*Ophthalmology Research: An International Journal*

***Volume 18, Issue 1, Page 10-37, 2023; Article no.OR.94903***
***ISSN: 2321-7227***

# Visual Contribution to Motor Skill DCD Disorders & Walking Physiology Using Spatial Cognition and Linear Geometries as Landmark Coordination Cues

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***Author's contribution***

*The sole author designed, analyzed, interpreted and prepared the manuscript.*

***Article Information***

DOI: 10.9734/OR/2023/v18i1375

**Open Peer Review History:**
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/94903

***Original Research Article***

***Received: 12/10/2022***
***Accepted: 20/12/2022***
***Published: 05/01/2023***

## ABSTRACT

**Problem:** Awareness of children, who experience movement, particularly motor coordination difficulties, has increased dramatically over the last ten years. These motor coordination problems of children with Developmental Coordination Disorder (DCD) or/and Attention-Deficit / Hyperactivity Disorder (ADHD) have been frequently associated with poor visual and spatial eye-vision processing.

**Background:** Motor control difficulties for DCD and ADHD children have been discussed in detail. However, just a little is known about the influence of the natural environment on these disorders. Even more, the built environment's impact as a spatial cognition and coordination functionality has never been considered.

**Aim:** This pilot and innovative study aim to identify the correlation between and evaluate the visual contribution of the so-called "*spatial compound linear geometries*" and DCD children's motor/walking control.

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**Methodology:** Twenty children aged 5 to 8 years with DCD difficulties (two intervention groups, one with 10 boys and the other one with 10 girls) were assessed by a statistical structural evaluation in three built environments (two urban parks and one pocket park), under two conditions (rich or not in trees, flora, and PnP linear geometries), and different motor coordination control situations (static balance, dynamic balances, dark condition).

**Results:** The worst performances (regarding movement disorders and motor coordination problems) were observed for both groups with DCD children playing in parks poor in or without trees, flora, and spatial compound linear geometries. Instead, a significant performance (strong statistical correlation) was found for the same intervention group (DCD children's boys or girls) playing in parks rich in trees, flora, and vegetation (natural environment). The best performance (very strong statistical correlation) was detected in parks rich in a natural environment and linear geometries.

**Conclusions:** While the natural environment contribution is bibliographically known, the best performance finding of the visual contribution of the spatial compound linear geometries, as spatial landmarks enriching the visual-spatial motor/walking functionalities for Children with DCD disorder, could provide new cognitive approaches towards an understanding of children's Developmental Coordination Disorder and walking physiology. DCD children's performance, scores, and cues were related to both the natural environment and the spatial compound linear geometries as spatial landmark motor coordination cues and spatio-temporal clues. The significant variability in sensory processing among children with DCD, ADHD, and co-occurring symptoms can contribute to understanding how neurological and social factors correlate across diagnoses. Also, derived observations for stepping errors, Gait analysis (variables), and spatio-temporal clues conclude that visual eye-based processing interrelates with motor coordination problems, performance, inattention, environmental conditions (dark), sex identity (boys, girls), and DCD hyperactivity.

**Applications:** Development of interactive visual applications for (i) human spatial cognition and movement improvement; and (ii) children's motor control and coordination refinement.

*Keywords: Developmental Coordination Disorder (DCD); children's motor skill disorders; visual-spatial cognition & landmarks; spatial linear geometries; visual walking physiology.*

## 1. INTRODUCTION

The basic idea behind this research paper comes from a recent paper on the influence of spatial compound linear geometries, usually found in low-density urban environments, on birds' visual avian navigation and nest nidification [1]. Should these "*visual-spatial compound linear geometries*" improve as cognitive landmarks the human spatial cognition and walking physiology? In each case, the "*visual-spatial compound linear geometries*" (i.e. shapes and mutually detect parallel or perpendicular line pairs in observed linear or rectangular image-geometries), that normally occur in low-density urban environments, should be regarded as auxiliary georeferencing, coordination, and navigation tool [1].

Motor skill Developmental Coordination Disorder (DCD) is a popular topic in the walking physiology research domain. "DCD occurs in approximately 5% of children and describes a condition in which motor coordination is below the level expected given a child's age and opportunity for learning. Motor coordination problems can seriously affect a child's life, including activities of daily living (e.g., eating, dressing, grooming), self-esteem, pastime activities, social relationships, and academic attainment" [2].

"Children with DCD display static and motor difficulties that persist into adulthood and cannot be better explained by a medical or neurological condition" [2,3]. "The difficulties that individuals with DCD experience significantly impact activities of daily living, scholastic achievement, interpersonal relationships, and employment. In addition, secondary consequences of DCD include higher anxiety, poorer levels of physical fitness, and negative self-perceptions" [4-8]. "Despite significant growth in research into DCD over the last four decades, and international clinical practice guidelines being released, there are still pending questions regarding etiology, the influences of co-occurrence, movement behavior, and ways in which change can be promoted" [2,6,9-12].

Many children with DCD demonstrate strong abilities and skills in other areas – they may have sensitivity to the needs of others, a creative imagination, advanced reading skills, and strong oral communication skills. The bibliography approaches this field just with mathematical modeling and theoretical ecological concepts. No spatial topology of the built environment is considered yet. So, “Children with DCD do have strengths and weaknesses which are best explained by theoretical models, which can be biological, cognitive, environmental, or a combination thereof. These mathematical models can be used for all individuals, not just children, whether their behavior is typical or atypical the natural environment contribution is bibliographically known” [13].

So far, the visual contribution and influence of spatial cognition on motor control, in the low-density built environment, have not been considered yet. In this domain, the bibliography for motor (DCD) coordination problems and environmental issues is restricted to the biological and cognitive dimensions of the environment. In related published papers, biological influence included height, sex, age, physical fitness, stunting, and maturational status. On the other hand, environmental variables included geographical regions, and road and school characteristics as factors rather than coordination landmarks [14-16].

The presented in this paper research topic aimed to capture the breadth of the recent focus on motor control difficulties and to incorporate a visual contribution to DCD coordination disorders and walking physiology using spatial cognition on motor skills and the spatial compound linear geometries as landmarks.

## 1.1 Developmental Coordination Disorder (DCD)

“A medical condition that makes it difficult for people to plan and control movements. DCD is a medical condition that makes it difficult for children to learn to move skillfully. Their movements look clumsy, and they often make mistakes. DCD is usually diagnosed in children between ages 5–8, and it affects one (1) in every twenty (20) children. That means, on average, one child in every school class may have DCD—so it might even affect someone you know. DCD causes big problems for these children. They find it hard to do everyday tasks like feeding themselves or getting dressed, which can be very frustrating for them. Think about a time when you reached for something, maybe a cup of juice, and knocked it over! Although you had probably made this movement successfully many times before, sometimes movements do not turn out as we planned. This is rare for most of us, but it is a daily problem for children with developmental coordination disorders” [17].

“The DCD children also struggle with playground games and sports, as they are not able to move as well as other children their age. This means they often struggle to make friends or do well in school. These things make day-to-day life more difficult for children with DCD. The good news is that scientists are starting to understand what causes DCD. They are also finding ways to help children with DCD to move better” [5,6,11,12,16].

The DCD disorder was documented in DSM IV (Book “Diagnostic and Statistical Manual of Mental Disorders” / American Psychiatric Association (APA); 2022, https://psychiatry.org) as follows [3]:

### 1.1.1 The four APA/DSM IV diagnostic criteria for DCD

**Criterion A:** Performance in daily activities that require motor coordination is substantially below that expected given the person’s chronological age and measured intelligence. This may be manifested by marked delays in achieving motor milestones (for example walking, crawling, sitting), dropping things, ’clumsiness’, poor performance in sports, or poor handwriting.

**Criterion B:** The disturbance in Criterion A significantly interferes with academic achievement or activities of daily living.

**Criterion C:** The disturbance is not due to a general medical condition (for example cerebral palsy, hemiplegia, or muscular dystrophy) and does not meet the criteria for a Pervasive Developmental disorder.

**Criterion D:** If mental retardation is present the motor difficulties are more than those usually associated with it.

The DSM 5th ed. (DSM-5) includes changes to some key disorders of childhood. Two new childhood mental disorders were added to the DSM-5: social communication disorder (or SCD) and disruptive mood dysregulation disorder (or DMDD) [3].

### 1.1.2 What causes DCD

“Scientists do not yet know the exact cause of DCD. Research using brain scanning techniques is starting to indicate why DCD might occur.

Scientists have shown that children with DCD have different brain activity than children without DCD. There are three main brain areas involved in the movement, which are less active in children with DCD" [18].

"The first area is an area across the center of the brain that helps to plan and prepare movements. The second area is more toward the front of the brain and is involved in copying and imagining movement. The third area is at the back of the brain and helps us to coordinate our movements. The lower activity in these areas might explain why children with DCD struggle to perform everyday movements" [18,19].

In the following Fig. 1, the precentral gyrus (green) helps to plan and prepare movement (1); the inferior frontal gyrus (red) is involved in copying and imagining movement (2), and the cerebellum (gray) helps coordinate movements (3).

