Quiet Eye Training facilitates visuomotor coordination in children with developmental coordination disorder

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Abstract

Introduction: Quiet eye training (QET) has been shown to be more effective than traditional training (TT) methods for teaching a throw and catch task to typically developing 8-10 year old children. The current study aimed to apply the technique to children with Developmental Coordination Disorder (DCD).

Method: 30 children with DCD were randomly allocated into TT or QET intervention groups. The TT group were taught how to control their arm movements during the throw and catch phases, while the QET group were also taught to fixate a target location on the wall prior to the throw (quiet eye1; QE1), followed by tracking the ball prior to the catch (quiet eye2; QE2). Performance, gaze and motion analysis data were collected at pre/post-training and 6-week retention.

Results: The QET group significantly increased QE durations from pre-training to delayed retention (QE1 = +247ms, QE2 = +19%) whereas the TT group experienced a reduction (QE1 = -74ms, QE2 = -4%). QET participants showed significant improvement in the quality of their catch attempts and increased elbow flexion at catch compared to the TT group (QET = -28°, TT = -1°).

Conclusion: QET changed DCD children’s ability to focus on a target on the wall prior to the throw, followed by better anticipation and pursuit tracking on the ball, which in turn led to improved catching technique. QET may be an effective adjunct to traditional instructions, for therapists teaching visuomotor skills to children with DCD.

1. Introduction

Developmental Coordination Disorder (DCD) affects between 1.7-6% of children (depending on the stringency of diagnostic criteria; Hendrix, Prins & Dekkers, 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, Chambers & Utley, 2006). Not only does DCD impact all areas of motor performance (Catin, Ryan & Polatajko, 2014), but it can influence academic achievement (Liberman, Ratzon & Bart, 2013; Chen; Tsai, Hsu, Ma & Lai, 2013), social development (Tseng, Howe, Chuang & Hsieh, 2007; Chen, Tseng, Hu, & Cermak (2009) and long term physical health (Cairney & Veldhuizen, 2013).

Whilst uncertainty remains regarding the precise aetiology of DCD (Vaivre-Douret, 2014; Caravale, Baldi, Gasparini & Wilson, 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. Wilson & McKenzie, 1998; Sigmundsson, Hansen & Talcott, 2003; Piek & Dyck, 2004; Tsai, Wilson & Wu, 2008). 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, Mon-Williams, Wann, Pascal & Thompson, 1998; Robert, Ingster-Moati, Albuisson, Cabrol, Golse, & Vaivre-Douret, 2014). For example, children with DCD are unable to utilise predictive information to assist with the mapping of required movement patterns (Debrabant, Gheysen, Caeyensberghs, Van Waelvede, & Vigerhoets, 2013; Smits-Engelsman et al., 2003), and cannot make use of advanced (partial) visual cues to support the efficient planning of subsequent movements (Mon-Williams et al., 2005; Wilmut & Wann, 2008).

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; 2011b). Importantly, the deficits experienced by children with DCD are most pronounced in complex, interceptive tasks (Bairstow, & Laszlo, 1987; Wilmut & Wann, 2008; Mak, 2010), and as such there is a need for research to further examine visuomotor control and motor performance in these less constrained settings using 'real-world' tasks (Wilson, Miles, Vine and Vickers, 2013).

Ball catching is a complex dynamic task that requires modifications to planned movement responses based on visual information about the flight of the ball (Williams, 1992; Olivier, Ripoll & Audiffren, 1997). Children with DCD find this task difficult (e.g. Van Waelvelde et al., 2004; Utley, Steenbergen & Astill, 2007; Przysucha & Maraj, 2013) 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 (Utley et al., 2007; Astill, 2007). In this study we investigated whether this freezing strategy is driven by deficits in perception of ball flight characteristics that can be corrected through the use of QET.

