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A Low-cost Feasibility Training Study for DCD Children's Perceptual-motor Therapy

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Abstract. The motor coordination problem of children with developmental coordination disorder (DCD) has been frequently associated with poor visual and spatial eye-vision cognition. Virtual reality (VR) and immersive environments in occupational therapy and rehabilitation fields are major changes nowadays and VR has been shown to encourage more repetition allowing for faster motor skill development and recovery. In addition, spatial cognition has attracted the attention of the scientific community recently in mental rotation, DCD orientation, spatial navigation, and cognitive mapping. This feasibility study demonstrated the usability of an immersive VR environment as a spatial cognition recording tool for children with motor skill disorders. Eighty children aged five to eight years; five intervention groups; four virtual 3D environments with *flora* (trees, plants) and *linearity* (spatial linear structure geometries as landmark coordination cues) as design parameters; and trial walk-through exercises on a predefined trial visual pathway and on the same motor coordination control situations (darkness, no time-pressing). Participants' time performance and walk-through satisfaction were recorded and analyzed statistically. Walking physiology was shown to be more stable and robust (in path completion rates, time performance, and walk-through level of satisfaction) in virtual 3D environments rich in *flora* and *linearity*. The VR training functionality and the immersive learning performance enjoyed a 19% reduction in time performance and 102% more walk-through satisfaction, and their effectiveness and robustness were validated statistically. Children with motor skill difficulties train and learn better in virtual 3D environments rich in *flora* and *linearity*. Hence, immersive walk-through trials in digital environments rich in *flora* and *linearity*, as training interventions, could be regarded as a perceptual-motor therapy (PMT) as they seemed beneficial in improving DCD children's motor function.

Keywords: Developmental coordination disorder, motor skill disorder, perceptual-motor therapy, VR training and learning, spatial cognition, landmark coordination cues, environmental geometry, walk-through satisfaction, reality modeling, motor imagery.

1. Introduction

Today, despite the increasing use of technology in the clinical field, only a few studies have been found interested in the role of AR and gaming technology in improving DCD (developmental coordination disorder) treatment in children. Regardless of the literature is at a very early stage, some preliminary qualitative data can be recollected from the reviewed studies.

Results coming out from these studies, despite restrictions, barriers, and limitations, release a good potential for DCD treatment. Three out of these studies reported significant results in the outcome measures (Ashkenazi et al., 2013; Avila-Pesantez et al., 2018; EbrahimiSani et al., 2020). In addition to these studies, Federica Lino et al. (Lino et al., 2021) grounded their study approach on changing children's practices and customs involved in playing computer games. In these studies, to provide positive gains in motor control, they supposed that a change from non-active to active video game playing could provide an advantage in motor performance.

1.1. Virtual reality and developmental disabilities

Applications of immersive virtual reality in developmental disabilities therapy have been reported extensively last few years in the adult population (Liu et al., 2023a; Huang and Yang, 2022; Huang, 2020). However, there is limited research evidence on how young patients experienced VR (Liu et al., 2023b), though the bibliography for intellectual capacity and ability in children is extensive (Paredes et al., 2019).

Currently, there are still no systematic, nor comprehensive cognitive training virtual reality applications for patients suffering from behavioral or voice disorders that alter intellectual ability, spatial cognition, ADL (activities of daily living) functioning, motion functionality, and adaptive aspects (developmental coordination disorder, DCD; attention-deficit/hyperactivity disorder, ADHD; generalized anxiety disorder, GAD; learning disorder, LD; tuberous sclerosis complex, TSC; ASD; neurological development disorders, NDS; dysphonia; etc.).

Virtual reality has been shown to encourage repetition with low-cost virtual and controlled trial exercises allowing for faster motor skill development, ADL autonomy, and brain recovery (Montoya and González, 2022). One-to-one interaction and expensive equipment are necessary for traditional rehabilitation approaches to be effective, and several studies demonstrate their effectiveness (Perez-Trejos et al., 2022; Bernal et al., 2020; Calvache-Mora, 2020; Uribe, 2019). However, recent studies based on the augmentation of specific kinematic feedback (virtual exercise trials), show improvement in motor skill functionality (Hamari, 2019). Therefore, virtual therapy -i.e., VR-controlled trials with reinforced feedback in a virtual environment/RFVE (Liu et al., 2023a; Liu et al., 2023b) and gamification (Harami, 2019)- combined with traditional rehabilitation methods and techniques (Montoya and González, 2022; Perez-Trejos et al., 2022) promises better results in occupational therapy for disorders.

Furthermore, in occupational therapy curricula, there is a lack of reports and scientific knowledge for VR-based simulated learning contributions required in medical therapy (Bennett et al., 2017), though there is strong evidence of using VR in health professionals' education and training (Bracq et al., 2019).

Recent publications regarding occupational therapy evaluation (on usability, patient satisfaction, and exercise trial performance) show drawbacks and problems in therapy availability, real-time data access, a generic clinic environment, and delays in feedback reports (Lim et al., 2023; Rodrigues et al., 2020). These shortcomings could be addressed in immersive VR-based occupational therapy because therapy availability is increased while at the same time keeping the cost low, data and big data access in real-time or near real-time are provided, personalized clinic virtual environments are available, and training feedback is reported in real-time (Lim et al., 2023; Fan et al., 2023; Hwang and Shim, 2021; Rodrigues et al., 2020; Sosa and Franco, 2019).

Regarding training oriented to the accreditation of motor programming skills and mental rotation skills, VR enables children to manipulate 3D objects having immediate feedback on task success in a realistic context. This represents one of the most important advantages of VR technology in ecological terms (Cirulis et al., 2020; Wilson et al., 2016a; Wilson et al., 2016b).

1.2. Spatial cognition

The concept "*spatial cognition*" refers to a complex, multifaceted set of processes that are engaged in a large variety of tasks, including, for example, mental rotation, DCD orientation, birds' spatial navigation, spatial working memory, and cognitive mapping (Glöckner et al., 2021; Lee et al., 2020; Bowman and Liu, 2017; Cheng et al., 2013).

Spatial cognition with natural objects (e.g., trees, plants, man-made constructions, etc.) is often projected to avian navigation, and robot georeferencing applications (Basdekidou, 2022; Glöckner et al.; 2021; Cĩrulis et al., 2020; Wilmut and Barnett, 2017). Additionally, environmental geometry with landmark coordination cues (e.g., built-environment linearity) is usually projected to geo-referencing (Basdekidou, 2023; Lee et al., 2020; Wilmut and Barnett, 2017), walking coordination (Basdekidou, 2023; Ankowski et al., 2012), and walking physiology applications (Basdekidou, 2023; Bowman and Liu 2017; Cheng et al., 2013).

Hence, "*spatial cognition*" is an active research topic compatible with the previously discussed topic "*virtual reality and developmental disabilities*".

1.3. Perceptual-motor therapy for DCD children

Only a few studies applied VR to DCDs despite the good chances offered in the digital era. In this domain, Patricia McClurg and Christine Chaillé (1987) investigated how selected computer games utilizing spatial skills would improve their scores on a spatial ability measure and proved that 3D object manipulation would enhance the development of spatial ability and visuospatial skills. In the 90's Joan McComas et al. investigated the generalization effects of the improvement in visuospatial abilities gained through VR, shown to be related to activity in the environment, particularly to walking and other forms of locomotion, and confirming the generalization of the effects outside of the VR environment (McComas et al., 1998). The above-mentioned findings need to be further investigated especially with the influences from the built and natural environment, as well as regarding the extension of the generalization effect to more complex real-world daily tasks (Blank et al., 2019).

Peter Wilson et al. (Wilson et al., 2016b) highlighted that VR could have an impact on different dimensions considered by the International Classification of Functioning/ICF (World Health Organization, 2007). Such ICF dimensions include the level of impairment, activity performance, cognition skills, participation, environment, and personal factors (e.g., motivation or interests). Furthermore, Peter Wilson et al. in their study showed that an imagery protocol promotes motor skill acquisition as most children, in the intervention groups, improved their motor performance significantly (Wilson et al., 2016b).