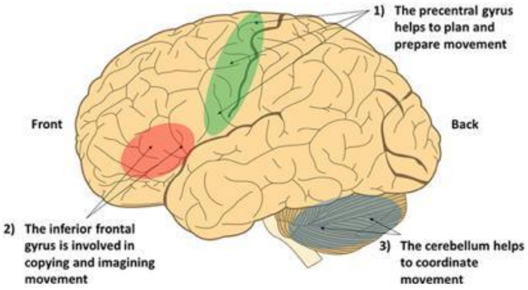

**Fig. 1**. **Brain areas that are important for movement but are less active in children with DCD**

"Typically Developing (TD) children learn important movements, such as throwing, catching, or kicking, through practice. As they practice, they build up a picture in their minds about how the movement should look and feel when they do it well. Following they use the picture to help them plan how to do the movement. TD children learn by comparing how the movement looks and feels against the mental picture. If the movement matches the picture, they know we did it right. If it does not match, they know they did it wrong and can try to correct it. Scientists call this picture an *internal model*. A mental picture of what a movement should look like and feel like when we do it well" [5,9,18,19].

"Scientists think that children with DCD (the TD counterparts) might struggle with movements because they cannot create an internal model as they practice. This makes it hard for them to plan movements because they do not know how the movements should look or feel. This means that they do not know if they are doing a movement correctly, and so they struggle to improve" [11,12,17,18,19].

The brain areas shown in Fig. 1 are believed to help create internal models [18]. This could explain why children with DCD, facing static and motor coordination problems, have less activity in these brain areas [19].

### 1.1.3 Can DCD be treated?

"Children with DCD may face difficulties all their lives, so they must learn to live with them. They might adapt tasks to make life easier. For example, they may use Velcro-strap shoes to avoid tying laces, or they might avoid wearing certain shirts because they struggle to fasten the buttons. They might even completely avoid doing certain activities. For example, they may skip Physical Education K-2 lessons in school or avoid taking part in playground games and sports teams" [2,3,11,18].

"This is a problem because regular exercise is important for physical and mental health. The good news is that, once it has been diagnosed, children with DCD can be helped to improve their movement skills. Current techniques focus on doing repetitive physical practice. Therapists may ask children with DCD to repeat movements repeatedly. To help the children, therapists might make tasks easier or split them up into smaller parts" [3,4,5,12,18].

However, scientists have suggested that just practicing movements is not enough to help children with DCD to improve. Instead, mental training that targets the less-active brain regions could be helpful.

### 1.1.4 DCD conclusion

DCD is a complex medical disorder that can make everyday movements difficult and frustrating for many children. Although the cause is not fully known, science is helping us to understand the role of brain activity in DCD.

"Motor imagery can help children with DCD to improve their movements, but more recent research shows that combining imagery with action observation maybe even better. Scientists are now hopeful that Combined Action Observation and Motor Imagery (AOMI) can support children with DCD to move better, helping them to perform their daily activities more easily, and improving their quality of life" [5,12,19].

## 1.2 Can Mental Training Help Children With DCD?

Scientists believe that mental training and cognitive techniques can help children with DCD. One mental training technique that can improve movement is called "*motor imagery*" and another cognitive technique is "action observation". Both techniques are based on eye-based visual-spatial cognition.

**Motor imagery:** Motor imagery involves imagining movements, encouraging people to imagine both how a movement should look and how a movement should feel. In the "*motor imagery*" technique, a near object is chosen, reached, and grasped by an actor (pilot-player); then it is brought back toward him. The actor thinks about what he sees, listen to, and how the movement feels (e.g., were there any sounds the actor heard as he moved?). Now, without moving, the actor imagines seeing his hand and arm reach and grasp the object and imagines the feelings and sounds of doing it.

That is the "*motor imagery*" technique. A lot of visual-spatial cognition and eye-based cognitive functionality is involved. Scientists in Australia have shown that motor imagery training can help children (aged 7–12) with DCD improve their movements [20].

"The scientists asked one group to imagine and then practice doing movements like catching a ball, several times over five weeks. Children who did this motor imagery improved more than other groups that just did physical practice, or that did no training" [21].

In the motor imagery technique, the brain areas shown in Fig. 1 are all more active. "Since these brain areas are less active in children with DCD, motor imagery helps to activate them. By doing motor imagery to activate these brain areas regularly, children with DCD might be able to improve their movements" [19].

**Action observation:** Watching movements is called "*action observation*" (i.e., watching people perform movements, either on video or in live demonstrations). Action observation is a cognitive eye-based technique very useful to DCD children. "Although motor imagery helps, it is not easy for children with DCD to imagine how a movement looks and feels. Many children with DCD struggle to imagine themselves doing movements. Scientists are investigating ways to help make "*motor imagery*" easier for these children. One way to help is by showing them movements" [20].

In Physical Education K-2 lessons children often watch teachers do a movement and then copy it. This activates similar areas of the brain to "*motor imagery*". For example, children with DCD could be given a video showing them what the movement should look like and asked to imagine the feelings of doing the movement at the same time (Fig. 2).

**Combined Action Observation & Motor Imagery (AOMI):** The AOMI eye-based visual-spatial technique is performed by watching a video of a movement while at the same time imagining the feeling of performing the movement. For instance, watching a favorite soccer player taking a penalty kick on T.V. while trying to imagine yourself kicking the ball and scoring the winning goal.

"Doing AOMI means children with DCD do not have to imagine what the movement looks like because it is shown to them on video. This should make it easier, as they only need to imagine the feeling of the movement whilst they watch the video. Scientists have started to investigate brain activity when people do AOMI. It causes more activity in the brain areas involved in the movement than just doing motor imagery" [21].

AOMI performs better than "*motor imagery*" or "*action observation*" alone for improving movement in motor coordination problems (e.g., helping children with DCD to improve their spatial cognition) [19].

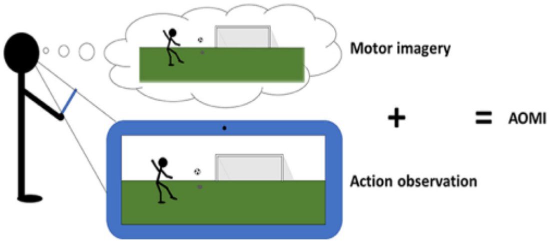

**Fig. 2. Combined Action Observation and Motor Imagery (AOMI) involves watching a video of a movement (such as kicking a ball) and, at the same, time imagining the feeling of doing that movement**

"Scientists in the UK have started to research whether AOMI can help children with DCD to move better. One study looked at how well children with DCD (aged 7–12) could copy the movements of another person, and they found that AOMI improved their ability to copy [19]. AOMI was even more helpful than *motor imagery*. This means that AOMI may help these children learn movements more easily when copying demonstrations. Other scientists have shown that AOMI can help children with DCD (aged 7–11) to learn more quickly and to move their hands and eyes more skillfully" [22].

"As AOMI involves watching how the movement should look whilst imagining how the movement should feel, it might help children with DCD to develop an internal model that they can use to help them improve their movements" [18,19].

Current research is trying to find out exactly how effective AOMI can be in helping children with DCD to get better at everyday movements [22]. AOMI as an eye-based mental and cognitive technologies can help DCD children get better visual-spatial cognition, motor planning, and movement control.

### 1.3 Can Birds Visual Avian Navigation and Nest Nidification Georeferencing Functionalities Help Children With DCD?

DCD disorder is a (mind-based) visual-spatial motor coordination problem, like (sensor-based) robot pose self-determination in computer vision [23-25], and (eye-based) visual avian navigation and nest nidification georeferencing in birds' migration [1]. While the fundamental concepts behind robot pose estimation and birds' navigation and nidification are "spatial cognition" and particularly the observed "visual-spatial compound linear geometries", they are not considered so far in the DCD bibliography.

The 3D visual geometry of the built urban environment, in low-density urban areas, is rich in self-positioning and georeferencing functionalities and should be examined and investigated also for motor coordination ones.

### 1.4 Article's Objective

The purpose of this study is to explore the visual contribution of the built environment in urban areas among children with DCD and co-occurring symptoms in comparison to children with typical development (TD); and then to determine how potential natural environment and visual-spatial compound linear geometries, usually found in low-density built urban environments, may influence these symptoms.

## 2. METHODOLOGY

### 2.1 The Preliminary Procedures

**Enrollment:** This study was carried out, between October 2021 and March 2022, at two city parks and one pocket park located in the Kalamaria district of Thessaloniki, Greece. Twenty DCD participants (10 boys and 10 girls) were recruited through developmental and community pediatricians, psychologists, and physical/occupational therapists. Children were recruited as DCD, for the last 10 years, is commonly diagnosed in elementary school. Additionally, another twenty TC participants (10 boys and 10 girls as well), aged 5 to 8 years, were selected via social media and enrolled.

**Eligibility:** DCD participants' inclusion criteria were: (i) age 5 to 8 years; (ii) current diagnoses of DCD by a registered health care provider; and (iii) right-handed (i.e., hand used for writing).

Those with pre-term birth (<36 weeks' gestation) or any neuropsychiatric, neurological, and/or chronic disorders were excluded. Children with a diagnosis of attention-deficit/hyperactivity disorder (ADHD), learning disorder (LD), or generalized anxiety disorder (GAD) were included given the high co-occurrence with DCD [26,27].