The departure point for the current study is Wilson et al.'s (2013) examination of the visuomotor processes underpinning throwing and catching in children. This study found a specific gaze behaviour termed the quiet eye (QE) could distinguish between the motor coordination skill and throwing and catching performance of children. The QE was defined by Vickers (1996, 2007) as the final fixation or tracking gaze on an object (for > 100ms to within 3° of visual angle) before the onset of a critical movement and has been found to be a key predictor of perceptual-cognitive skill in a wide range of movement tasks (see review by Vine, Moore & Wilson, 2014). QE durations of experts in a wide range of motor tasks are typically longer suggesting additional time is needed to organize the neural networks underlying the planning and control of motor skills.

The study by Wilson et al. was the first to examine the QE in children, and found that those with low motor coordination ability (< 20th percentile of MABC-2; Henderson, Sugden & Barnett, 2007) 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; Henderson et al., 2007). It was suggested that the longer QE fixation prior to the throw (held on a virtual target on the blank 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 the catch attempt (Wilson et al., 2013).

As well as being a key marker of proficient performance, the QE has been shown to be trainable (Vine, et al., 2014). The objective of QE training (QET) is to help performer's adopt the QE of a highly skilled prototype so they know 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, 2011). Miles, Vine, Wood, Vickers and Wilson (2014) performed the first QET study in children, assessing the effectiveness of a QET intervention in improving performance in a throwing and catching task. Miles and colleagues found that their video-based QET intervention significantly increased the duration of QE1 and QE2, and improved catching performance by 23% in comparison to traditional training instructions, which produced no significant training effects. Although the authors did not assess the longer-term effects of QET in this population (i.e. at a delayed, as opposed to immediately post-training retention test), the findings represented 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 Miles et al. (2014) 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 more effective gaze and attention can improve their ability to make accurate online predictions to guide and adapt movement patterns, in real-world tasks. Second, there are significant health implications for interventions that can improve ball skills in children with DCD. Magalhães, Cardoso & Missiuna (2011) identified poor ball skills as an important limiting factor in activity participation for children with DCD, and longitudinal work by Barnett et al. (2008, 2009) has linked childhood object control proficiency with adolescent physical activity levels and fitness.

We hypothesised that children with DCD would be able to learn the visuomotor coordination of more skilled performers more effectively via QET, than traditional training (TT), both in a retention (immediately post-training) test, and a 6-week delayed retention test. Specifically, this would consist of: (1) longer QE1 durations on a "virtual" target on the wall prior to the throw, and (2) earlier and longer QE2 durations on the ball prior to catch, at retention and delayed retention conditions. Additionally, we hypothesised that QET would provide a performance advantage over TT in retention conditions. Specifically, this would consist of (3) more expert-like arm mechanics; and (4) improved catching performance.

2. Methods

2.1 Participants

Participants were 30 children aged 8-10yrs who were diagnosed with DCD by an occupational therapist (DCD; 19 male, 11 female; 9.07yrs ±0.87). The children were recruited from primary schools in the South West of England, through Vranch House Clinic in Exeter and the UK Dyspraxia Foundation (www.dyspraxiafoundation.org.uk). The children were not taking part in any other motor coordination therapy during their participation in this study. Ethical approval was obtained from a local ethics committee and full participant and parental consent was obtained prior to commencing the study.

Each child individually completed the Movement Assessment Battery for Children (2nd Edition; MABC-2; Henderson et al., 2007) to quantify their coordination ability. This involved 8 tasks that measured the child's manual dexterity, aiming and catching, and balance skills. Equipment for the MABC-2 was provided with the MABC-2 assessment pack, and standardised testing procedures were followed. The MABC-2 percentile rank scores were used to confirm the diagnosis of DCD. All children scored at or below the 5th percentile, which is described by Henderson et al. (2007) as “highly likely to have a movement disorder”.

Parents also completed the Attention Deficit/Hyperactivity Disorder (ADHD) Rating Scale-VI (Parent Version; Dupaul et al., 1998) prior to testing. Eight of the 30 participants (QET = 4, TT = 4) scored below the 93rd percentile for inattention and the 90th percentile for hyperactivity, which Dupaul et al. (1998) propose as an indication of ADHD (see Table 1)[1]. Additionally, all children were classified as ‘normal’ intelligence based on their teachers’ / parents’ reports.

****Table 1 near here****

2.2 Procedure

In addition to the initial MABC-2 assessment phase, participants individually attended two further sessions held at the University of Exeter. These sessions were termed the training and retention phases.