Movement coordination in children with motor difficulties is an active research topic (Fan et al., 2023; Scott et al., 2021; Parr et al., 2020; Slowiński et al., 2019) and in this domain, the visual contribution to motor skill DCD disorders has attracted the attention of the scientific community recently (Liu et al., 2023a; Basdekidou, 2023; Wilmut et al., 2022). Additionally, motor skill learning and the therapeutic potentiality of DCD children in immersive VR-based controlled exercise trials have been reported recently (Grohs et al., 2020; Grohs et al., 2019). Finally, reports about the environmental influences on motor coordination in DCD children highlight the importance of spatial cognition in motor skill learning approaches (Pereira et al., 2021; Guardia et al., 2018).

Hence, "*motor image-based movement coordination*" in children with developmental coordination disorder, as a "*perceptual-motor therapy*", is an active research topic compatible with the previously discussed topics "*virtual reality and developmental disabilities*" and "*spatial cognition*" (Lee et al., 2020; Wilson et al., 2016a).

1.4. Concept

The proposed concept "*DCD - spatial cognition with flora and linearity as motor imagery*" combines the above three scientific popular topics and takes advantage of the conducted ongoing research per topic.

The concept is subject to trial virtual exercises and effectiveness evaluation (with *path completion rate*, *time performance*, and *walk-through level of satisfaction* as the three dependent evaluation variables) of controlled visual walk-throughs with two independent configuration and design parameters, the *trees and plants* (flora) as natural environment elements and the *spatial compound linear geometries* (linearity) as landmark coordination cues in built environments.

The following three research questions outline the proposed concept. *Do the elements of the natural environment and the geometry of the built environment affect the ability to move (stable and robust functionality) of children with motor difficulties and to what extent?* (Kinateder and Cooper, 2021; Lee et al., 2020). *Could the natural environment's elements and the built environment's landmark coordination cues be considered auxiliary geo-referencing, coordination, and navigation tools?* (Shegeva and Goel, 2021; Glöckner et al., 2021). *Do perceptual-motor therapy and increases in virtual reality performance translate into increases in actual gross motor performance, motor skill acquisition, gait walking physiology, physical activity, attitudes toward physical activity, self-confidence, and mental health?* (Wilson et al., 2016a; Slowiński et al., 2019; Bowman and Liu, 2017).

The first question is analyzed in this training study as the main research *objective* (the feasibility study's *hypothesis*) and the other two could be studied in future research.

1.5. Purpose and significance

The article's purpose is to explore the feasibility of using low-cost off-the-shelf hardware and software for motor imagery-based VR intervention tests, to treat DCD children and to determine the effect of these interventions on motor function, spatial cognition learning, and perceptual-motor therapy.

The main aim of this pilot study is to identify the correlation between and evaluate the visual contribution of *flora* (natural environment) and *linearity* (built environment) as spatial coordination cues in DCD children's motor/walking control and perceptual-motor therapy.

The particular significance of this study lies in the fact that low-cost equipment and off-the-shelf motor imagery protocols (with no specific requirements on *flora* and *linearity* modeling accuracy) can be used for DCD training interventions as *perceptual-motor therapy*.

1.6. Motivation and requirement analysis

The following problems were identified in clinical treatments: high costs due to frequent repetitions and safety measures, low participation satisfaction rate, a requirement for in-place treatment with time constraints, and low retention.

The proposed VR-based immersive and personalized walk-throughs, once incorporated into DCD clinical treatment (visual scenes rich in *flora* and *linearity*), reduce cost (flexibility in context creation and low-cost off-the-shelf h/w and s/w), eliminate risks, increase learning satisfaction (DCD children engagement and interactivity), can be conducted remotely in real-time and without time constraints, and offer better retention in training and spatial cognition by means of autonomous experimental learning through non-formal treatment.

Therefore, the training study we propose may prove effective in *perceptual-motor therapy* procedures to promote motor skill acquisition.

2. Methods and Procedures

Type of Study. We performed quantitative research without manipulation of the independent variable "3D digital environment setup" (non-experimental) of a cross-sectional type and with descriptive (*mean*, *std. dev*) and correlative (r, p) analysis (Du et al., 2023).

2.1. Participants

Selection – Sample size. Cluster sampling was used to select eight public elementary schools, with the same social-economic background from Thessaloniki's greater area (April 2022). The total sample size was determined with G*power statistical software, based on assuming an effect size of 0.4 and at least 80% power. A sample size of 63 participants was deemed to be adequate to examine the study hypothesis. Finally, we determined the sample size to be 80 children, regarding the possibility of some extreme individual variabilities (outliers).

Eligibility. DCD participants' inclusion criteria were age 5 to 8 years; current diagnoses of developmental coordination disorder by a registered health care provider; and right-handed (hand used for writing). Those with pre-term birth (<36 weeks' gestation) or any neuropsychiatric, neurological, and/or chronic disorders were excluded. Participants were screened to ensure they met the clinical criteria for developmental coordination disorder outlined in the diagnostic and statistical manual of mental disorders (DSM-5, 5th edition) (APA, 2022).

Ethical consent. The studies involving human/children participants were reviewed according to the *Declaration of Helsinki* and the doi: 10.1089/cyber.2019.0269. *Liverpool John Moores Ethics Committee*. All children assented to participate, and before the tests, parents or legal guardians gave their informed consent. The departmental review and research ethics board of the Landscape Architecture Department / University of Kavala Institute of Technology (City of Drama, Greece) approved this study (June 2020).

Enrollment - Intervention groups. During April 2022 eighty (80) child participants, aged 5 to 8 years, enrolled. Forty (40) participants with typical development (TD; 20 boys and 20 girls) were selected via social media and enrolled and another forty (40) with motor skill disorders (DCD; 20 boys and 20 girls) were recruited through developmental and community pediatricians, psychologists, and physical/occupational therapists. Since motor skill difficulties are commonly diagnosed in elementary schools in Europe, we decided 50% of the participants to be DCD children.

The 80 participants were grouped into five (5) non-parallel intervention team groups: 1st group with 20 TD boys; 2nd group with 20 TD girls; 3rd group with 20 DCD boys; 4th group with 20 DCD girls; and 5th group with 40 DCD boys and girls.

Place – VR/AR studios. The trial cases (VR walk-throughs) were carried out, between April 2022 and February 2023, at the premises of INVR virtual and augmented reality camp at the center of Thessaloniki, Greece.

2.2. Instruments

Head-mounted display equipment and training simulators. All participants performed the exercises with head-mounted display equipment in dark conditions (darkness) and without pressing time (i.e., no time anxiety). The head-mounted equipment was a piece of low-cost equipment -kindly offered by the INVR studios (Thessaloniki, Greece)- accompanied by VR training real-time simulators compatible with the CAD and reality modeling software (Figure 1).

Figure 1. The INVR studio – Head-mounted equipment & training simulators
Picture credit: The INVR virtual reality corporation (www.invr.gr)

CAD and reality modeling software. From the initial planning phase (July 2022) we decided to use, for the low-cost feasibility study, off-the-shelf software. Thus, the judgment for the software selection resulted in the selection of Google's SketchUp because it creates flat 3D geometries rich in *linearity* in a simple and low-cost way, while at the same time, there are many external libraries available with 3D *flora*. SketchUp was used as the basic CAD platform for the four virtual urban 3D environments (case setups).

In addition, for the virtual coordination tests, Bentley's LumenRT was selected as the basic visualization and reality modeling software because of its native MDL language support for customizing GUI with event-driven functionality (in this way we gain independence from a general Web platform and in addition, we can control the spatial cognition test with a completely controlled process). The LumenRT, built on NVIDIA Omniverse platform, was used as the reality modeling platform for the initial, main, and validation coordination tests. In addition, for the performance validation testing the Warp VR app, and Stanford's Strivr app were used as reality modeling platforms (software courtesy of the Department of Forest and Natural Environment Sciences/International Hellenic University, Greece) (Styliadis, 2007).

For virtual reality interoperability between the SketchUp and LumenRT platforms, the DXF interchange format was used (virtual-urban CAD environments → reality modeling) (Styliadis et al., 2003).