Participants were screened to ensure they met the clinical criteria for DCD outlined in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) [3]. Children demonstrated motor deficits (DSM criterion A) with total test scores below the 16th percentile on the Movement Assessment Battery for Children (MABC-II, 2nd Edition) [28].

From the bibliography, it is known that Motor deficits interfered with daily functioning (DSM criterion B), began early in development (DSM criterion C), and were not better explained by an intellectual disability, visual impairment, or neurological condition (DSM criterion D) [12,19,26-29].

Diagnostic DSM criteria B and C were confirmed by a parent questionnaire developed by the investigators, which included questions about difficulties experienced in three domains: (i) motor (i.e., handwriting, riding a bike, self-care tasks, motor planning, learning new motor tasks, etc.); (ii) social (play and social skills, physically tired, lack of energy, etc.); and (iii) academic (reading, writing, math skills, etc.), as well as the age at which motor difficulties were first observed.

DSM criterion D was confirmed by questions on the parent questionnaire regarding all prior and current diagnoses, as well as visual impairments, and children obtaining a Full-Scale IQ score >70 on the Wechsler Abbreviated Scale of Intelligence (WASI-II, 2nd Edition) [29].

**Intervention groups:** Participants were divided into four parallel intervention groups: group A (10 DCD boys), group B (10 DCD girls), group C (10 TC boys), and group D (10 TC girls).

**Study design:** On each of the three experimental fields (urban parks) the motor coordination training was performed for four days. So, on the 1st day, baseline motor tests were administered, followed by the intervention (active or sham). During this first intervention, three treatment seasons (trials) were performed per experimental field with a time duration of 10, 15, and 5 min respectively. Participants repeated this protocol for three consecutive days (the 2nd, the 3rd, and the 4th day).

Participants returned two weeks later to repeat all motor coordination tests. Assessments were video recorded and blindly scored offline.

**Term's personalized description and innovative concept's definition:** For the experiments (trials) needs, one term's description has to be specifically personalized, as well as one new concept must be defined. Hence, the term "*natural environment*" is described, for clarification purposes regarding the presented research, as a low-density constructed urban area rich in trees, flora, and vegetation.

Also, the innovative concept "visual-*spatial compound linear geometries*" is defined as a set of line structures in a parallel or perpendicular relationship to each other (called sometimes in computer vision bibliography as PnP / "Perspective-n-Point" linear geometries; Providing an excellent pose estimation functionality in robots/computer vision) [1,23-25].

## 2.2 Visual Motor Coordination Training Protocol

Coordination patterns were used to assess motor coordination processing variabilities after nine (9) treatment sessions (i.e., 3 sessions per park). Multiple linear regressions were utilized to investigate the relationship between DCD, the natural environment, and the visual-spatial compound linear geometries [1].

Since the main aim of this study was to investigate a dynamic system to examine, estimate, and document changes in motor coordination in treatment seasons, specific calibration patterns were used for graphical printouts recording the plots of the changes because of the motor coordination problem. In this way Individual differences in coordination were evident.

The changing landscape provides benefits to the proposed approach and the children with DCD may reveal greater visual-spatial error variability than their TD counterparts (i.e., children with typical development). So, estimating, recording, and documenting this variability is a crucial task. So, data were recorded as time series continuously during the trials, so each time series contains three (3) treatment seasons, per experiment field, and per participant.

Children were asked to walk up and down a flat 10 m long pathway for 1 min, while the movement of their feet and trunk was recorded using motion analysis. The Gait pattern of children with DCD was characterized by wider steps, elevated variability in the time spent in double support and stride time, and greater mediolateral velocity and acceleration compared to their TC peers [30-32].

An elevated variability in medio-lateral acceleration was also seen in group A (boys) but not in group B (girls). In addition, the boys showed greater variability in velocity and acceleration in all three directions compared to the girls. The data suggest that the high incidence of trips and falls seen in children with DCD may be due to the gender difference [2,5,9,30,32].

## 2.3 Motor Coordination Performance Estimation - The Coordination Patterns

The following three figures demonstrate the coordination patterns used in the experimental trials as a motor coordination performance estimation tool (a multi-lane, a rectangle, and a compound tool) (Figs. 3-5).

**Fig. 3. A multi-lane coordination pattern used for DCD evaluation in the trial experiments**

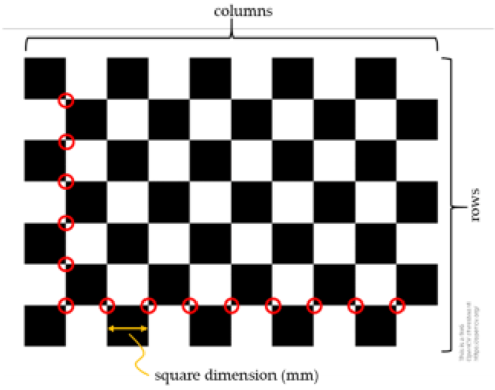

**Fig. 4. A rectangle coordination pattern used for DCD evaluation in the trial experiments**

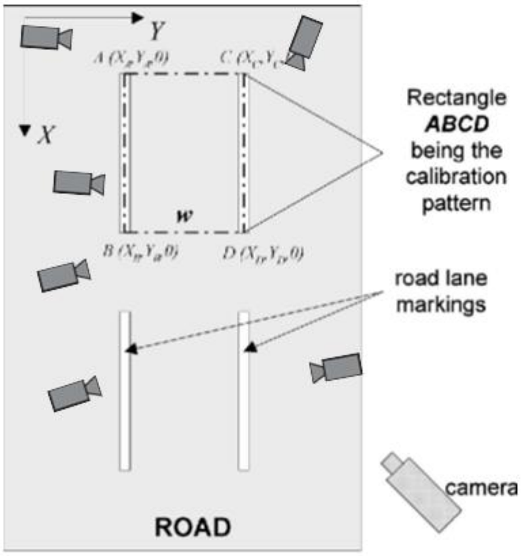

**Fig. 5. A compound (multi-lane & rectangle) coordination pattern used for DCD evaluation in the experiments**

Finally, in the next Fig. 6, a fully automated intelligent coordination multi-pattern (for DCD evaluation) is displayed.

**Fig. 6. A fully automated intelligent calibration multi-pattern (DCD evaluation)**

## 2.4 Motor Coordination Performance Estimation - The Procedure

The following Fig. 7 displays the experimental set-up used for the trials at the treatment seasons [31].

Also, next Fig. 8 demonstrates an experiment's 10 m long pathway and the full instrumental set-up (vertical puzzle) with the spatial locations of eight ProReflex cameras used for video recording [12].

### 2.4.1 The recorded individual spatial motor coordination variability in coordination patterns

The individual, per DCD children, motor coordination variability is recorded as an ellipse [Fig. 9, part A]. Then these recorded data were used for statistics and quality information regarding the spatial variability of the motor coordination differences between DCD children and their TD counterparts [12,31].

The large grey ellipse encircles all the baseline markers and represents 0.65 of the mass of the fitted bivariate normal distribution [12]. So, in Fig. 9 (part A), markers represent individual covariance matrices from all the baseline trials (grey crosses), nine (9) baseline trials with score ≥ 8 (blue squares), six (6) retention trials from group A with score ≥ 8 (red-brown circles), and six (6) retention trials from group B with score ≥ 8 (red circles).

The markers are encircled by ellipses that represent 0.65 of the mass of fitted bivariate normal distribution. The large grey ellipse encircles all the baseline markers and represents 0.80 of the mass of fitted bivariate normal distribution.

Also, in Fig. 9 (parts B–E) representative examples of the covariance matrices are demonstrated (the values in the matrices are also color-coded). Finally, markers in Fig. 9 (part A) that correspond to these exemplar matrices are indicated with a black circle and corresponding label.