2.2.1 Training Phase

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 was no significant difference between the MABC-2 percentile scores of the TT (M = 1.95 ± 0.51) and QET (M = 2.21 ± 0.46) intervention groups, $t_{(28)} = 0.37$, $p = .713$. The training phase started the week after assessment.

2.2.1.1 Apparatus. The training phase involved first fitting the participant with an Applied Science Laboratories’ Mobile Eye gaze registration system (ASL,

1 It is recognised that DCD and ADHD can co-occur in roughly the percentages found in the current study and that ADHD brings additional deficits in attentional control (Crawford & Dewey, 2008). However, adding ADHD status as a covariate in subsequent analyses made no difference to the results, or our conclusions for the efficacy of QET. Future research could seek to compare ‘pure’ DCD participants with those suffering from co-occurring ADHD.

Bedford, MA), which measures point of gaze at 30Hz. The system incorporates a pair of lightweight (78 g) glasses fitted with eye and scene cameras and a portable recording device worn in a backpack by the participant. Gaze data were collected wirelessly for offline downloading and analyses. Reflective markers were also placed on the acromion process of the shoulder, lateral epicondyle of the elbow and styloid process of the ulna for 2D analysis of elbow flexion-extension. A Digital SLR camera (Fujifilm 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.

2.2.1.2 Task. The throw and catch task from the MABC-2 (Task 4, 8-10 years of age) was used to assess catching performance, as it is validated for this age-group and has been used in previous research (e.g., Wilson et al., 2013; Miles et al., 2014). This task requires participants to stand behind a line 2m from a blank wall and throw a tennis ball underarm at the wall. They then attempt to catch the ball cleanly in their hands on its return without it bouncing. Participants are permitted to move freely (e.g. step forward) once they have thrown the ball in order to complete a catch. The complete task was first explained to the participant, and then demonstrated once by the researcher. Each participant then completed 5 practice trials, as prescribed in the procedures of the MABC-2, before completing the 10 scored (baseline) trials.

2.2.1.3 Training protocol. The training protocol was similar to that of Miles et al. (2014), which involved breaking the task into two elements; the throw and the catch. For each element, the TT and QET participants were individually shown a video of approximately one-minute duration that showed 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 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 video footage of a highly skilled model performing the throw and catch task but with differing instructions overlaying the images (Miles et al., 2014). Figure 1 demonstrates the use of the synchronised split-screen vision-in-action approach (Vickers, 2007), with the visual field of the model shown on the left of the screen (as taken by the eye tracker), and the sagittal view of the model's throwing action on the right (as taken by the external motor camera). 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 motor footage was dimmed and the gaze footage highlighted, to reveal point of gaze of the expert model for the targeting (QE1) and tracking (QE2) QE periods. The highlighting of the videos matched the instructions emphasised for the training group. See appendix 1 for the full scripted instructions that accompanied the training videos.

****Figure 1 near here****

After the training phase ended, participants completed ten post-training (immediate retention) trials whilst wearing the eye tracking system, but without any verbal prompts or guidance (similar to baseline).

2.2.2 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 eye tracker and markers, and completed ten final, delayed retention trials of the throwing and catching task. Each participant was awarded a £10 shopping voucher for completing the study and along with their parents, was debriefed as to the purpose of the study.

2.3 Measures

2.3.1 Gaze behaviour. Gaze data were 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 relative to the specific phases of the task (pre-throw, throw, catch).

2.3.1.1 QE1 (pre-throw). QE1 onset was defined as the final fixation (within 1° of a "virtual" target location on the wall) before the onset of the foreswing of the throwing arm. The offset of QE1 occurred when gaze deviated from the target location by more than 1° for longer than 100ms. QE1 duration 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 previous studies for the throw and catch task (Miles et al., 2014). In far aiming tasks (e.g., basketball free-throw, darts, golf putting) a longer QE1 duration has consistently been associated with superior performance.