(GUI) dialog box (recording spatial cognition functionality in virtual coordination tests). We thought it was very important to develop our own GUI (head-mounted equipment's communication with the LumenRT software) adapted to the spatial cognition test. Thus, we would have absolute control and independence with minimal cost avoiding the purchase of any interface software. Therefore, between September 2021 and January 2022, we designed and developed a dialog box (Figure 2) in a way that the coordination test supervisor has absolute control of the function of this dialog and exclusive responsibility for the spatial cognition trial cases (see https://github.com/styl-florina/VR-spatial-cognition-learning for description, readme, and Wiki).

We decided to develop a dedicated GUI dialog box, instead of using a Web form, because that's how we succeeded GUI customizing into the selected reality modeling platform (Bentley's LumenRT built on NVIDIA's Omniverse), as well as event-driven functionality in real-time as a very important parameter in a spatial cognition test for developmental coordination disorder (e.g., "digital camera event" activation by hitting the button "2. Virtual Camera") (Figure 2).

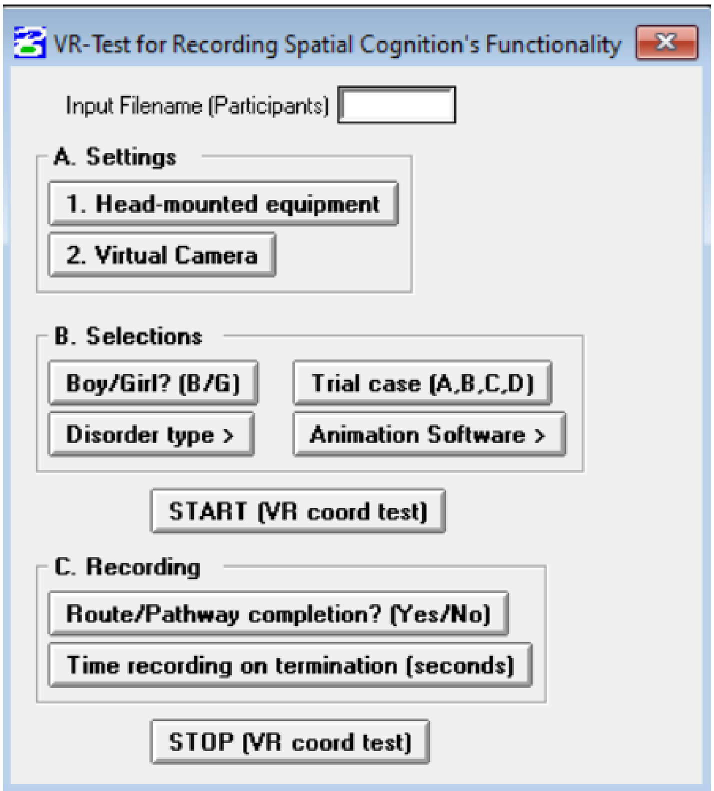

Figure 2. The dialog box for the virtual coordination test's recording spatial cognition functionality.

Additionally, we developed an MDL s/w routine to support the dialog box for a controlled head-mounted fly-through during the virtual trial exercises (coordination tests), route completion, and time performance recording. The implementation of the overall testing and evaluation environment based on the same programming language (MDL/native C++, the core LumenRT coding language) enhanced functionality with LumenRT and portability with the head-mounted display equipment (supported by NVIDIA Omniverse training simulators written in C++), as well as giving the overall study autonomy and maintenance confidence (see https://github.com/styl-florina/VR-spatial-cognition-learning for the MDL code files).

(GUI) dialog items. Head-mounted settings, camera settings, boy/girl, trial case (selection from four virtual-urban 3D environments), disorder type, animation software, START coordination test, route/pathway completion, time recording on termination, and STOP (Figure 2).

For the "*Virtual Camera*" dialog item we use a digital camera. In occupational therapy, with action-heavy content, video simulation requires recording footage in 4k UHD quality (2.160 p.), because with this resolution the playback looks smoother and more fluid. The higher resolution video looks better with higher frame rates because the higher frames/second the slower the "slow-motion" footage will be.

For instance, any frame rate >30 fps (i.e. more than 30 distinct still images will be shown in play-back per second) will be ideal for occupational therapy virtual exercises for disorders. The developed fly-through control GUI dialog (Figures 3, 5, and 6A) supports frame rates up to 70 fps (it is not possible for a normal human eye to perceive more than 60 fps). Ticks are the way CAD software views increment of time. There are 4.800 ticks in a second, so a digital camera can actually access time down to 1/4800th of a second. Given a standard, NTSC video frame rate, there are 30 frames in a second, and therefore 160 ticks in each frame. Therefore, for the proposed VR training and learning trial exercises and for a 60-fps rate, 80 ticks/frame were needed.

Hence, for the best motion blur that looks realistic, the following parameters of this digital camera were used in the VR trials: Shutter angle (FoV/Field-of-View): 62.4^o; Focal length (*f*): 35mm; Lens: Wide (option from telescopic to fish-eye); Camera's target position: Floating (option: fixed); video recording Speed: 80 time-ticks/frame; visual pathway's route-segmentation "Frames": 100; etc. (Figure 3).

(GUI) fly-through producer. For setting up a digital camera to function the visual navigation in four virtual-urban 3D environments, we developed the "*Fly Through Producer"* dialog box (Figure 3).

2.3. Study design

In this study, a single-blinded, quasi-experimental pre-post and follow-up design was determined, and all children were tested individually.

Procedure description

(i) Initial pilot coordination test: Eight children (four TD, and four DCD in one intervention group), one visualization and reality modeling software, one pathway, four (4) case setups, five (5) walk-through/participant/case-setup with 30-min break intervals between the case setups, one day per walk-through for the intervention group and all these four case setups (i.e., one week trial period).

The initial pilot coordination test led to topology adjustments regarding the visual pathway and the virtual-urban 3D environments.

(ii) Immersive walk-through trials: Eighty children, five non-parallel intervention groups (see "Intervention groups" in sub-section 2.1), one visualization and reality modeling software, one pathway, four (4) case setups, 25 walk-throughs/participant/case-setup with 30-min break intervals between the case setups, 2-hour for each intervention group/setup (about 4 min termination time and 20 children/group) and one day for each intervention group and walk-through for all the four setups (i.e., totally 1 week for all groups/walk-through, and 25 weeks trial period for the 25 walk-throughs). The tests for each intervention group were completed on the same day and they were always conducted on an individual basis per participant.

(iii) Robustness test - study's validation trials: Forty DCD children, one intervention group (20 DCD boys and 20 DCD girls), three (3) visualization and reality modeling software tested on the same day with 30-minute time intervals per software platform, six (6) pathways tested on one week with one pathway/day (with same trip length and walking physiology difficulty), one case setup (rich in *flora* and *linearity*), 10 walk-throughs/participant (i.e., 10 weeks trial period).

The visual pathway. A particular visual pathway from predefined position A to predefined position B has been designed (Figure 3). This pathway has been used in all four trial cases (named case setup A, B, C, and D) with a different walk-through visualization functionality per trial case (Figure 4).

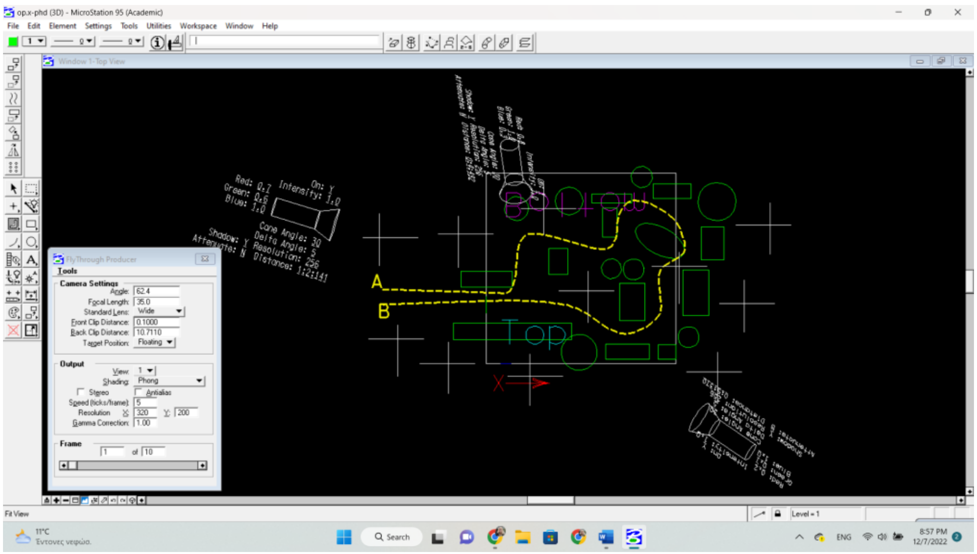

Figure 3. The visual pathway from position A to position B.