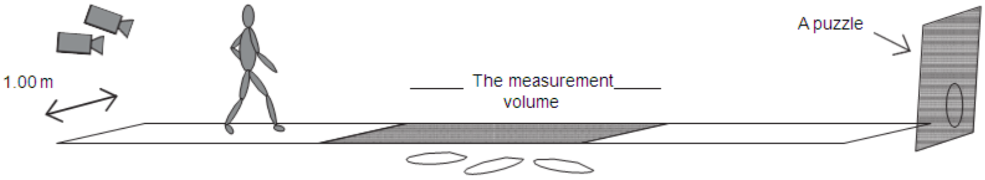

Fig. 7. A view of the experimental set-up

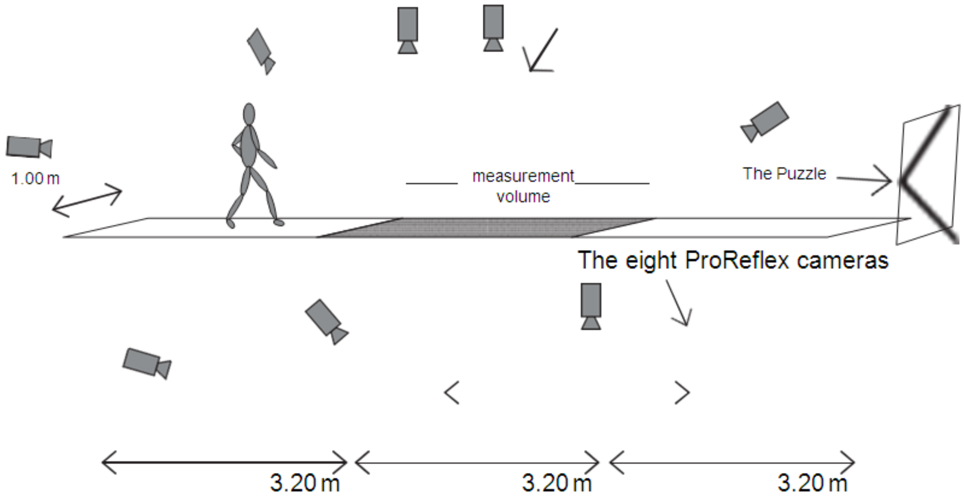

Fig. 8. Experimental set-up: A vertical puzzle was placed at the end of the pathway

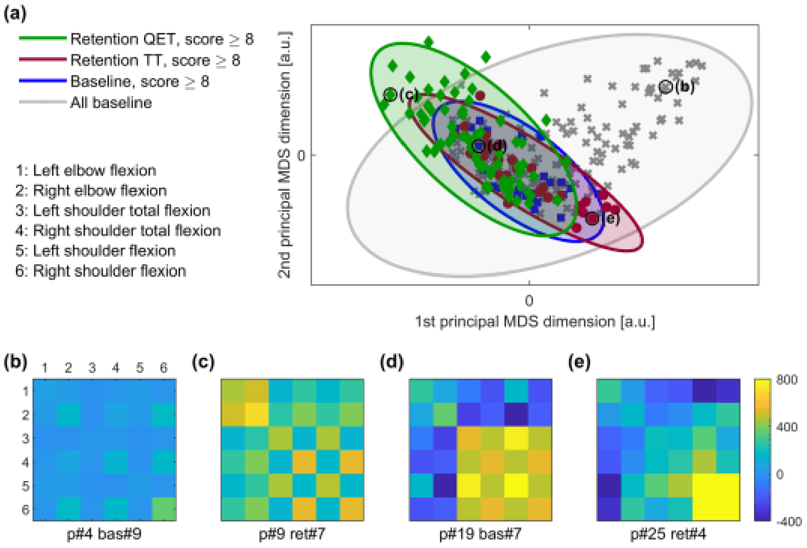

Fig. 9. The individual per DCD children spatial motor coordination variability (Recorded as an ellipse)

### 2.4.2 Coordination patterns evaluation

Fig. 10 (part A) provides a summary of the three-step approach adopted to compare coordination before and after training. To consider the temporal relationships (coordination) between kinematic measures, the covariance between them was first computed. The covariance between the two data sets from group A and group B is defined as:

$$\mathrm{cov}\ (A, B) = 1/(N-1)\ \Sigma_{i=1,N}(A_i - \mu_A)(B_i - \mu_D)$$

Where: $\Sigma_{i=1,N}$; $\mu_A$ and $\mu_D$ are the mean values of the trial data for groups A and B respectively (data from the initial and the repeat, after 2 weeks, measurements); and N is the number of participants in the groups (i.e., N=10).

Also, Fig. 10 (parts B, and D) shows exemplar time-series data of the catching period of two different trials. Covariances between pairs of the time series were next saved in a matrix. Then, after computing the covariance matrices for all trials for all participants, the distance between these covariance matrices by applying a Riemannian geometry approach was estimated (Fig. 10, parts C, and E) [12,33]. Riemannian geometry allows curved-space data analysis, where the Euclidian space operators didn't apply, which is the case for covariance matrices [33].

Once the distances between all the pairs of the covariance matrices were calculated, *Multidimensional Scaling* (MDS) was used to analyze and visualize the differences and similarities between trial coordination patterns. MDS is a data analysis technique widely applied to visualize the similarities and differences between data sets [34]. MDS allows the covariance matrix representation of each participant as a dot in an abstract geometric space. For the presented research (visual contribution to motor skill disorders) and visualization purposes, just the first two (i.e., the most significant) dimensions of this abstract space were used.

Finally, Fig. 10 (part F) shows a visualization of all the covariance matrices from all trials, by using two first principal dimensions of the MDS of all the Riemannian distances between pairs of the covariance matrices from the current study.

### 2.4.3 Pipelines & kinematic measures regarding the spatial variability of the motor coordination differences between DCD children and their TD counterparts

The following analysis pipelines and kinematic measures are demonstrated in Fig. 10 (parts A, B, C, D, E, F):

(Part A): The data processing and analysis pipeline.

(Parts B and D): The time series of kinematic measures:

1: Left elbow flexion;
2: Right elbow flexion;
3: Left shoulder total flexion;
4: Right shoulder total flexion;
5: Left shoulder flexion;
6: Right shoulder flexion.

(Parts C, E): Their *covariance matrices* CM1 and CM2, covariance values are color-coded.

(Part F): The two first principal dimensions of multidimensional scaling. Each dot represents a covariance matrix from a single trial. Dots representing covariance matrices CM1 and CM2 are indicated with black circles. Distances between the dots on the plane of the principal MDS dimensions (black line) are an approximation of the Riemannian distance, δ(CM1,CM2), between the covariance matrices [12,32,5].

### 2.4.4 Testing statistical significance

To evaluate the findings' statistical significance, a non-parametric Mann-Whitney-Wilcoxon test was used as implemented in Matlab with the command "ranksum". Additionally, where appropriate for multiple comparison control, Benjamini Hochberg false discovery ratio method was used, as it is implemented in Matlab with the command "mafdr" [35,36].

The function "distance_riemann" computes the Riemannian distances and can be found in a freely available toolbox called *Covariance Toolbox* (https://github.com/alexandrebarachant/covariancetoolbox). The Matlab command for MDS is "cmdscale" [35,36].

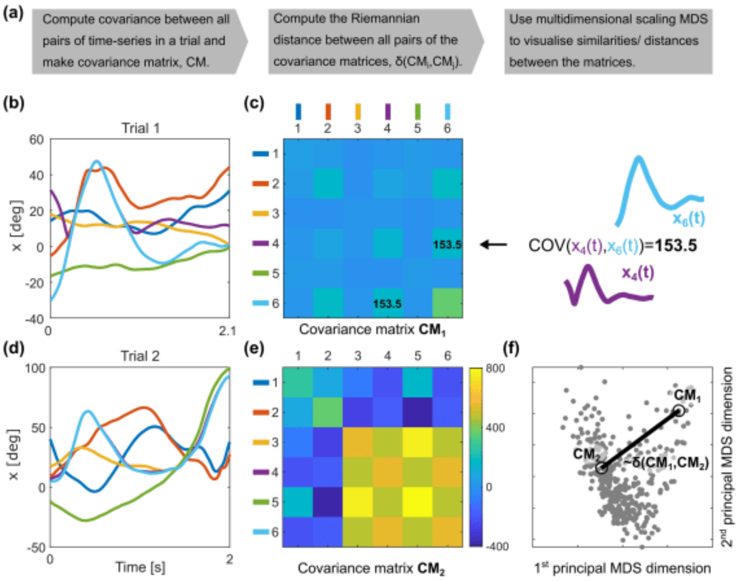

**Fig. 10. Pipelines & kinematic measures regarding the spatial variability of the motor coordination differences between DCD children and their TD counterparts**

## 3. FIELD EXPERIMENTS

Three (3) urban grounds in Kalamaria, Thessaloniki, Greece (two city parks and one pocket park) were selected as experimental fields. A total of nine (9) treatment seasons were executed; three seasons for each experimental field.

### 3.1 Experimental Field I – City Park A'

Georgiou Gennimata 10-12, Kalamaria 551 33, Greece.

3GPS co-ordinates (Google App) & www.GPS-Coordinates.org
Latitude (φ): 40.57748, Longitude (λ): 22.96178

#### 3.1.1 Photography for the 1st treatment season (10 min trial)

The following figure demonstrates the ground for the 1st treatment season (DCD motor coordination assessments in a natural environment without spatial compound linear geometries, i.e., PnP linear geometries) (Fig. 11).

#### 3.1.2 Photography for the 2nd treatment season (15 min trial)

The following figures demonstrate the ground for the 2nd treatment season (DCD motor coordination assessments rich in nature and PnP linear geometries) (Figs. 12-14).

**Fig. 11. The first Experimental City Park in Aghios Ioannis, Kalamaria, Thessaloniki, Greece Participant children navigate at the 1st Experiment's City Park (Rich in a natural environment)**

**Fig. 12. The neighborhood of the first Experimental City Park (Rich in PnP linear geometries)**

**Fig. 13. The neighborhood of the first Experimental City Park (Rich in PnP linear geometries)**

**Fig. 14. A navigation space at the corner of the first Experimental City Park (Rich in nature and PnP linear geometries)**

### 3.1.3 Photography for the 3rd treatment season (5 min trial)

The following figure demonstrates the ground for the 3rd treatment season (DCD motor coordination assessments poor in nature and PnP linear geometries) (Fig. 15).