2.3.1.2 QE2 (pre-catch). QE2 onset occurred after the ball rebounded from the wall and was defined as the final tracking gaze on the tennis ball for more than 100ms before the catch was attempted, or the trial ended (Wilson et al., 2013; Miles et al., 2014). The offset of QE2 occurred when gaze deviated off the ball for more than

100ms or when the trial ended [2]. QE2 duration was the time between QE2 onset and offset (ms). As QE2 duration is dependent on ball flight time (FT) – a longer ball flight offers more time to track the ball - we calculated a relative QE2 duration, or the percentage of total flight time accounted for by QE2. This was calculated as ((QE2 * 100) / FT) and was expressed as a percentage (Wilson et al., 2013). In interceptive tasks (e.g., goal keeping, shotgun shooting, service return) an earlier and longer QE duration has been associated with superior performance.

2.3.2 Performance.

*2.3.2.1 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). A measure of catching quality was also determined from the video footage providing a more sensitive measure of catching performance. The qualitative performance scale developed by Przysucha & Maraj (2010) was used (see Table 2), with modifications made to reflect the specific nature of the catching task used in this study. The first author blindly scored the catch attempt according to the adapted 11-point scale, and a second blinded researcher scored 10% of the trials to check for inter-rater reliability using the inter-observer agreement method (see Wilson et al., 2013). The analysis revealed a satisfactory amount of agreement of 95%.

2.3.2.2 *Elbow angle at catch attempt (EA°)*. Elbow angle was selected as a measure of catching biomechanics. A well-developed catching technique involves flexing the elbow joint just before the ball contacts the hands to absorb the speed of

2 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.

the ball (Van Waelvelde et al., 2004). Dartfish (version 5.5) video analysis software was used to calculate the elbow angle at the moment of attempted catch (using the reflective markers visible from the side-on video camera). EA was defined as the elbow angle at the point at which the ball contacted the participant's hands.

****Table 2 near here****

2.4 Analysis

The performance data was scored during the testing sessions, and verified later using the motor video. Mixed design analyses of variance (ANOVA; Statistical Package for Social Sciences, version 20; SPSS Inc., Chicago, IL) were determined for each of the dependent variables using a group (TT vs QET) between factor, and test (Baseline [BL] vs Retention 1 [R1] vs Retention 2 [R2]) as the repeated measures factor. 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 interaction effects. Linear regression analyses were also performed to determine which variables significantly predicted the variance of catching performance at both R1 and R2. Gaze (QE1 duration, QE2 onset, QE2 duration) and arm kinematics (EA) variables were individually entered into the regression analysis.

3. Results

3.1 Gaze Behaviour (Training Manipulation Check)

3.1.1 QE1 duration (ms). ANOVA revealed the predicted significant interaction effect between group and test, $F_{(2,48)} = 5.37$, $p = .008$, $\eta_p^2 = .18$. 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 from R1 to R2 (Mean Difference = -20ms, p = .765; See Figure 2a).

3.1.2 QE2 onset (ms). As predicted, a significant interaction between the independent variables, $F_{(2,46)} = 6.79$, $p = .003$, $\eta_p^2 = .23$, was found. Post hoc analyses revealed no significant differences between the 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 this did not change between R1 and R2 (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 indicating they maintained this difference (Mean Difference = 15ms, p = .411; see Figure 2b).

3.1.3 QE2 Duration (ms). ANOVA revealed a significant interaction between the independent variables, $F_{(2,46)} = 3.39$, $p = .042$, $\eta_p^2 = .13$. Post hoc analyses revealed no significant difference between the 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 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; see Figure 2c)[3].

****Insert Figure 2 near here****

3.2 Performance

3.2.1 Catching performance (%). ANOVA revealed a significant main effect for test, $F_{(2,56)} = 4.65$, $p = .023$, $\varepsilon = .748$, $\eta_p^2 = .14$, with significant improvements in performance between BL and R1 (Mean Difference = 14%, $p < .001$) but not between the other tests (*p's* > .122). Although the percentage of balls caught was slightly higher for the QET group compared to the TT during R1 and R2, there was no significant main effect for group, and no significant interaction between these variables, *F*'s < 1.27 (see Figure 3a).

