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Effects of Eye–Hand Coordination Training in Immersive Virtual Reality Environments on Reaction Time and Tactical Effectiveness in Male Youth Handball Players: A Randomized Controlled Trial

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Abstract

Perceptual-cognitive skills and rapid visuomotor responses are key determinants of performance in handball. Immersive virtual reality (IVR) has emerged as a promising tool for enhancing these abilities in sport. The aim of this parallel-group randomized controlled trial (RCT) was to evaluate the effects of an IVR-based hand–eye coordination training program on reaction time, cognitive processing speed, and tactical effectiveness in male youth handball players. A total of 24 players aged 12–15 years volunteered to participate and completed the study. Participants were randomly assigned to either an experimental group (n = 12), which completed an 8-week IVR hand–eye coordination training program using the Rezzil Player exergame, or a control group (n = 12), which continued its regular handball training. Visual and auditory reaction times, cognitive processing speed assessed using the Symbol Digit Modalities Test (SDMT), and the Tactical Effectiveness Index (TEI) were evaluated. The findings revealed significant between-group differences in auditory reaction time ($F_{(1,22)}$ = 9.26; p = 0.005) and visual reaction time ($F_{(1,22)}$ = 4.25; p = 0.049), with the experimental group demonstrating faster responses than the control group following the intervention. Improvements in tactical effectiveness and SDMT performance were also observed in the experimental group; however, these differences did not reach statistical significance (p > 0.05). In conclusion, the IVR-based hand–eye coordination training program positively influenced reaction time and tactical effectiveness in youth handball players, supporting the potential application of immersive technologies in talent development and performance enhancement.

Trial registration: NCT07655999

1 Introduction

Successful performance in handball depends on the continuous interaction between perceptual, cognitive, and motor processes. Players are required to detect relevant environmental cues, process information under severe spatial and temporal constraints, and execute appropriate motor responses within fractions of a second. These demands emerge from the dynamic nature of the game, where the behavior of teammates and opponents continuously shapes the decision-making process (Davids et al. 2005). Consequently, the ability to efficiently perceive, integrate, and act upon environmental information is considered a key determinant of performance in handball. Effective perceptual processing facilitates technical-tactical decision-making and supports the execution of adaptive motor behaviors in complex and rapidly changing game situations (Magnaguagno and Hossner 2020; Kim et al. 2026). Recent evidence further suggests that success in youth sports depends not only on the development of physical capacities but also on efficient multisensory information processing and the ability to generate rapid visuomotor responses adapted to contextual demands (Boncuț et al. 2026).

Beyond response speed alone, the ability to select and execute the most appropriate action according to game demands is a key determinant of handball performance. In this context, tactical effectiveness can be defined as a player's ability to make accurate decisions and execute effective technical-tactical actions in continuously changing situations involving cooperation and opposition (Wagner et al. 2014).

Perceptual processes and decision-making are closely linked to tactical behavior (Davids et al. 2005), as the accurate interpretation of environmental cues enables players to anticipate actions, identify opportunities, and adapt their responses to situational demands. This relationship is particularly important during youth development, where tactical intelligence and efficient problem-solving are central objectives of the learning process and important contributors to long-term athletic development.

Among the variables reflecting the efficiency of these perceptual-cognitive processes, reaction time is considered a key indicator of how quickly an athlete detects, processes, and responds to environmental stimuli. Reaction time plays a critical role in sports performance and is influenced by both innate characteristics and sport-specific training (Bernárdez-Vilaboa et al. 2026). It is defined as the interval between the presentation of a stimulus and the initiation of the corresponding motor response (Bourara et al. 2023). Consequently, the assessment of reaction time is of considerable interest in sport, given its close association with the speed and effectiveness of competitive responses. Several testing protocols have been developed for this purpose; however, many lack ecological validity and fail to adequately reflect the specific demands of individual sports (Janicijevic and Garcia-Ramos 2022; Lynall et al. 2021).