Four virtual-urban 3D environments. The visual exercises, as walk-throughs from position A to position B, took place in four (4) on-purpose-designed virtual-urban 3D digital environments (reality modeling case setups) developed in the selected CAD software platform. The basic design parameters for these four CAD environments were the *flora* (trees and plants) as the natural objects and the *linearity* (spatial compound linear geometries, i.e. shapes and mutually detect parallel or perpendicular line pairs in observed linear or rectangular image-geometries in built-environment) as the landmark coordination cue.

The first 3D digital environment case setup was designed without a significant presence of *trees* and *plants* and with simple residential structures without particular emphasis on *linearity*. The second case setup was modeled with a significant presence of *trees* and *plants* but with simple residential structures without particular emphasis on *linearity*. The third 3D digital environment was reconstructed without a significant presence of *trees* and *plants* but rich in residential structures with a particular emphasis on spatial compound *linearity* geometry. The fourth case setup was established with a significant presence of *trees* and *plants*, as well as a significant presence of residential structures with a strong presence of spatial compound *linearity* geometry (Glöckner et al., 2021; Bowman and Liu, 2017) (Figure 4).

Virtual coordination test. The virtual test aims to record mean performance per group in route completion rate (%); termination time performance (seconds); and walk-through level of satisfaction (for measuring satisfaction we used a 5-point Likert rating scale from 1 to 5: “1” no satisfied, “2” slightly satisfied, “3” satisfied, “4” very satisfied, and “5” extremely satisfied). The coordinated walking physiology for forward progression while maintaining body balance and limiting energy expenditure, was considered as the test’s basic principle.

3. Results

The VR-based motor coordination feasibility case study (initial pilot, main coordination test, and validation test) was performed at the VR/AR studios of INVR between April 2022 and February 2023. The 80 participants interacted in “reality modeling” while performing the A→B pathway in all four virtual-urban 3D environments. The article's authors recorded their performance in "time" on termination (seconds) using the dedicated dialog box presented in Figure 2.

DCD coordination test procedure

The test was administered on an individual basis with an intervention group completing the trial on the same day for all its members and for all 4 environments (case setups). Consequently, it took one week (5 working days) for the 5 intervention groups (see “Intervention groups” in sub-section 2.1).

Initially, at the beginning of the process, there was a uniform briefing of the group members on the equipment, the A→B path (color, striping), the navigation conditions (darkness), and the comfort of time. This was followed, on an individual per participant basis, by the integration and activation of the VR/AR head-mounted equipment ("1. Head-mounted equipment"), its interconnection through the built-on NVIDIA’s Omniverse LumenRT real-time training simulators with the digital camera ("2. Virtual Camera"), selection data (“Boy/Girl?”, “Trial case”, “Disorder type”, and “Animation s/w”), and the start of the test ("START") (Figure 2).

Immediately after completing a walk-through, individual performance data (“Route completion”, “Termination time”, Figure 2) and satisfaction levels were recorded. The test was repeated by the same participant, after a 30-minute break for the next virtual-urban 3D environment (“Trial case: A, B, C, D”, Figure 2). From the article’s authors, Mrs. Chrysanthi Basdekidou was the main process operator, while Mr. Athanasios Styliadis had the overall coordination and responsibility.

Chronological scheduling

Ethical consent approval:	June 2020
Concept definition-tasks scheduling:	March-April 2021
Hardware and software selection:	May 2021
MDL GUI programming and testing:	September 2021 – January 2022
Head-mounted equipment testing:	February 2022 – March 2022
Participants selection:	April 4th – April 22nd, 2022
Initial pilot coordination test:	April 25th – April 29th, 2022
VR coordination tests (INVR studios):	May 2nd, 2022 – November 30th, 2022
Study’s validation test:	December 1st, 2022 – Feb. 11th, 2023
Statistical analysis:	February 13th – February 28th, 2023

3.1. Spatial cognition test synthesis

Participants wore head-mounted displays and each trial case’s visual pathway starts from position A, finishes to position B, and lasts about 3 minutes. A yellow broken-line indicated a predetermined path to direct the participants from position A to position B, for children's facilitation (Figure 3), which meaning was explained to the children in advance. The pathway line has a curved form for cognitive stimulation.

In the virtual coordination tests, Prof. Athanasios Styliadis (President of the Landscape Architecture Department/IHU) supervised the procedure and the doctoral student Ms. Chrysanthi Basdekidou was the facilitator for the cases when a child completely lost his orientation or stopped the exercise out of frustration. In addition, there was a specialist child psychologist available (part-time employment). Walk-through trials, other than guiding participants, aim at recalling some daily familiar activities, activating emotions, memories, and stimulating cognitive functions (such as spatial orientation, perception, executive processes, etc.) for spatial cognition learning.

The participants were tested individually and each of the 5 groups completed the tests on the same day (i.e., intervention group 1 members tested on Monday for all four virtual-urban 3D environments with 30-minute intervals between the setups, group 2 members tested on Tuesdays, and so on).

As can be seen in Figures 5, 6A, 6B, 6C, and 6D, the participants saw the physical environment (with a variable degree of *flora*) and the specially designed geometric forms (with a variable degree of *linearity*) as trial cases for motor function testing.

For the main coordination test, from May 2022 to November 2022, all participants (five groups) performed twenty-five (25) walk-throughs in slightly different virtual-urban 3D environments, from position A to position B, to ensure the reliability of the statistical analysis (1-week time window for testing the five intervention groups per walk-through). Hence, five working days (1 week) were allocated to the five groups for testing all four case setups on the same day per group for each walk-through. Consequently, the main coordination test for all the immersive walk-throughs lasted 25 weeks.

Assessments were video recorded and blindly scored offline. In all trials, the pathway was the same (A→B) and the supervisor's task was to record in real-time, per participant, the completion or not of the route (binary value) and the time performance (seconds). Further, just after a trial case, walk-through level of satisfaction per participant (rating from 1 to 5) and route completion rate per group (%) as statistical analytics were recorded. The four virtual-urban 3D environments (trial cases), where the default pathway A→B was projected, are presented in Figure 4, the images/colors/layers outline design is displayed in Figure 5, the coordination test's screenshots are displayed in Figures 6A, 6B, 6C, and 6D, and the participants' locomotion in Figure 7.

. **Figure 4.** The four virtual-urban (trial) 3D environments
[Top-left] Case setup A': 3D environment without *flora* and poor in *linearity*;
[Top-right] Case setup B': 3D environment rich in *flora* but poor in *linearity*;
[Bottom-left] Case setup C': 3D environment poor in *flora* but rich in *linearity*;
[Bottom-right] Case setup D': 3D environment rich in *flora* and *linearity*.

The Virtual-urban 3D environments

The four 3D environments were implemented as trial cases with the following case setups:

Case setup A’: Participant children navigate virtually in a 3D environment without *flora* (trees, plants) and poor in *linearity* (spatial compound linear geometries) (Figure 4, top-left);

Case setup B’: Participant children navigate virtually in a 3D environment rich in *flora* (trees, plants) but poor in *linearity* (spatial compound linear geometries) (Figure 4, top-right);

Case setup C’: Participant children navigate virtually in a 3D environment poor in *flora* (trees, plants) but rich in *linearity* (spatial compound linear geometries) (Figure 4, bottom-left);

Case setup D’: Participant children navigate virtually in a 3D environment rich in *flora* (trees, plants) and *linearity* (spatial compound linear geometries) (Figure 4, bottom-right);

Virtual-urban 3D environment texturing

The texturing procedure for the four environments was based on a combination of raster images (flora), colors, and modeling layers. Hence, we are using (a) two 2D raster images for the palm tree and shade tree as the *flora*; (b) two colors (color 18 for the palm tree, and color 34 for the shade tree); and (c) six modeling levels for the essential design file segmentation.

