Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Research Bulletin*, 67(4), 304-309. doi: 10.1016/j.brainresbull.2005.06.035
- Zhu, Y. C., Cairney, J., Li, Y. C., Chen, W. Y., Chen, F. C., & Wu, S. K. (2014). High risk for obesity in children with a subtype of developmental coordination disorder. *Research in Developmental Disabilities*, 35(7), 1727-1733. doi: 10.1016/j.ridd.2014.02.020
- Zwicker, J. G., Harris, S. R., & Klassen, A. F. (2013). Quality of life domains affected in children with developmental coordination disorder: a systematic review. *Child Care Health and Development*, 39(4), 562-580. doi: 10.1111/j.1365-2214.2012.01379.x
- Zwicker, J. G., Missiuna, C., Harris, S. R., & Boyd, L. A. (2011). Brain activation associated with motor skill practice in children with developmental coordination disorder: an fMRI study. *International Journal of Developmental Neuroscience*, 29(2), 145-152. doi: 10.1016/j.ijdevneu.2010.12.002