Because reaction time can be improved through training, a variety of interventions have been proposed to enhance perceptual processing, decision-making, and response speed (Vickers 2007; Antúnez Medina et al. 2004). These approaches include eye–hand coordination exercises, anticipation tasks, and activities designed to accelerate cognitive processing. The effectiveness of reaction-time and decision-making training depends on the interaction among three primary factors: individual athlete characteristics, task demands, and environmental conditions (Araújo D et al. 2019). Consequently, in team sports characterized by dynamic and unpredictable situations, the development of decision-making and technical-tactical skills is essential for promoting comprehensive and individualized athlete development (González-Víllora et al. 2015).

Eye–hand coordination is particularly important in handball because it underlies fundamental actions such as catching, passing, intercepting, and shooting. Its development requires efficient integration of visual information and motor responses, contributing to both movement accuracy and adaptation to rapidly changing game demands. Therefore, training programs targeting eye–hand coordination may improve reaction time while also enhancing the effectiveness of tactical actions.

Traditionally, these abilities have been trained through reaction-based drills, light systems, and other analog training devices. However, recent technological advances have enabled the development of immersive virtual reality (IVR) environments capable of reproducing sport-specific scenarios with a high degree of experimental control and perceptual realism. These platforms allow precise manipulation of environmental constraints while preserving the perception–action couplings that characterize handball performance, potentially increasing the transfer of training adaptations to real-game situations (Magnaguagno and Hossner 2020; Bernárdez-Vilaboa et al. 2026).

In recent years, IVR has emerged as a promising tool for sports training because of its ability to provide highly interactive, multisensory, and contextually relevant experiences. Previous studies have reported

positive effects on sports performance, skill acquisition, and functional rehabilitation across a variety of sports, including ball sports and combat sports (Shahrbanian et al. 2012; Rolf and Holmqvist 2023; Rusmanto et al. 2023; Sha'lan 2023). Likewise, the growing popularity of exergames has highlighted the potential of these technologies to increase motivation, training adherence, and physical activity participation among young athletes (Rodríguez-Fuentes et al. 2024).

Despite these promising findings, evidence regarding the effects of immersive virtual reality–based training programs on perceptual-cognitive and tactical effectiveness variables in youth handball players remains limited. Therefore, the aim of the present study was to design and implement an immersive virtual reality–based eye–hand coordination training program and evaluate its effects on reaction time and tactical effectiveness in male youth handball players.

2 Materials and methods

2.1 Study Design

A parallel-group randomized controlled trial (RCT) was conducted to evaluate the effects of an 8-week eye–hand coordination training program performed in IVR environments using the exergame Rezzil Player on reaction time and tactical effectiveness in youth handball players. The primary outcome measures included visual reaction time, auditory reaction time, cognitive processing speed, and tactical effectiveness. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki (World Medical Association 2013). Ethical approval was obtained from the local ethics committee of the University of Vigo (CP-220126-14), and the trial was prospectively registered at ClinicalTrials.gov (Identifier: NCT07655999).

2.2 Participants

A total of 31 male adolescent handball players from local clubs were initially assessed for eligibility (age: 13.42 ± 1.20 years), with a mean handball playing experience of 3.84 ± 2.79 years. Following the application of the eligibility criteria, 26 players met the inclusion criteria and were enrolled in the study. Subsequently, two players declined participation, resulting in a final sample of 24 participants (Table 1; Fig. 1).

The inclusion criteria were: (1) being between 12 and 15 years of age; (2) being a male handball player; (3) having at least one year of handball experience; and (4) not participating in any other organized competitive sport. Exclusion criteria included diagnosed neurological disorders, fear of or intolerance to the use of virtual reality head-mounted displays, and diagnosed musculoskeletal disorders or injuries.

Participants were randomly assigned in a 1:1 ratio to either an experimental group (n = 12) or a control group (n = 12). The randomization sequence was generated before the start of the trial using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA). Stratified randomization was performed according to players' playing positions and team affiliation to ensure balanced group allocation.