**Fig. 15. A park-pathway at the corner of the first Experimental City Park**
**(An urban unconstructed plot, poor in nature and without PnP linear geometries)**

## 3.2 Experimental Field II – City Park B’

I. Passalidi 132, Kalamaria 551 33, Greece.

GPS co-ordinates (Google App) & www.GPS-Coordinates.org
Latitude (φ): 40.58285, Longitude (λ): 22.95621

### 3.2.1 Photography for the 1st treatment season (10 min trial)

The following figure demonstrates the ground for the 1st treatment season (DCD motor coordination assessments in a natural environment without spatial compound linear geometries, i.e. PnP linear geometries) (Fig. 16).

**Fig. 16. The City Park, rich in nature and without PnP linear geometries, in Passalidi Area, Kalamaria, Thessaloniki, Greece**

### 3.2.2 Photography for the 2nd treatment season (15 min trial)

The following figures demonstrate the ground for the 2nd treatment season (DCD motor coordination assessments rich in nature and PnP linear geometries) (Figs. 17-19).

**Fig. 17. The neighborhood of the second Experimental City Park (Rich in PnP linear geometries)**

**Fig. 18. A navigation space at the corner of the second Experimental City Park**
*(Rich in nature and PnP linear geometries)*

**Fig. 19. A navigation pathway at the corner of the second Experimental City Park**
*(Rich in nature and PnP linear geometries)*

#### 3.2.3 Photography for the 3rd treatment season (5 min trial)

The following figure demonstrates the ground for the 3rd treatment season (DCD motor coordination assessments poor in nature and PnP linear geometries) (Fig. 20).

**Fig. 20. A park-pathway at the corner of the second Experimental City Park**
*(An urban unconstructed plot, poor in nature and without PnP linear geometries)*

### 3.3 Experimental Field III – Pocket Park

Aghiou Panteleimonos 20, Kalamaria 551 33, Greece.
GPS co-ordinates (Google App) & www.GPS-Coordinates.org
Latitude ($\varphi$): 40.58128, Longitude ($\lambda$): 22.96236

#### 3.3.1 Photography for the 1st treatment season (10 min trial)

The following figures demonstrate the ground for the 1st treatment season (DCD motor coordination assessments in a natural environment without spatial compound linear geometries, i.e. PnP linear geometries) (Fig. 21).

**Fig. 21. The Pocket Park, rich in nature, in Aghios Panteleimon Area, Kalamaria, Thessaloniki, Greece**

#### 3.3.2 Photography for the 2nd treatment season (15 min trial)

The following figures demonstrate the ground for the 2nd treatment season (DCD motor coordination assessments rich in nature and PnP linear geometries) (Figs. 22-24).

**Fig. 22. The Pocket Park rich in nature and PnP linear geometries**

**Fig. 23. The Pocket Park rich in nature and PnP linear geometries**

**Fig. 24. A navigation space at the corner of the Pocket Park**
*(Rich in nature and PnP linear geometries)*

### 3.3.3 Photography for the 3rd treatment season (5 min trial)

The following figure demonstrates the ground for the 3rd treatment season (DCD motor coordination assessments poor in nature and PnP linear geometries) (Fig. 25).

**Fig. 25. A park-pathway at the corner of the Pocket Park**
*(An urban unconstructed plot, poor in nature and without PnP linear geometries)*

## 4. RESULTS

### 4.1 Statistical Analysis

Statistical analysis was performed in SPSS [37]. The primary analysis was intention-to-treat and all forty (40) participants from the four groups were involved. The statistical approach was based on previously established methods [38].

The linear mixed effects model examined changes between groups from pre- to post-intervention with fixed effects for Group, Day, the interaction of Group and Day, and random effects for participants including the intercept to account for repeated measures [39,40].

**Children with Developmental Coordination Disorder exhibit greater stepping error despite similar gaze patterns and state anxiety levels to their typically developing (TD) peers:** “Children with DCD and ADHD symptoms showed greater variability of atypical sensory processing patterns compared with TD children. Low registration and sensory sensibility issues were more prevalent in the DCD group. ADHD children showed higher rates of low registration, sensory sensibility, and sensory seeking, and all children in the co-occurring symptoms group presented sensory sensibility” [41].

In the following Fig. 26, a birds-eye schematic of the walking task is displayed. Starting with their left foot, participants had to walk along the path, step into the blue target box, and over either no obstacles, one (nearest) obstacle, or two obstacles. The distance between the start line, target box, and obstacles was personalized to each child’s preferred walking speed, such that their fourth step would naturally place their right foot into the target box, and their sixth and eighth steps would place their right foot over the first and second obstacles, respectively [32,42].

In the following Fig. 27, a plot of the stepping errors (as “error ellipses”) in coordination patterns, of individual participants, is illustrated with the two principal dimensions of a multidimensional spatial scaling.

- (Parts A–J) display the “error ellipses” data for individual TD/typically developing participants (green).
- (Parts K–S) display the “error ellipses” data for individual DCD participants (brown-red).

Small dots represent individual covariance matrices of each participant (grey – baseline, colour – retention); the dots are encircled by ellipses that represents 0.65 of the mass of fitted bivariate normal distribution [12].

To show how individual participants compare with all others, the two large ellipses indicate the entire baseline (grey) and the entire retention (black) data; they represent 0.8 of the mass of fitted bivariate normal distribution.

- (Part T) shows overlap between "error ellipses" by representing the covariance matrices of the retention trials in which on average participants achieved improvement $\Delta_{SCR} \geq 1$.

Titles show participant's identifier, median retention catching score, median baseline catching score and $\Delta_{SCR}$ [12,43].

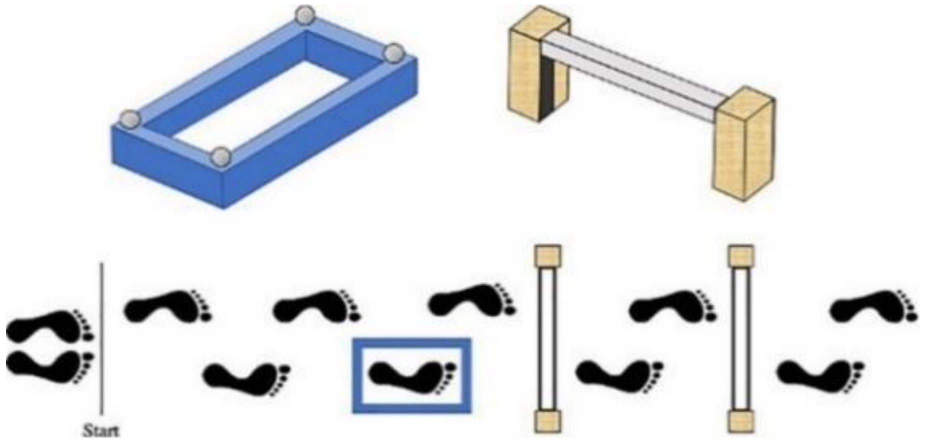

**Fig. 26. Children with developmental coordination disorder exhibit greater stepping error, despite similar gaze patterns and state anxiety levels to their (td) typically developing peers**

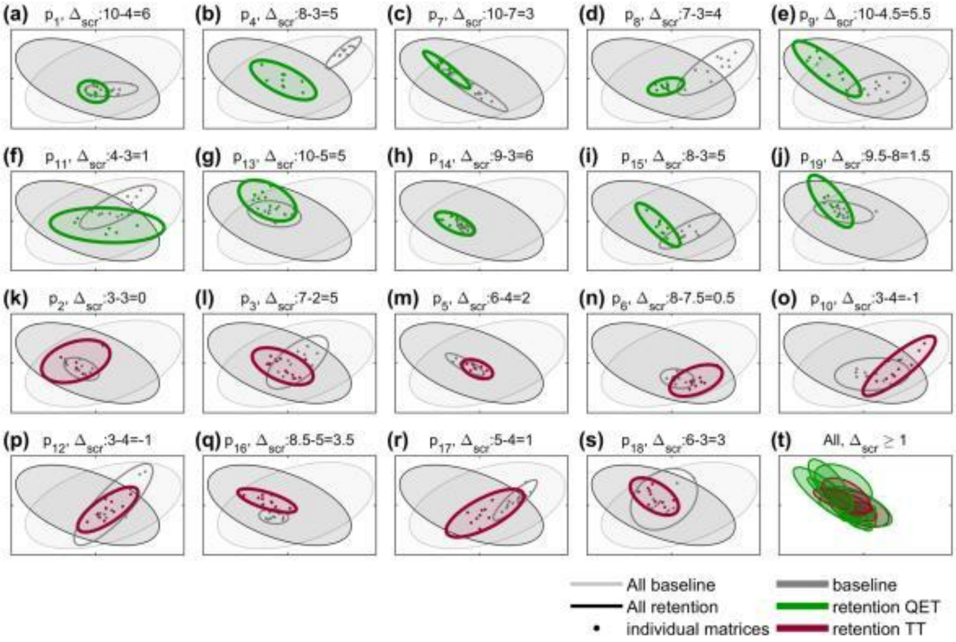

**Fig. 27. Plot of the changes (stepping errors) in coordination patterns of individual participants Picture by courtesy of Piotr Słowiński et al. [12]**