Segmenting the 3D model in levels (modeling layers) adds design flexibility and functionality (Styliadis et al., 2003; Styliadis, 2007). Therefore, we committed level 1 for the visual pathway (broken-line style in yellow coloring), level 2 for the digital camera route-line (angle: 62.4°, *f*=35mm, floating target), level 10 for poor *linearity*, 20 for rich *flora*, 30 for poor *flora*, and 40 for rich *linearity*.

Based on the appropriate combinations (flora imagery, coloring, and layering), we achieved a flexible and functional development of the four trial case environments, as follows:

Case setup A’: levels 1 and 10 on (all the other levels display-off)

Case setup B’: levels 1, 20, and 10 on (all the other levels display-off)

Case setup C’: levels 1, 30, and 40 on (all the other levels display-off)

Case setup D’: levels 1, 20, and 40 on (all the other levels display-off)

Finally, the simple *palm* and *shade* 2D tree raster images (jpg) were attached to two, perpendicular to each other, rectangular 2D tree-frames and correlated to the segmentation levels and colors as follows: The *palm* tree image to levels 20 and 30 with color no. 18, and the *shade* tree image to levels 20 and 30 as well but with color no. 34 (Figure 5).

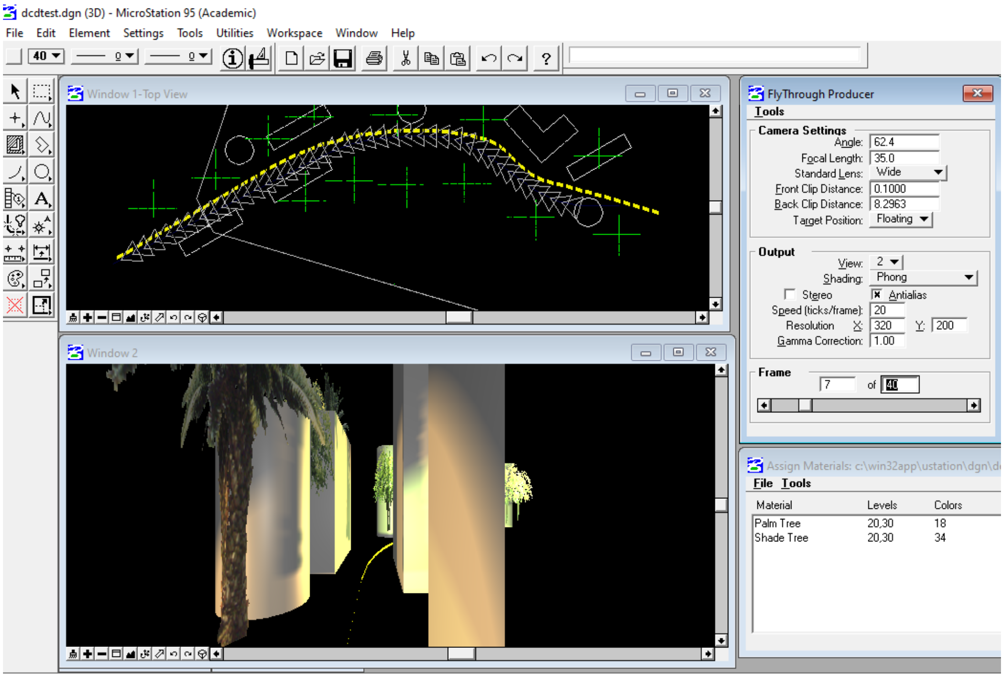

Figure 5. The flora raster images/colors/layers correlation.

Screenshots from walk-through trials

We performed the coordination test per participant on an individual base and in turn for all four 3D environments on the same day. Sample motor imagery screenshots are displayed in following Figures 6A, 6B, 6C, and 6D.

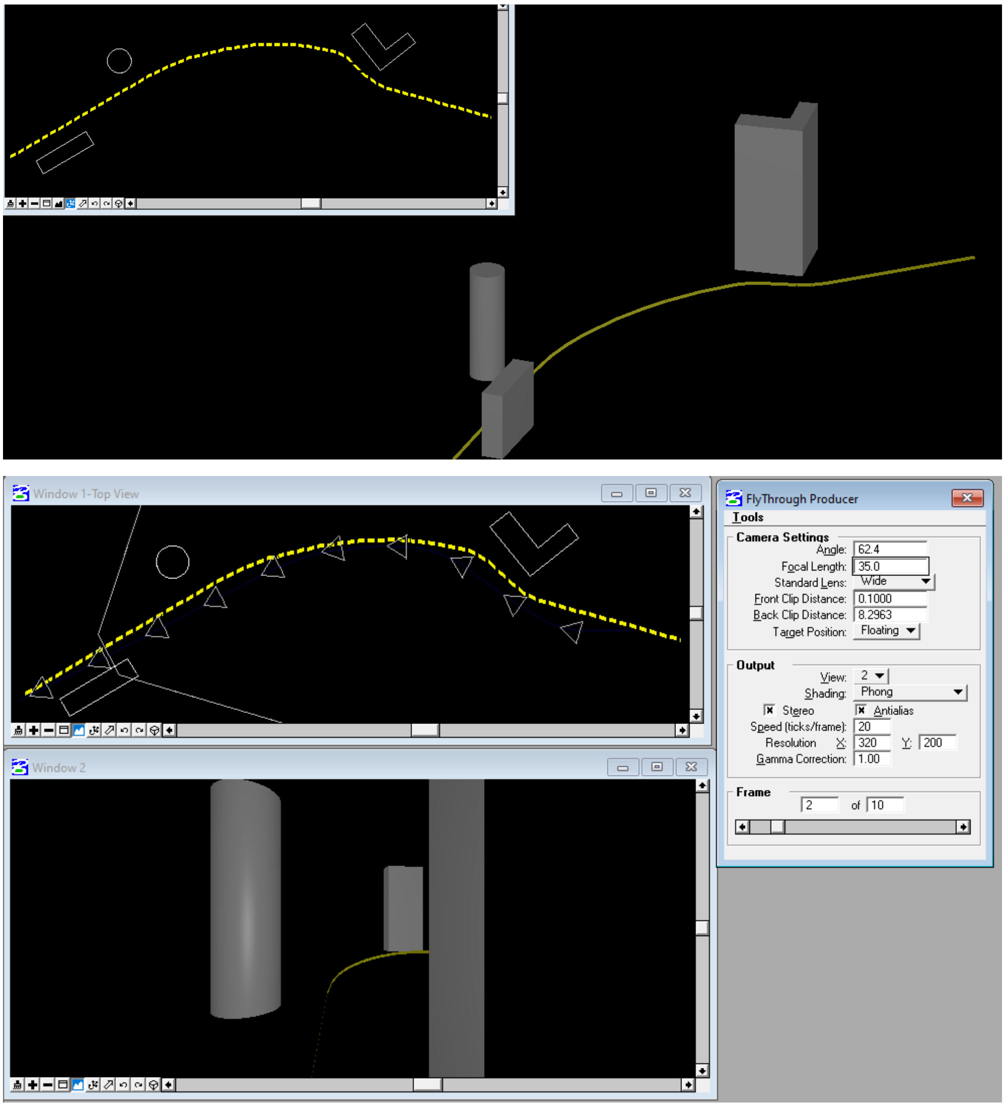

Figure 6A. Case setup A' – Motor imagery screenshots.