Table 1
Descriptive characteristics of the study sample

Variable	Total Sample (n = 24) Mean ± SD / %	Experimental Group (n = 12) Mean ± SD / %	Control Group (n = 12) Mean ± SD / %
Age (years)	13.04 ± 1.04	12.67 ± 0.78	13.42 ± 1.16
Handball experience (years)	3.00 ± 1.91	2.92 ± 1.78	3.08 ± 2.11
Playing position			
Goalkeeper	12.5%	16.7%	8.3%
Wing player	41.7%	41.7%	41.7%
Backcourt player	29.2%	25.0%	33.3%
Line player	16.7%	16.7%	16.7%
Handedness			
Right-handed	95.8%	100.0%	91.7%
Left-handed	4.2%	0.0%	8.3%
Note: SD = standard deviation.			

Prior to study commencement, participants and their parents or legal guardians received detailed information regarding the study objectives, procedures, potential risks, and expected benefits. Written informed consent was obtained from all parents or legal guardians before participation, and assent was obtained from all participants.

2.3 Procedures

Before the start of the study, participants and their parents or legal guardians received detailed information regarding the study objectives, procedures, potential risks, and expected benefits. Written informed consent was obtained from all parents or legal guardians, and assent was obtained from all participants prior to participation.

The intervention lasted 8 weeks. Reaction time to auditory and visual stimuli was assessed using the Fast Reflex smartphone application, whereas cognitive processing speed was evaluated using the Symbol Digit Modalities Test (SDMT). Assessments were conducted at two time points: before the intervention (Week 0) to establish baseline values and after completion of the intervention (Week 9) to determine potential changes in the study outcomes.

Participants were randomly assigned to one of two study groups: an experimental group, which participated in an immersive virtual reality-based eye–hand coordination training program, and a control

group, which continued their regular handball training activities without exposure to IVR during the intervention period. The experimental group completed two training sessions per week throughout the 8-week intervention, following a progressive increase in the complexity of the visual stimuli presented. Attendance and adherence to the intervention were monitored using standardized training records.

In addition to the experimental assessments, competition performance data were collected before and after the intervention. For field players, shooting effectiveness was calculated as the percentage of goals scored relative to the total number of shots attempted. For goalkeepers, save percentage was calculated as the ratio of successful saves to total shots faced. To enhance the comparability of performance outcomes, the matches selected for analysis were played either against the same opponent or against teams of a similar competitive level.

2.4 Intervention

The experimental group completed an eye–hand coordination training program delivered through IVR. Training sessions were conducted using the exergame *Rezzil Player: MicroWall* in combination with a Meta Quest 2 virtual reality headset and two handheld controllers (Meta Platforms, Menlo Park, CA, USA). The intervention consisted of one familiarization session with the VR equipment using the *First Steps* application, followed by 13 training sessions using *Rezzil Player: MicroWall*. This software has previously been used by our research group to assess response times in individuals with neurological disorders (Campo-Prieto et al. 2022).

The training task required participants to identify a red visual stimulus appearing randomly on a virtual panel and touch it as quickly as possible using the handheld controllers. Performance was quantified based on the total number of targets successfully reached within a predetermined trial duration (1 min) and the response speed achieved by each participant.

The intervention comprised a total of 14 sessions distributed over an 8-week period. During Week 1, participants completed the familiarization session (*First Steps*) and one training session using the 3 × 3 panel configuration. During Week 2, two training sessions were performed using the 3 × 3 panel. In Week 3, participants completed two sessions using the 60° panel. During Week 4, one session was conducted with the 60° panel and one with the 180° panel. In Week 5, two sessions were performed using the 180° panel. During Week 6, participants completed two sessions using the 360° panel. Finally, one session was performed with the 60° panel during Week 7 and one session with the 3 × 3 panel during Week 8 (Figs. 2 and 3).