**Table 1. First Experimental Field / 1st, 2nd, and 3rd Treatment Seasons (DCD Childrens' Performance in each item of the "visual-*spatial motor coordination*" concept)**

| "Motor Coordination" Items | | Number of children | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Item No.** | **Task** | **Improved** | | | **Not improved** | | | **Decreased** | | |
| | | **Treatment season** | | | **Treatment season** | | | **Treatment season** | | |
| | | **A'** | **B'** | **C'** | **A'** | **B'** | **C'** | **A'** | **B'** | **C'** |
| #1 | Accelerated speed with accuracy | 2 | 16 | 0 | 8 | 4 | 1 | 10 | 0 | 19 |
| #2 | Ability to accurately pedal a bike | 2 | 14 | 0 | 6 | 5 | 0 | 12 | 1 | 20 |
| #3 | Static balance | 4 | 17 | 0 | 7 | 3 | 1 | 9 | 0 | 19 |
| #4 | Dynamic balance during slow and controlled movements | 3 | 18 | 0 | 8 | 2 | 1 | 9 | 0 | 19 |
| #5 | Dynamic balance during fast and explosive movements | 0 | 15 | 0 | 6 | 4 | 0 | 14 | 1 | 20 |

**Table 2. Second Experimental Field / 1st, 2nd, and 3rd Treatment Seasons (DCD Childrens' Performance in each item of the "*visual-spatial motor coordination*" concept)**

| "Motor Coordination" Items | | Number of children | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Item No.** | **Task** | **Improved** | | | **Not improved** | | | **Decreased** | | |
| | | **Treatment season** | | | **Treatment season** | | | **Treatment season** | | |
| | | **A'** | **B'** | **C'** | **A'** | **B'** | **C'** | **A'** | **B'** | **C'** |
| #1 | Accelerated speed with accuracy | 3 | 17 | 0 | 8 | 3 | 0 | 9 | 0 | 20 |
| #2 | Ability to accurately pedal a bike | 2 | 16 | 0 | 6 | 3 | 0 | 12 | 1 | 20 |
| #3 | Static balance | 5 | 17 | 0 | 8 | 3 | 1 | 7 | 0 | 19 |
| #4 | Dynamic balance during slow and controlled movements | 3 | 18 | 0 | 8 | 2 | 1 | 9 | 0 | 19 |
| #5 | Dynamic balance during fast and explosive movements | 0 | 17 | 0 | 6 | 3 | 0 | 14 | 0 | 20 |

**Table 3. Third Experimental Field / 1st, 2nd, and 3rd Treatment Seasons (DCD Childrens' Performance in each item of the "*visual-spatial motor coordination*" concept)**

| **"Motor Coordination" Items** | | **Number of children** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Item No.** | **Experimental Tasks** | **Improved** | | | **Not improved** | | | **Decreased** | | |
| | | **Treatment season** | | | **Treatment season** | | | **Treatment season** | | |
| | | **A'** | **B'** | **C'** | **A'** | **B'** | **C'** | **A'** | **B'** | **C'** |
| #1 | Accelerated speed with accuracy | 2 | 14 | 0 | 8 | 6 | 0 | 10 | 0 | 20 |
| #2 | Ability to accurately pedal a bike | 2 | 13 | 0 | 6 | 6 | 0 | 12 | 1 | 20 |
| #3 | Static balance | 3 | 17 | 0 | 8 | 3 | 1 | 9 | 0 | 19 |
| #4 | Dynamic balance during slow and controlled movements | 2 | 16 | 0 | 9 | 4 | 0 | 9 | 0 | 20 |
| #5 | Dynamic balance during fast and explosive movements | 0 | 13 | 0 | 5 | 5 | 0 | 15 | 2 | 20 |

## 4.2 Trial Statistics

### 4.2.1 First experimental field's statistics

For the first experimental field (City Park A') the statistics considering 1st treatment season (10 min trial) for DCD children's visual motor coordination assessments in a natural environment without PnP linear geometries (Fig. 11); 2nd treatment season (15 min trial) assessments in a natural environment rich in PnP linear geometries (Figs. 12-14); and 3rd treatment season (5 min trial) assessments in a flat urban environment poor in nature and PnP linear geometries (Fig. 15).

So, in the Table 1, the number of children who (i) improved, (ii) stayed at the same performance level, or (iii) whose performance worsened are presented for each treatment season and for each item of the "*visual-spatial motor coordination*" concept.

As an improvement is considered a positive change in a score of at least 1 point, and accordingly a negative change in a score of at least 1 point is considered performance degradation.

### 4.2.2 Second Experimental Field's Statistics

For the second experimental field (City Park B') the statistics considering 1st treatment season (10 min trial) for DCD children's visual motor coordination assessments in a natural environment without PnP linear geometries (Fig. 16); 2nd treatment season (15 min trial) assessments in a natural environment rich in PnP linear geometries (Figs. 17-19); and 3rd treatment season (5 min trial) assessments in a flat urban environment poor in nature and PnP linear geometries (Fig. 20).

So, in the Table 2, the number of children who (i) improved, (ii) stayed at the same performance level, or (iii) whose performance worsened are presented for each treatment season and for each item of the "*visual-spatial motor coordination*" concept.

As an improvement is considered a positive change in a score of at least 1 point, and accordingly a negative change in a score of at least 1 point is considered performance degradation.

### 4.2.3 Third Experimental Field's Statistics

For the third experimental field (Pocket Park) the statistics considering 1st treatment season (10 min trial) for DCD children's visual motor coordination assessments in a natural environment without PnP linear geometries (Fig. 21); 2nd treatment season (15 min trial) assessments in a natural environment rich in PnP linear geometries (Figs. 22-24); and 3rd treatment season (5 min trial) assessments in a flat urban environment poor in nature and PnP linear geometries (Fig. 25).

So, in the following Table 3, the number of children who (i) improved, (ii) stayed at the same performance level, or (iii) whose performance worsened are presented for each treatment season and for each item of the "*visual-spatial motor coordination*" concept.

As an improvement is considered a positive change in a score of at least 1 point, and accordingly a negative change in a score of at least 1 point is considered performance degradation.

## 4.3 Gait Analysis and Variables

Gait analysis is an assessment of the way the body moves, usually by walking or running, from one place to another. The purpose of gait analysis is to detect any abnormalities in locomotion [30].

The 10 specific Gait variables used in the current project's Gait analysis were: Stride time (ms); Support time (ms); Swing time (ms); Double support time (ms); Support (%); Swing (%); Double support (%); Stride length (mm); Step width ratio (%); and Medio-lateral excursion (mm).

Gait parameters Walking speed (m $s^{-1}$), stride and step time (s), length (m), width (m); the duration of the double and single support phases (%); and cadence (steps/min) were used in order to describe the spatio-temporal characteristics of gait. To avoid duplication and redundancy in the model "step time", "length", and "width" as spatial step characteristics were analyzed. These Gait variables are preferred instead of (combining them with) stride characteristics. Means and standard deviations (variability) were investigated as they provide more clarity for interpretation as opposed to, for example, coefficients of variation [30].

Other Gait variables are: Cadence (n); Stance time (ms); Step overlap (%); Abduction ($^{o}$); Ground reaction force (GRF; Nm), as well as the asymmetry between left and right limbs in: Step length (mm), Step width (mm), Step angle ($^{o}$); Step time (ms), Stance time (ms), and Ground reaction force (GRF; Nm).

Where: “Cadence” or “rhythm” is the number of steps per time unit; “Abduction” consists of taking the step with an external rotation of the lower limb, that is, with the toe pointing outwards; “Stride length” or “Long step” is the linear distance between the placements of both feet; “Step width” is the linear distance between two equivalent points of both feet; “Step angle” is the direction (azimuth) of the foot during the step; and “Ground reaction force” (GRF) is the gait, kinematic measure, parameter which can validate the state of disorder of the patient's movement (the purpose of this variable is to explore the possibilities of employing the GRF derived from kinematics of the center of gravity (COG) in the study of dynamics of human gait). More detailed definitions for the Gait variables should be found in [30].

“The Gait disorder could be graphically defined as margins of stability during a steady state and perturbed gait, to quantify reactive gait stability, in response to various perturbation types in young and older adults” [44]. A graphical display explanation of Gait disorder, during steady state (left) and perturbed gait (right), is displayed in Fig. 28.

**Gait analysis and motor coordination problem assessment in dynamic balances:** The following two tables display mean estimation data from the three experimental fields (i.e., the two city parks and the one pocket park and for a natural environment rich in visual-spatial compound (PnP) linear geometries, for all the four trial groups (Parentheses in Table 4 for the DCD and TC boys) and (Table 5 for the DCD and TC girls).

For more information regarding the involved anxiety in dynamic balances in DCD motor coordination problems see [5].

### 4.4 Statistical Estimation Quality Assessment

In the following Table 6, the statistics of motor coordination problems, for six (6) experimental tasks, are displayed. The six (6) experimental tasks were: Accelerated speed with accuracy; Ability to accurately pedal a bike; Static balance; Dynamic balance during slow and controlled movement; Dynamic balance during fast and explosive movement; and Motor coordination control in dark conditions.