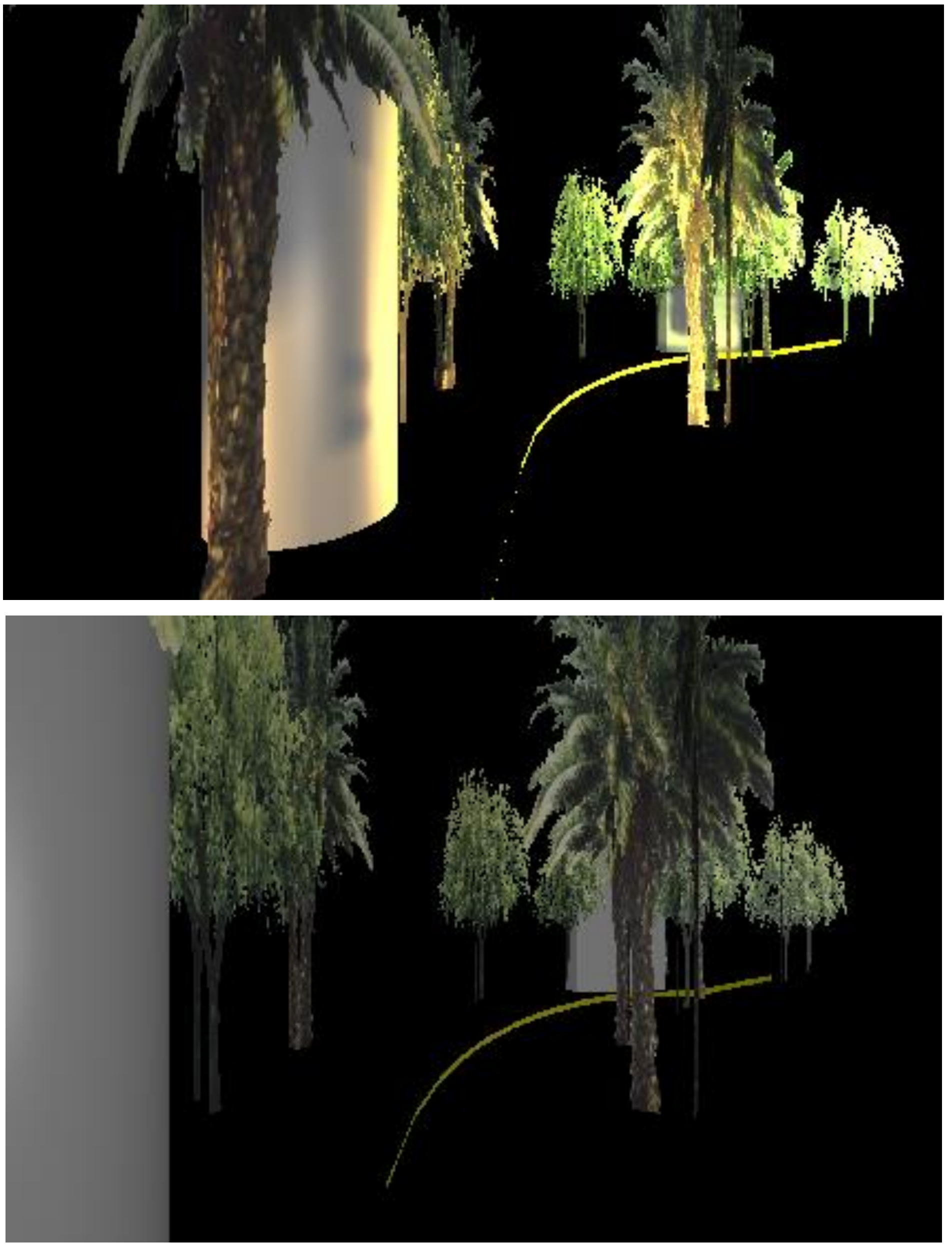

Figure 6B. Case setup B’ - Motor imagery screenshots.

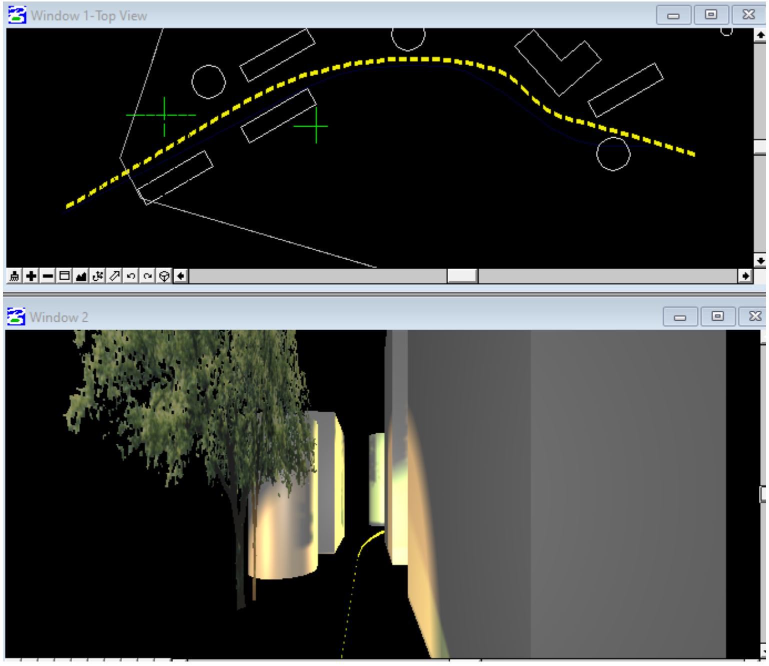

Figure 6C. Case setup C' - Motor imagery screenshots.

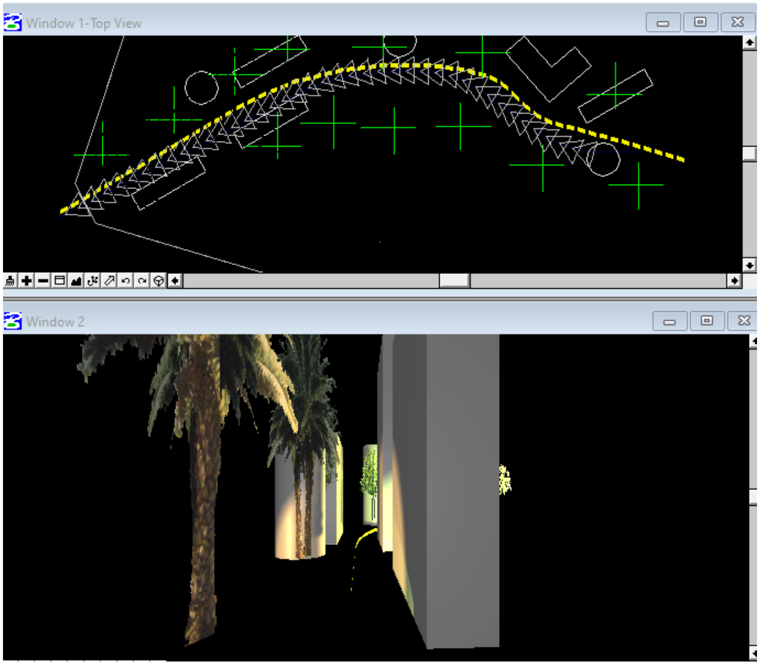

Figure 6D. Case setup D' - Motor imagery screenshots.

Locomotion

Finally, Figure 7 presents the participants' locomotion setup (draft drawing).

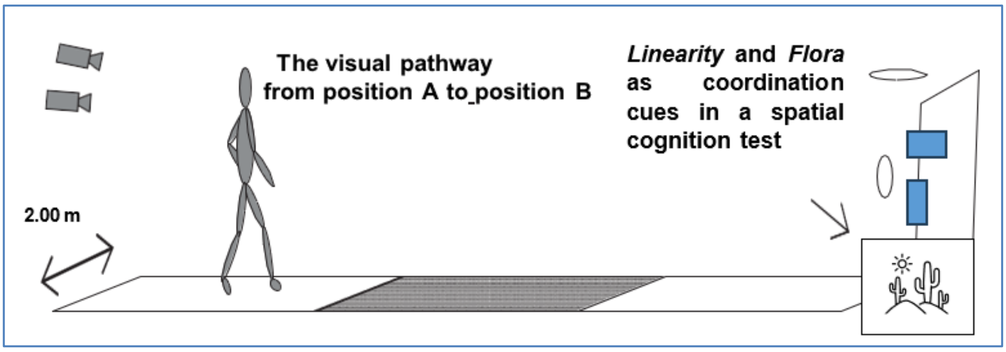

Figure 7. A view of the experimental participants' locomotion setup
Picture by courtesy@Ch. Basdekidou et al. (Article's authors)

3.2. Statistical analysis

The visual pathway from position A to position B and the four 3D digital environment setups were initially designed in SketchUp, and following they were textured and rendered in LumenRT/NVIDIA Omniverse software. During the main coordination test period (May-November 2022) and for every different 3D digital environment, a total of twenty-five (25) trial visual pathways (routes) from position A to position B were performed per group in slightly different each time *flora* and *linearity* topology. Statistical significance was set at $p<0.010$ and SPSS statistics ver. 29 software platform (IBM Inc., Chicago, IL, USA) was used for analysis.