The control group did not participate in any immersive virtual reality–based activities throughout the intervention period.

In parallel, both the experimental and control groups continued to participate in their regular handball training sessions prescribed by their club. Training schedules and content were identical for both groups throughout the intervention period.

2.5 Testing procedures

Participants were assessed at two time points: before the intervention (baseline) and immediately after completion of the eye–hand coordination training program (post-intervention). The order of test administration was identical across both assessment sessions, and all evaluations were conducted by the same examiner, who was experienced in the administration of physical performance and cognitive assessments.

In addition to the primary outcome measures, variables related to the feasibility and user experience of the IVR intervention were evaluated. The safety and tolerability of the intervention were assessed using the *Simulator Sickness Questionnaire* (SSQ) (Campo-Prieto et al. 2022), whereas participants' subjective experience with the virtual reality system was evaluated using the *Game Experience Questionnaire – Post-Game Module* (GEQ) (IJsselsteijn et al. 2013).

The primary outcome measures were visual reaction time, auditory reaction time, cognitive processing speed, and the tactical effectiveness index (TEI). Reaction time was assessed using the *Fast Reflex* smartphone application (Kubas 2018), employing both visual and auditory response modalities. In the visual reaction time test, participants were instructed to touch the screen as quickly as possible when it changed color from red to green. In the auditory reaction time test, participants were required to respond in the same manner upon hearing an auditory signal emitted by the device. In both tests, response times were automatically recorded by the application and expressed in milliseconds. Prior to testing, participants completed three familiarization trials, after which the subsequent three trials were recorded for analysis. Cognitive processing speed was assessed using the *Symbol Digit Modalities Test* (SDMT) (Arango-Lasprilla et al. 2017). This test requires participants to match a series of symbols with corresponding numbers as quickly and accurately as possible according to a predefined key. The final score was determined by the total number of correct responses recorded within a 90-second period, while the number of errors committed during task performance was also documented. Finally, tactical effectiveness was assessed using a TEI derived from official competition statistics. The index incorporated both positive actions (goals scored, shooting percentage, 7-m throws earned, ball recoveries, defensive blocks, saves, and save percentage) and negative actions (7-m throws conceded, turnovers, 2-min suspensions, and disciplinary sanctions). All variables were standardized using *z*-scores ($z = [x - \mu]/\sigma$). For negative performance indicators, *z*-scores were multiplied by − 1 so that higher values consistently reflected greater tactical effectiveness. Standardized scores were then summed to obtain a raw score: Raw TEI = Σ(*z* positive indicators) + Σ(− *z* negative indicators). To facilitate interpretation and comparison among players, the raw score was subsequently transformed to a 0–100 scale using min–max normalization: TEI **=** [(Raw TEI − TEImin)/(TEImax − TEImin)] × 100, where *TEImin* and *TEImax* represent the minimum and maximum values observed in the sample, respectively. Accordingly, a score of 0 represents the lowest tactical effectiveness recorded in the sample, whereas a score of 100 represents the highest observed tactical effectiveness.

2.6 Statistical analysis

A descriptive analysis was performed for all study variables. Continuous variables were summarized using measures of central tendency and dispersion (mean ± standard deviation), as well as minimum and maximum values. Categorical variables were expressed as frequencies and percentages. Descriptive analyses were stratified according to study group (experimental or control).

To evaluate the effects of an IVR exergame-based reaction time training program on auditory and visual reaction time, information processing speed, and tactical effectiveness, both descriptive and inferential analyses were conducted considering the two assessment time points (pre-intervention and post-intervention) and the study groups.

Prior to the intervention, baseline equivalence between the experimental and control groups was assessed using independent-samples *t*-tests to verify the homogeneity of the groups for all outcome variables. Subsequently, within-group changes between pre- and post-intervention assessments were examined using paired-samples *t*-tests, allowing the identification of changes associated with the intervention in the experimental group and with the placebo program in the control group.