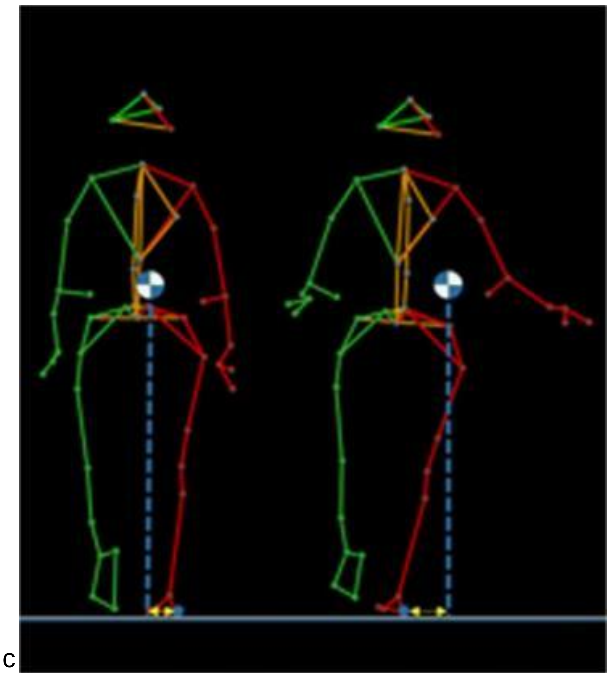

**Fig. 28. Margins of stability during steady state (left) and perturbed (right) gait to quantify reactive gait stability**

**Table 4. Means (standard deviations) of the ten Gait variables for group A' (10 boy-children with DCD) and group C' (10 TD peers without DCD), in both dynamic balances (slow controlled movement and fast explosive movement)**

| The 10 Gait variables | DCD boy-children | | TC boy-children | |
|---|---|---|---|---|
| | Slow Movement | Fast Movement | Slow Movement | Fast Movement |
| 1. Stride time (ms) | 837.0 (75.7) | 897.0 (92.5) | 843.0 (48.6) | 840.0 (64.0)** |
| 2. Support time (ms) | 516.0 (52.3) | 563. (65.9) | 511.0 (37) | 507.0 (43.1)** |
| 3. Swing time (ms) | 321.0 (27.8) | 334.0 (34.5) | 333.0 (16.6) | 330.0 (21.7) |
| 4. Double support time ms | 96.0 (16.2) | 119.0 (23.5) | 83.0 (12.3) | 84.0 (15.1)**‡ |
| 5. Support (%) | 61.6 (1.69) | 62.7 (2.01) | 60.6 (1.36) | 60.3 (1.72)*† |
| 6. Swing (%) | 38.4 (1.58) | 37.3 (2.01) | 39.5 (1.28) | 39.3 (1.32)**† |
| 7. Double support (%) | 11.4 (1.30) | 13.2 (1.75) | 9.9 (1.30) | 10.0 (1.38)*‡ |
| 8. Stride length (mm) | 1072.0 (92.8) | 972.0 (85.5) | 1097.0 (83.6) | 1061.0 (79.1)*** |
| 9. Step width ratio (%) | 71.3 (13.8) | 70.7 (9.3) | 72.4 (13.2) | 72.1 (13.6) |
| 10. Medio-lateral excursion (mm) | 33.0 (7.8) | 40.0 (9.8) | 36.0 (6.4) | 34.0 (5.6)* |

*Group by vision interaction: *P < 0.05; **P < 0.01; ***P < 0.001. Group effect: †P < 0.05; ‡P < 0.01*

**Table 5. Means (standard deviations) of the ten Gait variables for group B' (10 girl-children with DCD) and group D' (10 TD peers without DCD), in both dynamic balances (slow controlled movement and fast explosive movement)**

| The 10 Gait variables | DCD girl-children | | TC girl-children | |
|---|---|---|---|---|
| | Slow Movement | Fast Movement | Slow Movement | Fast Movement |
| 1. Stride time (ms) | 722.0 (70.1) | 917.0(96.3) | 803.0 (44.2) | 822.0 (61.0)** |
| 2. Support time (ms) | 502.0 (50.3) | 577.(67.9) | 511.0 (37) | 507.0 (43.1)** |
| 3. Swing time (ms) | 311.0 (27.1) | 345.0 (35.2) | 333.0 (16.6) | 320.0 (23.3) |
| 4. Double support time ms | 90.0 (13.9) | 122.0 (24.6) | 83.0 (12.3) | 84.0 (15.1)**‡ |
| 5. Support (%) | 60.2 (1.39) | 64.7 (2.81) | 63.2 (1.36) | 65.1 (1.72)*† |
| 6. Swing (%) | 32.5 (1.22) | 39.3 (2.91) | 39.5 (1.28) | 39.3 (1.32)**† |
| 7. Double support (%) | 10.9 (1.25) | 14.2 (1.99) | 8.9 (1.30) | 10.9 (1.38)*‡ |
| 8. Stride length (mm) | 1045.0 (92.1) | 979.0 (88.5) | 1077.0 (81.6) | 1061.0 (79.1)*** |
| 9. Step width ratio (%) | 70.1 (11.9) | 73.7 (9.9) | 79.4 (15.1) | 72.1 (11.6) |
| 10. Medio-lateral excursion (mm) | 30.5 (6.9) | 45.0 (10.5) | 36.0 (6.6) | 34.8 (8.6)* |

*Group by vision interaction: *P < 0.05; **P < 0.01; ***P < 0.001. Group effect: †P < 0.05; ‡P < 0.01*

**Table 6. DCD children – Stepping Errors Statistics of Motor Coordination Problems (For six (6) experimental tasks)**

| **The six (6) Experimental Tasks** | **Mean ± SD of Stepping Errors** | | |
|---|---|---|---|
| | **Experiments in an environment with nature but without PnP linear geometries** | **Experiments in an urban environment rich in nature and PnP linear geometries** | **Experiments in an urban environment poor in nature and PnP linear geometries** |
| Accelerated speed with accuracy | 2:41 ± 0:83 | 2:35 ± 0:70 | 2:63 ± 0:95 |
| Ability to accurately pedal a bike | 2:70 ± 1:00 | 2:66 ± 0:88 | 2:73 ± 1:20 |
| Static balance | 2:81 ± 0:53 | 2:71 ± 0:41 | 2:89 ± 0:62 |
| Dynamic balance during slow and controlled movement | 2:67 ± 0:94 | 2:61 ± 0:84 | 2:71 ± 0:98 |
| Dynamic balance during fast and explosive movement | 3:31 ± 0:98 | 3:24 ± 0:80 | 3:39 ± 1:12 |
| Motor coordination control in dark conditions | 3:87 ± 1:10 | 3:52 ± 0:91 | 4:12 ± 1:28 |

## 5. DISCUSSION

This study aimed to investigate the contribution of vision to walking control in DCD children. A comparison of the spatio-temporal gait pattern in low-density constructed urban environments rich in nature but poor in visual-spatial compound linear geometries, and in environments rich both in nature and linear geometries, revealed that children with DCD were significantly affected by the absence of visual cues like the spatial compound linear geometries [1,2,32]. This was shown by distinct differences in the spatio-temporal variables in anxiety, dynamic balances, and dark conditions [5,31]. “More particularly a lengthening of the support phase and a shortening of the stride length, ultimately resulting in a markedly slower walking velocity. None of these adaptations reached significance in the control children, indicating that the removal of visuals had virtually no effect on TD children” [12,19].

“It might be argued whether the longer support phase and shorter stride length are adaptations in their own right or are simply the result of a decrease in the speed of execution, i.e., walking velocity. Slower performance seems to be a common characteristic of some movements of children (particularly girls) with DCD, especially in more demanding conditions like darkness. It seems, however, that this notion of the slowness of execution mainly applies to speeded tasks or those requiring a task to be performed as fast as possible, where it appears that motor-impaired subjects tend to trade speed for accuracy” [5,12,16].

“Slowness in the current walking task, participants were instructed to walk at their preferred speed, so the decrease in walking velocity should not be interpreted as a failure in performance, but rather as an adaptation to a specific condition (i.e., walking without visual cues). Therefore, it might be assumed that the differences in the gait pattern of children with DCD between the light and dark conditions indicate adaptive changes to meet the task demands, suggesting that these children experience more difficulties with the lack of visual information than TD children. Because of the interrelationship of walking velocity, stride time, and length, the question of which parameter(s) is adjusted seems to be trivial” [5,12,31,32].

“Overall, when walking in the dark, DCD children fall back onto a safer and slower walking physiology strategy. While none of the participants seemed to show signs of fear of the dark and while a sound process of habituation was observed, it cannot be ruled out that motivational factors, such as anxiousness or prudence, may have played a role in the choice of a more secure strategy” [3,5,6,22].