All 80 participants were involved, and the primary analysis was intention-to-treat with three variables: path completion rate; route completion time (time performance); and walk-through satisfaction (Du et al., 2023). "*Path completion rate*" as a binary variable recorded a true/false value, "*time performance*" as a scale variable recorded route completion time in seconds, while the variable "*walk-through satisfaction*" rated scale questions and as a qualitative and ordinal one recorded the levels of participants satisfaction ("1" no satisfied; "2" slightly satisfied; "3" satisfied; "4" very satisfied; and "5" extremely satisfied).

"Time performance" and "walk-through satisfaction" per participant were the two variables in correlate/bivariate analysis by *means*, *std. deviation*, Pearson correlation (r), and sig. (2-tailed) (p). The following Tables 1-2 demonstrate the results.

Table 1. TC children: 20 boys and 20 girls

	TD Boys					TD Girls				
	Route compl. Rate (%)	Time (seconds) mean (*Std.*)	Satisfaction (1..5) Mean (*Std.)*	Time - Satisfaction *r*	*p*	Route compl. Rate (%)	Time (seconds) Mean (*Std.)*	Satisfaction (1..5) mean (*Std.)*	Time - Satisfaction *r*	*p*
Case A	100	168.70 (15.489)	1.30 (0.57124)	-.882*	<.001	100	177.60 (18.503)	1.35 (0.67082)	-.891*	<.001
Case B	100	144.30 (14.349)	2.30 (1.12858)	-.948*	<.001	100	148 (13.727)	2.10 (1.02084)	-.939*	<.001
Case C	100	137.40 (13.508)	3.00 (1.02598)	-.927*	<.001	100	142.55 (13.272	2.50 (1.05131)	-.956*	<.001
Case D	100	117.25 (12.798)	4.25 (0.63867)	-.916*	<.001	100	121.05 (13.300)	4.10 (0.71818)	-.932*	<.001

* Correlation is significant at the 0.010 level (2-tailed).

For both TC children groups (boys and girls) and for the four environment 3D modeling setups (cases A-D): the path completion rate recorded an absolute mean value of 100%; and in the relationship between the variables *time performance* and *walk-through satisfaction*, there was a strong negative correlation (*r*), particularly in B, C, and D case setups and a very significant statistical association (p<0.001) in all cases. Therefore, the lower the *time performance*, the greater the *walk-through satisfaction* in all case setups.

Table 2. DCD children: 20 boys and 20 girls

	DCD Boys					DCD Girls				
	Route compl. Rate (%)	Time (seconds) mean (*Std.*)	Satisfaction (1..5) Mean (*Std.)*	Time - Satisfaction *r*	*p*	Route compl. Rate (%)	Time (seconds) Mean (*Std.)*	Satisfaction (1..5) mean (*Std.)*	Time - Satisfaction *r*	*p*
Case A	74	188.70 (10.240)	1.10 (0.30779)	-.625*	<.003	71	200.40 (15.056)	1.00 (0.000)	.[a]	.
Case B	81	167.75 (14.549)	2.15 (1.13671)	-.921*	<.001	79	172.60 (14.005)	2..20 (1.12631)	-.934*	<.001
Case C	87	161.80 (14.652)	2.45 (1.31689)	-.980*	<.001	85	164.85 (13.933)	2.41 (1.30699)	-.957*	<.001
Case D	98	142.60 (12.546)	3.80 (0.89443)	-.922*	<.001	98	143.80 (12.038)	3.80 (0.89441)	-.945*	<.001

*. Correlation is significant at the 0.010 level (2-tailed).
[a]. Cannot be computed because at least one of the variables is constant.

For both DCD children groups (boys and girls) the path completion rate recorded mean values <100%, particularly in case setups A and B. It is noteworthy that the top-rated case D' favored the completion of the route (test) with the same path completion percentage (98%) for DCD boys and girls.

In the relationship between the variables *time performance* and *walk-through satisfaction*, there was a strong negative correlation (*r*), in B, C, and D case setups and a very significant statistical association ($p<0.001$) in all cases. Therefore, the lower the *time performance*, the greater the *walk-through satisfaction* in case setups B, C, and D.

In case of setup A, the lowest path completion rates were observed, and the relationship between the two variables was moderately negative for boys (-0.625) and undocumented in girls because the variable *walk-through satisfaction* had a fixed value “1” (no satisfied participant).

Mean (DCD boys and girls) data from Tables 1 and 2 were calculated in Table 3 to demonstrate the case setup D (a VR training and learning environment rich in *flora* and *linearity*) better VR training functionality and excellent immersive learning performance in spatial cognition tests for DCD children.

Table 3. Case D – VR training and learning environment for DCD children (mean data)

versus	**Case A setup**		**Case B setup**		**Case C setup**		**Mean setup**	
	Time performance	Walk-through satisfaction	Time performance	Walk-through satisfaction	Time performance	Walk-through satisfaction	Time performance	Walk-through Satisfaction
Case D time performance	+35.86%	----	+18.83%	----	+14.05%	----	+22.92% (i.e. **19% reduction**)	---
Case D walk-through satisfaction	----	+261.90%	----	+74.71%	----	+56.38%	---	**+101.59%**

Based on the results from Table 3, the superiority of case setup D is clearly seen with a 19% reduction in time performance and 102% more walk-through satisfaction (see the two rightmost columns in Table 3).

3.3. Validation

Three different visualization and "reality modeling" software platforms validated the baseline results for DCD children through a robustness test (Table 4). Aiming at the reliability of the verification, the validation test was projected on the same 3D digital environment reality modeling setup rich in *flora* and *linearity* and performed ten (10) times, in slightly different each time motor imagery topology, on six (6) different pathways (A→B paths) but with the same trip-length and with the same walking physiology difficulty.

The six different trial visual pathways were regarding different spatial cognition topologies from starting position A to terminating position B (Figure 3). The intervention group was crewed with 20 DCD boys and 20 DCD girls (i.e., sex-balanced staffing) and tested ten times with a 30-min time interval between software platforms (1-day time window per pathway with all children tested on the same day in all these three software platforms). The mean results of these six trial visual pathways (regarding path completion rate, time performance, and walk-through satisfaction) are displayed in Table 4.

Robustness validation test. The robustness check, for 40 DCD children (20 boys and 20 girls), was performed on a 3D digital environment rich in trees, plants, and spatial compound linear geometries (reality modeling case setup D). The VR training functionality and immersive learning performance (in spatial cognition testing for DCD motion control), as it has been projected to all these visualization and reality modeling software platforms, enjoyed very similar results in scale variable *path completion rate*, scale variable *time performance*, and in qualitative ordinal variable *walk-through (level of) satisfaction* (Table 4).

Table 4. The Robustness check (40 DCD children - case setup D)

n=40 DCD children VR training and learning walk-throughs on 6 different pathways but with fixed start (A) - finish (B) positions	**Path completion rate** (Mean % values of 10 trials on 6 different pathways)	**Time performance** (Mean values in seconds of 10 trials on 6 different pathways)	**Walk-through satisfaction** (Mean scale values “1” to “5” of 10 trials on 6 different pathways)
LumenRT software	97.6% (*std.* 4.7655)	143.20 (*std*. 12.356)	3.80 (*std.* 0.89440)
Warp VR app	98.2% (*std.* 4.7782)	143.56 (*std*. 12.382)	3.80 (*std.* 0.89442)
Strivr app	98.1% (*std.* 4.7490)	143.45 (*std*. 12.377)	3.80 (*std.* 0.89441)

Hence, the VR training functionality and the immersive learning performance have been validated statistically for case setup D and DCD children participants.