Finally, a 2×2 multivariate analysis of variance (MANOVA) was performed, considering Time (pre-intervention vs. post-intervention) as the within-subject factor and Group (experimental vs. control) as the between-subject factor. This analysis was conducted to determine the interaction effect between group and time, thereby assessing the effectiveness of the intervention relative to the control condition.

All statistical analyses were performed using IBM SPSS Statistics (Version 25.0; IBM Corp., Armonk, NY, USA). Statistical significance was established at $p < 0.05$.

3 Results

The results related to the intrinsic aspects of the IVR program, specifically user safety, assessed using the Simulator Sickness Questionnaire (SSQ), and participants' perceived experience, evaluated through the Game Experience Questionnaire (GEQ-post game) following the use of a Head-Mounted Display (HMD), are presented in Tables 2 and 3.

Table 2
Distribution of responses and dimension scores for the Simulator Sickness Questionnaire (SSQ)

Dimension	Not at all	Slightly	Moderately	Severely	SSQ Score (0–3)
Nausea	100.00%	0.00%	0.00%	0.00%	0.00
Oculomotor	96.70%	3.30%	0.00%	0.00%	1.75
Disorientation	97.80%	2.20%	0.00%	0.00%	2.14
Total Severity	98.16%	1.84%	0.00%	0.00%	1.44

The Simulator Sickness Questionnaire (SSQ) results indicated a very low incidence of symptoms associated with virtual reality (VR) use during the intervention. Across all assessed dimensions, most responses were classified as *"Not at all"*, with percentages ranging from 96.7% to 100%. No participant reported symptoms of nausea, resulting in a score of 0.00 for this dimension. In the oculomotor dimension, 96.7% of responses indicated the absence of symptoms, while only 3.3% reflected mild symptoms. Similarly, in the disorientation dimension, 97.8% of responses corresponded to the absence of symptoms and 2.2% to mild symptoms. The overall severity score was very low (1.44), with 98.16% of responses indicating no symptoms and only 1.84% reporting mild discomfort. No moderate or severe symptoms were reported in any of the assessed dimensions. Overall, these findings suggest that the program was associated with a very low incidence of VR-related adverse symptoms during the intervention. The intervention did not induce clinically relevant levels of cybersickness or simulator-related discomfort, supporting its usability, tolerability, and safety for participants.

Table 3
Distribution of responses grouped by dimensions of the Post-Game Module of the Game Experience Questionnaire (GEQ)

Dimension	Not at all	Slightly	Moderately	Quite a bit	Score (0–3)
Positive Experience	13.76%	16.92%	38.28%	18.46%	1.61
Negative Experience	100.00%	0.00%	0.00%	0.00%	0.00
Tiredness/Fatigue	53.40%	23.08%	15.38%	7.69%	0.77
Returning to Reality	76.92%	23.08%	0.00%	0.00%	0.23

The results of the GEQ Post-Game module showed a predominantly positive experience following the intervention. In the Positive Experience dimension, responses were mainly concentrated in the categories "moderately" (38.28%) and "quite a bit" (18.46%), obtaining the highest score (1.61). Conversely, the Negative Experience dimension showed a complete absence of adverse responses (100% in the "none" category; score = 0.00). Furthermore, more than half of the participants reported no feelings of tiredness or exhaustion (53.40%), while 76.92% indicated no difficulty returning to reality after the virtual experience. These dimensions obtained low scores (0.77 and 0.23, respectively), suggesting a well-tolerated experience with minimal impact after exposure to virtual reality.

Tables 4 and 5 present the results obtained following the intervention. Table 4 shows the training variables analyzed according to task modality (3×3, 60°, 180°, and 360°), difficulty level, and assessment time point. For the Total Hits variable, performance improved across all training modalities following the intervention, although the magnitude of improvement varied according to task difficulty. The largest increase was observed in the 3×3 condition (+ 32.67%), followed by 60° (+ 11.13%), whereas only marginal gains were recorded in the 180° (+ 3.02%) and 360° (+ 0.38%) conditions. These findings suggest that the intervention exerted a greater effect on tasks characterized by lower spatial complexity.