“Still, some features of the adaptive walking strategy indicate that adaptations are likely to be associated with stability. In this discussion, the fact that walking in the dark induces a change of the relative temporal phasing of the gait cycle in favor of the stable double support phase in children with DCD, suggests that the adaptations involve more than just a slowness of execution. Particularly, in the discussed experimental trials, in 9 out of the 20 children with DCD, the spatio-temporal adaptations were accompanied by an increase in the medio-lateral excursions of the center of mass (CoM), indicating that walking in the darkness (even with spatio-temporal adaptations) is at least partially related to difficulty with balance and motor skill disorder. Regarding gait stability, the margin of stability (MoS) expresses the deviation of the center of mass (CoM) that an individual can handle before the loss of balance occurs” [5,12,22].

In this paper, spatial language and spatial topology-affected motor behavior in a landmark spatial search task have been examined. Results revealed that DCD children’s performance, scores, and cues were related to both the natural environment and the spatial compound linear geometries as visual landmark cues. Children with DCD, ADHD, and co-occurring symptoms show more sensory processing issues than typically developing children [3,5,11,31].

The current article is the first to examine the therapeutic efficacy of spatial compound linear geometries (as visual landmark motor coordination cues) on motor learning in DCD children. Independent of intervention, all children's motor performance improved over the four (4) training days and skill improvements were retained in the repeat experimental trials after 4 weeks [1,6,32].

“The research literature suggests that poor motor performance in DCD children may be associated with deficits in motor learning. However, research concerning the presence of motor learning deficits in DCD is inconsistent, with some studies reporting limited skill improvement following practice and others reporting positive effects of practice" [8,39,40]. "Studies supporting the latter emphasize that children with DCD can acquire motor skills, though they may display slower rates of motor learning, requiring more intensive practice to reach desired levels of motor competence. In the current trial, the fine motor performance of the non-dominant limb improved significantly with practice, independent of intervention. This finding supports the capacity of DCD children to learn novel motor skills in low-density built environments rich in nature and visual linear geometries as landmark motor coordination cues" [1,12,31,32,43].

Generally, motor learning involves both online and offline processes. Online learning includes skill gains obtained during active training, whereas offline learning includes gains occurring between training sessions (i.e., consolidation). In the presented trials and within all four groups, most of the motor learning took place online. This suggests that DCD children may show less efficient offline motor learning, or consolidation, which has been previously suggested in the DCD literature and warrants further study [5,8,12,16, 31].

## 6. RESEARCH LIMITATIONS

The results of this study may be limited by several factors. For example, it is important to acknowledge that the sample size (i.e., the 40 children allocated in four groups) is relatively small, and the age range (5 to 8 years old) of the participants is relatively heterogeneous. Hence, researchers should therefore take care when extrapolating the paper's findings to DCD children of all ages.

"Additionally, developmental aspects of emotional self-perception may question the accuracy of the simple self-report measure of state anxiety. However, the similarity in gaze behaviors between the four groups may reinforce a similarity in their experienced anxiety, given the wealth of research showing how anxiety can alter visual exploration during locomotor tasks" [5,12,43].

"Regardless, future research would benefit from attempts to objectively capture physiological state-anxiety responses to complement additional measures of self-report. Finally, it should be reiterated that the paper's findings only allow commentary on the stepping performance of DCD children in the absence of task-related anxiety. It is therefore important for future research to experimentally manipulate anxiety in order to fully explore its role in motor skill disorder" [5,31,39].

The sample size calculation estimated that ten (10) participants per group would provide adequate power to detect group differences, but this number was deemed too small for a more reliable statistical analysis because many measurements deviated too much and had to be discarded. As a result, the sample size (i.e., the 10 participants/group) was not large enough, and it may have decreased the ability to detect potential group differences or efficacy and may have limited the generalizability of the findings. There was also a high degree of variability in performance on a number of measures, which may have decreased the ability to detect group differences given the small sample size.

"Another limitation was the demanding nature of the trial, which required children to maintain their attention and motivation over four consecutive days with one repetition in two weeks. This may have been difficult, particularly for a small sample size regarding children with co-occurring attention, learning, and anxiety disorders, and may have contributed to performance variability. Co-morbidities and the fact that children with DCD are a heterogeneous group who display many different types of motor skill deficits, constitute a significant challenge for future trials" [39,40,42,43].

## 7. CONCLUSIONS

Motor coordination problems can seriously affect a child's life, including activities of daily living, self-esteem, pastime activities, and social relationships, as well as educational and training attainments. In this paper, how spatial language and topology affected motor behavior in a landmark spatial search task was examined. Results revealed that DCD children's performance, scores, and cues were related to both the natural environment and the spatial compound linear geometries as landmark motor coordination cues and spatio-temporal clues in low-density urban environments [1,5,12,18].

This study reports significant variability in sensory processing among children with DCD, ADHD, and co-occurring symptoms even using a small trial sample. These differences can contribute to understanding how neurological and social factors correlate across diagnoses [15,17,19].

Derived important observations and conclusions include:

- There is variability in visual eye-based processing patterns, as spatio-temporal clues, between DCD, ADHD, and typically developing children (TD peers) and within disorders as well.
- Visual eye-based processing interrelates with motor coordination problems, performance, inattention, and hyperactivity.
- There is a stepping error difference between DCD boys and girls, particularly in dynamic balances (slow controlled movement and fast explosive movement) and in dark conditions.
- Experiments in low-density urban environments rich in nature and spatial compound linear geometries, as landmark motor coordination cues, enjoy less stepping error (as compared to experiments in environments with nature but without linear geometries).
- The biggest stepping error, for both DCD boys and girls, was recorded in experiments in urban environments poor in nature and spatial compound linear geometries.
- Visual contribution to motor skill DCD disorders using spatial cognition and linear geometries as landmark motor coordination cues.
- Visual contribution to walking physiology using cognitive approaches, Gait analysis (variables), and spatio-temporal clues.

**Applications:** Development of 3D digital graphical environments (with a variety of landmark motor coordination cues and spatio-temporal clues) supporting interactive tests, apps, and visual exercises for (a) human spatial cognition and movement improvement; and (b) children's motor control and coordination refinement [1,3,17,19].

**Open research issues:** As open research, cases could be considered one in-depth research and documentation for the differences between DCD boys and girls in motor coordination control in static and dynamic balances, as well as in dark conditions. A similar differential analysis could also be considered in low-density built environments rich in visual-spatial compound linear geometries used as landmark motor coordination cues [1,5,12,31].

For Gait analysis, as an assessment of the way the body moves, apart from the specific ten (10) variables used for trials' data analysis, other variables like Cadence, Stance time, Step overlap, Abduction (ABD), as well as the asymmetry between left and right limbs in: Step length, Step width, Step angle, Step time, Stance time, and Ground reaction force (GRF) should be examined and estimated [3,16,30].

Future studies that characterize baseline cortical excitability and neuro-metabolites, using techniques such as transcranial magnetic stimulation (TMS) and magnetic resonance spectroscopy (MRS), could help in refining application (i.e., stimulation intensity, montage, and target) [3,32,38].

## 8. GLOSSARY

**Action observation**: Watching people perform movements, either on video or in live demonstrations.

**Attention Deficit / Hyperactivity Disorder (ADHD)**: A diagnosis of attention-deficit/hyperactivity disorder.

**Children with Typical Development (TD):** Children with typical development are fluent in smiling, crawling, manipulating objects, walking, self-care, and talking. These are examples of developmental milestones that provide valuable insight into a child's development. Most children develop skills in similar patterns and at similar times.

**Combined Action Observation and Motor Imagery (AOMI)**: Watching a video of a movement while at the same time imagining the feeling of performing the movement.

**Developmental Coordination Disorder (DCD)**: A medical condition that makes it difficult for people (children) to plan and control movements.

**Generalized Anxiety Disorder (GAD):** GAD is a long-term condition that causes children and adults to feel anxious about a wide range of situations and issues, rather than one specific event. People with GAD feel anxious most days and often struggle to remember the last time they felt relaxed.

**Internal model**: A mental picture of what a movement should look like and feel like when we do it well.

**Learning Disorder (LD):** Having a learning disorder means that a child has difficulty in one or more areas of learning, even when overall intelligence or motivation is not affected. Some of the symptoms of learning disorders are: Difficulty telling right from left; Reversing letters, words, or numbers, after first or second grade.

**Motor imagery**: Imagining how performing a movement would look and feel.

**Sensory Processing Difficulties (SPD):** These difficulties are present in children with Developmental Coordination Disorder (DCD) and Attention Deficit and Hyperactivity Disorder (ADHD).

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the author, without undue reservation, to any qualified researcher.

## CONSENT AND ETHICAL APPROVAL

Written informed consent from participants' legal guardians and child assent were obtained at enrollment. The Landscape Architecture Department of the East Macedonia & Thrace University of Applied Sciences / Research Ethics Board approved this study (clearance number: LA.14/ Internal/ Protocol).

## ACKNOWLEDGEMENTS

As a doctoral student, I would like to acknowledge all the families of the children who took part in this research study. I also express my warm thanks to A/Prof. Alex Argiriadis (Frederick Univ) for providing helpful comments on a draft, as well as to Prof. A.D. Styliadis (IHU) and Prof. L. Dimen (UAB Univ) for statistical guidance. Finally, I would like to mention the contribution of the company ADAS / Autel Maxisys for providing the training and equipment essential to this study.

## COMPETING INTERESTS

Author has declared that no competing interests exist.

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*The peer review history for this paper can be accessed here:*
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