3.2.2 Qualitative catching score. ANOVA revealed a significant interaction between test and group, $F_{(2,56)} = 3.35$, $p = .042$, $\eta_p^2 = .11$. 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 significantly improved performance from BL to R1 (Mean Difference = 1.19, p = .

3 Due to word limit constraints, we do not present the statistical analysis for the relative QE2 (%) data, as they revealed similar effects as the absolute QE2 (ms) data. We do present these data in Figure 2 (d).

001) and there was no significant difference between R1 and R2 suggesting they were able to maintain this improvement (Mean Difference = -.13, p = .790; see Figure 3b).

3.2.3 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 participants' 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 excluded (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).

ANOVA revealed a significant interaction between test and group, $F_{(2,54)}$ = 14.42, $p < .001$, $\eta_p^2 = .35$. Post hoc analyses revealed no significant differences between the groups at BL (Mean Difference = 5°, p = .465) however the QET group had significantly lower elbow angles at R1 (Mean Difference = -26°, p = .001) and at R2 (Mean Difference = -24°, 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°, 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°, p = .067). The QET group however had a larger decrease in their elbow angle from BL to R1 (Mean Difference = -40°, $p < .001$) and although elbow angle difference significantly increased between R1 and R2 (Mean Difference = 11°, p = .021), the amount of elbow flexion for the QET group was still greater than the TT group in both post training tests (p's < .001; see Figure 3c).

****Insert Figure 3 near here****

3.3 Regression Analysis

At R1, QE2 duration was the only variable to significantly predict qualitative catching performance (R^2 = .17, *p* = .035, b = .22). Multiple hierarchical regression analyses revealed that QE2 duration neared significance for predicting performance over and above the effects of QE1 and QE2 onset (ΔR^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 (ΔR^2 = .19, *p* = .021, b = .19), and furthermore, QE2 onset significantly predicted performance over and above the effects of both QE1 and QE2 durations (ΔR^2 = .18, *p* = .019, b = -.19). EA however was not a significant predictor of qualitative performance (p = .147).

4. Discussion

The purpose of this study was to determine the effectiveness of QET 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, leading to significant increases in QE1 (pre-throw) and QE2 (pre-catch) durations. Importantly, not only were the QET group able to make immediate changes to their gaze behaviour after one hour of training (retention 1), but this effect was durable after a 6 week de-training period (retention 2; see Figure 2). To our knowledge this is one of the first training studies to show significant improvements in the goal-directed gaze behaviour of children with DCD in a full body, interceptive timing task. A previous diagnosis of DCD appeared to be no barrier to being able to model the optimal gaze behaviours of high performing individuals. Indeed children with DCD were able to adopt focused QE durations that were of a similar magnitude (e.g., within 45ms in QE2) to those used by highly coordinated children (Wilson et al., 2013) and experience similar post-training improvements in focus as TD children (e.g., within 6ms in QE2; Miles et al., 2014) in this same task.

Having identified that QET successfully brought about changes in gaze behaviour as hypothesised, it is important to determine whether such modifications underlay any improvements in task performance. The QET group changed their catching technique after training - increasing the amount of elbow flexion at the point of ball-hand contact (Figure 3c), and making more effective catch attempts (Figure 3b). In both cases, these improvements were evident immediately after training and were durable after six weeks. In comparison, the TT group only demonstrated a small initial increase in elbow angle flexion and improvements in catching technique, however these differed significantly from that of the QET group and were not durable following the de-training period.

The training advantage for QET is all the more intriguing, as the QET group received no additional explicit instructions related to changing technique. This result mirrors previous research that has also revealed that novices reveal more expert performance mechanics following QET compared to those following a TT intervention (e.g., Moore et al., 2012). The regression analyses revealed that the onset and duration of the tracking gaze (QE2) were the strongest predictors of the quality of the catch attempt, providing a potential explanation as to why QET was superior. In the language of Corbetta and Shulman's (2002) dual systems model of attention, QE provides effective goal-directed attention, linking relevant stimuli to appropriate motor responses, while reducing the impact of irrelevant distractions (visual, auditory, or kinaesthetic stimuli). Therefore, an extended QE duration provides more time for relevant task information to be relayed to the motor control system, resulting in movement kinematics and patterns of muscle activation that are more effective for successful skill performance (e.g., Moore et al., 2012; Vine et al., 2014).