Regarding right-hand reaction time (RMR) and left-hand reaction time (RML), substantial reductions were observed in the 3×3 and 60° modalities (RMR: −29.77% and − 28.31%; RML: −31.92% and − 5.04%, respectively), indicating enhanced response speed. In contrast, RMR increased in the 180° condition (+ 36.50%) but decreased markedly in the 360° condition (− 36.52%), reflecting a more heterogeneous response pattern as spatial demands increased. Similarly, RML exhibited a slight increase in the 180° modality (+ 5.01%) and remained virtually unchanged in the 360° modality (− 0.14%). Collectively, these results indicate more consistent improvements under less demanding spatial conditions and reduced adaptability in tasks requiring greater spatial processing.

Mean reaction time (RM) decreased in the 3×3 (− 23.12%), 60° (− 9.89%), and 180° (− 1.42%) modalities, whereas a slight increase was observed in the 360° modality (+ 0.80%). This pattern suggests that the intervention was more effective in enhancing perceptual-motor performance in tasks of lower complexity.

With respect to right-hand hits (GMD), increases were observed in the 3×3 (+ 16.79%), 180° (+ 4.03%), and 360° (+ 4.26%) conditions, while a slight reduction was found in the 60° condition (− 3.56%). Conversely, left-hand hits (GMI) showed substantial improvements in the 3×3 (+ 65.21%) and 60° (+ 39.83%) modalities, whereas only minor changes were observed in the 180° (+ 1.74%) and 360° (− 4.35%) conditions. These findings indicate a more pronounced enhancement of left-hand performance in tasks with lower levels of difficulty and spatial complexity.

Finally, the Best Streak variable demonstrated marked increases in the 3×3 (+ 137.16%), 180° (+ 46.00%), and 60° (+ 17.10%) modalities, whereas a substantial decline was observed in the 360° modality (− 54.00%). Overall, these results suggest that lower task complexity was associated with greater performance gains, whereas tasks involving higher spatial demands produced less stable adaptations and greater variability in performance.

Table 4
Descriptive statistics and percentage change of performance variables across training modalities.

Variable	Moment	3×3	60°	180°	360°
Total hits (n)	Pre	87.15 ± 9.44	78.15 ± 10.01	51.00 ± 3.92	39.31 ± 5.69
	Post	115.62 ± 9.00	86.85 ± 12.37	52.54 ± 7.73	39.46 ± 7.62
	Δ (%)	+ 32.67	+ 11.13	+ 3.02	+ 0.38
RMR (ms)	Pre	340.00 ± 141.98	340.15 ± 118.40	458.31 ± 79.14	738.77 ± 1077.17
	Post	238.77 ± 121.86	243.85 ± 145.41	625.62 ± 819.57	469.00 ± 147.51
	Δ (%)	−29.77	−28.31	+ 36.50	−36.52
RML (ms)	Pre	1609.69 ± 449.32	1954.62 ± 557.31	2651.00 ± 835.40	3927.69 ± 1395.73
	Post	1095.92 ± 119.01	1856.15 ± 532.22	2783.85 ± 591.85	3922.31 ± 1729.73
	Δ (%)	−31.92	−5.04	+ 5.01	−0.14
RM (ms)	Pre	671.85 ± 66.77	772.23 ± 91.20	1168.46 ± 88.68	1542.31 ± 253.81
	Post	516.54 ± 39.94	695.85 ± 103.83	1151.92 ± 174.67	1554.62 ± 356.83
	Δ (%)	−23.12	−9.89	−1.42	+ 0.80
GMD (n)	Pre	58.62 ± 12.10	51.69 ± 10.29	28.54 ± 6.64	21.62 ± 7.69
	Post	68.46 ± 11.23	49.85 ± 9.32	29.69 ± 6.88	22.54 ± 10.54
	Δ (%)	+ 16.79	−3.56	+ 4.03	+ 4.26
GMI (n)	Pre	28.54 ± 10.15	26.46 ± 10.44	22.46 ± 5.27	17.69 ± 7.73
	Post	47.15 ± 8.87	37.00 ± 10.26	22.85 ± 8.52	16.92 ± 10.67
	Δ (%)	+ 65.21	+ 39.83	+ 1.74	−4.35
Best streak (n)	Pre	3.31 ± 1.97	2.69 ± 1.60	1.00 ± 0.58	1.00 ± 0.41
	Post	7.85 ± 3.95	3.15 ± 1.28	1.46 ± 1.13	0.46 ± 0.52
	Δ (%)	+ 137.16	+ 17.10	+ 46.00	−54.00