4. Discussion

The best performance (in path completion rate, time performance, and walk-through level of satisfaction) was detected in the 3D digital environment modeling setup (case setup D) rich in *flora* (trees and plants) as natural environment items, and *linearity* (spatial compound linear geometries) as landscape coordination cues in the built environment (Cheng et al., 2013).

The girls appear to perform slightly less (in terms of time performance and walk-through satisfaction) than boys, but in trial case setup D (environment rich in *flora* and *linearity*), such differences are nullified.

Effectiveness – Feasibility – Safety. This narrow margin in performances statistically confirms the robustness of the proposed method for perceptual-motor therapy, visual training, and learning rehabilitation of children with motor skill DCD disorders, using motor imagery for spatial cognition and *flora* and *linear geometries* as landmark coordination cues in controlled VR trials (Kinateder and Cooper, 2021).

The sustainable entrepreneurship growth dynamic (mean metrics) was estimated for the 5th group (40 DCD children) as a mean value of six trial visual pathways, indicating well the proposed method's sustainable walking physiology, growth functionality, and positive outlook.

Limitations. Several factors may limit the results of this training study. For example, it is important to acknowledge that the sample size (i.e., the 80 participants allocated in four groups) is relatively small, and the children's age range (5 to 8 years old) is relatively heterogeneous (Pereira et al., 2021; Bowman and Liu, 2017).

The sample size calculation estimated that 20 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 20 participants/group) was not large enough, and it may have decreased the ability to detect potential group differences or efficacy and may have limited in this way the requested generalizability of the findings. There was also a high degree of variability in performance on several measures, which may have decreased the ability to detect group differences given the small sample size (Lim et al., 2023; Uribe, 2019; Bennett et al., 2017).

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 five groups may reinforce a similarity in their experienced anxiety, given the wealth of research showing how anxiety can alter visual exploration during locomotor tasks. Regardless, future research would benefit from attempts to assess the effects of reduced vision on spatial orientation (Kinateder and Cooper, 2021) and objectively capture physiological state-anxiety responses to complement additional measures of self-report. It is important for future research to experimentally manipulate anxiety to fully explore its role in motor skill disorder (Basdekidou, 2023; Ankowski et al., 2012).

Another limitation was the slightly demanding nature of the trial, which required children to maintain their attention and motivation over a relatively wide time of 2 to 4 minutes. 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 (Parr et al., 2020; Grohs et al., 2020).

Open research issues. Open research cases could be considered in in-depth research and documentation for the differences between DCD boys and girls, in visual walking trials, regarding 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 (Glöckner et al., 2021; Hwang and Shim, 2021).

Further studies in geometric intelligence would explore the role of symmetry as a spatial cognition cue (Shegeva and Goel, 2021) and future research would investigate eye visual information and memory retrieval processes (Stüber et al., 2021) and whether increases in VR performance translate to increases in real-world gross motor performance, walking physiology, physical activity, attitudes to physical activity, self-confidence, and mental health (Gudoniene and Rutkauskiene, 2019; Slowiński et al., 2019; Guardia et al., 2018).

Furthermore, future research should extrapolate the paper's findings to DCD children of all ages (over the 5-to-8-year time window) (Huang and Yang, 2022; Huang, 2020) and to children with a diagnosis of attention-deficit/hyperactivity disorder (ADHD), learning disorder (LD), or generalized anxiety disorder (GAD) given the high co-occurrence with motor skill DCD disorders (Cīrulis et al., 2020; Marshall et al., 2020; Bernal et al., 2020; Grohs et al., 2019).

This work encourages future trials to consider environmental landmarks (i.e., cues like "symmetry", "orthogonality", etc.) as a possible target for motor imagery-based VR/AR interventions in improving DCD children's spatial cognition for perceptual-motor therapy.

Future research questions:

- Could the natural environment's elements and built environment's landmark coordination cues be considered auxiliary geo-referencing, coordination, and navigation tools?
- Increases in VR performance translate to increases in real-world gross motor performance, walking physiology, physical activity, attitudes to physical activity, self-confidence, and mental health?

Applications and implications. Potential perceptual-motor therapy initiatives should include the development of flexible and parametric 3D digital VR environments, with a variety of natural elements, built geometries, and landmark spatio-temporal coordination clues, as the necessary background for motor imagery-based VR training and learning motor skill trials (Basdekidou, 2023; Wilmut et al., 2022; Basdekidou, 2022; Scott et al., 2021).

In this paper, we presented user-friendly interactive tests, GUIs, and VR/AR/MR visual exercises that could constitute the frame for perceptual-motor therapy (motor skill acquisition, human spatial cognition, movement improvement), and children's motor control and coordination refinement (Guardia et al., 2018; Wilmut and Barnett, 2017; Wilson et al., 2016a).

5. Conclusions

The following question defined the research objective scope in this work: "*Do the elements of the natural environment and the geometry of the built environment affect the ability to move (stable and robust functionality) of children with motor difficulties, and to what extent?*" Particularly, this study aimed to identify the correlation between and evaluate the visual contribution in VR training and learning of immersive walk-through trials and DCD children's motor/walking control. Hence, the main target was to determine whether the trial use of new high-fidelity active VR modeling setups as motor imagery protocol can enhance motor coordination in children with motor impairment.

The present feasibility study suggests that VR and AR-based walk-through interventions could have some beneficial effects on perceptual-motor therapy by improving motor function and spatial cognition.

The paper's novel finding showed that VR training and spatial cognition learning with immersive walk-through trials in virtual-urban 3D environments rich in *linearity* and *flora* might help improve and consolidate motor skill control in DCD children. Therefore, we had to inform parents and trainers to focus on using motor imagery-based VR training interventions to improve motor skills and spatial cognition in perceptual-motor therapy courses, as well as general daily living task-related skills.

Perceptual-motor therapy with walking physiology immersive VR training and learning -compared to typical clinic rehabilitation procedures- reduces costs, eliminates risk, and offers freedom and flexibility in content creation and functionality in walk-through virtual trials.

With the present paper and with the implementation of imagery-based interventions, we prove statistically and empirically that VR training functionality and immersive learning performance in 3D environment modeling setups rich in trees and plants (*flora*), and linear geometric structures (*linearity*) enjoyed a 19% reduction in time performance and 102% more walk-through satisfaction compared to other virtual setups poor in *flora* and *linearity*. Hence, the visual trials revealed that DCD children were significantly affected by the absence of visual cues like *flora* and the spatial compound *linear* geometries, leading subconsciously to a not safe and slower walking physiology strategy.

Highlights

- People learn better by doing. Motor imagery-based immersive VR training is a safe and engaging way to build DCD children's skills and confidence. It reduces costs, eliminates risk, and offers freedom and flexibility in content creation — without geographic or scheduling limitations.
- VR training means more engagement and interactivity compared to instructor-led training.
- Perceptual-motor therapy has by default better retention of training and learning procedures compared to physical motion control rehabilitation.
- DCD children show more sensory processing issues than typically developing children.
- Perceptual-motor therapy promotes motor skill acquisition and reduces training time compared to clinic training.
- Imagery-based interventions increase the level of satisfaction compared to clinic training.

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Abbreviations

ADL: activities of daily living
AR: augmented reality
ADHD: attention deficit / hyperactivity disorder
CAD: computer-aided design
DCD: developmental coordination disorder
GAD: generalized anxiety disorder
GUI: graphical user interface
(I)VR: (immersive) virtual reality
LD: learning disorder
MDL: MicroStation Development Language (native C++)
MR: mixed reality
PMT: perceptual-motor therapy
(P)OT: (pediatric) occupational therapy
RFVE: reinforced feedback in virtual environment
SPD: sensory processing difficulties
TD: children with typical development
TR: traditional rehabilitation
WPO: walking physiology observation

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