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; Wilmut & Wann, 2008). However it would appear that optimising the attentional control of these children, by manipulating their gaze behaviour through QET, helps them make more accurate predictions regarding the location and timing of the interception point, which in turn brings about the technique changes observed (Figure 3b,c). While this explanation fits within a cognitive, attentional improvement framework, in line with Vickers' (1996) original interpretation of QE, and supported by current neuroscience models (e.g., Corbetta & Shulman, 2002), the results could also be explained from an ecological perspective (Gibson, 1979; see Vickers, 2009 for a discussion).

The Gibsonian view of direct perception proposes that skilled movement depends on the establishment of direct optical relationships that develop unaided by neural representations. Rather than explaining the improvements in task performance in the current study in terms of superior motor pre-programming (prediction), a Gibsonian approach would suggest that the participants relied on the visual system to provide online updates to their movements (e.g., de Oliveira, Huys, Oudejans, van de Langenberg, & Beek, 2007). In this explanation, the longer QE1 and early QE2 onset simply permit a more optimal orientation of the performer so that they are ready to pick up the critical late information as the ball travels towards them (i.e. during QE2). While the finding that an early QE2 onset predicted performance at R2 might be more supportive of a pre-planning role for QE2, future research should seek to test the relative importance of preprogramming versus online control explanations for QE more explicitly (e.g., Vine, Lee, Moore, & Wilson, 2013).

Irrespective of the relative importance of improved pre-programming and/or online control in explaining the significant gaze, technique, and catching quality alterations, this study found no significant difference in success rate (% catches) for QET over TT (Figure 3a). There are a number of potential reasons for this lack of significant finding in the performance outcome measure. First, a binary performance measure (success vs failure) is unlikely to be as sensitive to training related changes as measures that take into account improvements in the processes underpinning motor performance. Second, since Miles et al. (2014) did find a significant catching success advantage for QET over TT in typically developing children, perhaps there is a ceiling effect for some DCD children. In the current study we did observe individual differences, with some DCD children experiencing greater benefits from QET compared to others. Dispositional and training-related factors that might explain this variation will be an important area of enquiry in future work.

Third, it is possible that the QET intervention period was simply too short for significant improvements in overall performance to catch up with the technical improvements found. The time frame for this training intervention (approximately one hour) was based on previous QET literature (Miles et al, 2014, Vine et al., 2014) performed with typically developing children and adult participants. Intervention studies involving children with DCD typically run for significantly longer periods and are more intensive in their nature (see Smits-Engelsman et al., 2013 for a review). Future longitudinal studies should aim to test the efficacy of repeated QET sessions run over weeks and months, thus determining the long-term effectiveness of QET as a successful treatment for DCD. Although the current task was centered on the throw and catch, other tasks such as kicking a ball against the wall and controlling the rebound (as found in soccer) could be used, potentially leading to increased participation in other playground games and organized sports.

In conclusion, the QET intervention proved to be an effective strategy for teaching children with DCD to change their gaze behaviour. Not only were these children able to learn to adopt an extended QE1 period, and an earlier and longer QE2 period, but these changes in gaze behaviour led to more optimal mechanics when catching a ball thrown against a wall. It is recommended that QET instructions be added to traditional throw and catch instructions, for teachers, therapists and parents teaching visuomotor skills to children with DCD.

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Figure captions

Figure 1: A screenshot of a QET training video for the catch attempt; showing the gaze video with circular cursor tracking the ball on the left, and the expert's body position on the right, which is dimmed to direct attention to the gaze video.

Figure 2: Mean QE1 duration (a), QE2 onset (b), QE2 absolute duration (c) and QE2 relative duration (d) of the QET and TT groups across baseline (BL), immediate retention (R1) and delayed retention (R2) tests. (Error bars represent S.E.M).

Figure 3: Mean catching success rate (a), qualitative performance score (b), and EA (c) of the QET and TT groups across baseline (BL), immediate retention (R1) and delayed retention (R2) tests. (Error bars represent S.E.M).