Abs

RMR = Right-Hand Reaction Time; RML = Left-Hand Reaction Time; RM = Mean Reaction Time; GMD = Right-Hand Hits; GMI = Left-Hand Hits. **Note.** Δ (%) = ((Post − Pre) / Pre) × 100. Positive values indicate an increase in performance. For reaction time variables (RMR, RML and RM), negative values indicate improved performance due to faster responses.

Table 5 presents the neurocognitive performance and reaction time outcomes, comparing the experimental and control groups across the different assessment time points. First, auditory reaction time showed a significant difference between groups. The experimental group reduced its reaction time by 11.05%, whereas the control group exhibited an increase of 18.93%. This divergent pattern indicates that the intervention enhanced auditory processing speed, while the absence of training may have led to a decline in performance. Given the critical role of auditory processing in anticipation and rapid response tasks, this finding further supports the effectiveness of the intervention in sensorimotor domains.

Similarly, visual reaction time improved in the experimental group, with a reduction of 28.28%, whereas the control group showed virtually no change between pre- and post-test assessments (− 0.24%). Although the between-group difference did not reach statistical significance, the observed improvements suggest that the training program may also contribute to faster processing of visual stimuli.

Table 5
Changes in neurocognitive and effectiveness variables from pre- to post-intervention.

Variable	Group	Pre-test	Post-test	Δ	F; Sig
Auditory reaction time (ms)	Experimental	300.20 ± 23.04	289.16 ± 13.90	-11.05	$F_{(1,22)} = 9.26$; $p = 0.005$
	Control	288.27 ± 32.00	307.20 ± 24.99*	+ 18.93	
Visual reaction time (ms)	Experimental	329.70 ± 36.87	301.42 ± 16.34*	-28.28	$F_{(1,22)} = 4.25$; $p = 0.049$
	Control	316.37 ± 21.50	316.14 ± 28.76	-0.24	
Tactical Effectiveness Index	Experimental	54.15 ± 18.97	65.09 ± 17.38*	+ 10.94	$F_{(1,22)} = 3.23$; $p = 0.091$
	Control	61.38 ± 20.78	59.73 ± 20.88	-1.65	
SDMT total responses	Experimental	47.83 ± 7.36	52.42 ± 8.35*	+ 4.58	$F_{(1,22)} = 0.65$; $p = 0.427$
	Control	53.26 ± 10.82	56.05 ± 14.03	+ 2.79	
SDMT errors	Experimental	1.42 ± 2.23	1.08 ± 1.16	-0.33	$F_{(1,22)} = 0.18$; $p = 0.677$
	Control	0.79 ± 1.08	0.84 ± 1.92	+ 0.05	

*$p < 0.05$

In contrast, no significant between-group differences were found for the Tactical Effectiveness Index, SDMT total responses, or SDMT errors ($p > 0.05$). Although the experimental group showed greater improvement trends than the control group in some measures, these differences did not reach statistical significance and therefore cannot be conclusively attributed to the intervention.

The effects of the immersive virtual reality (IVR) program according to playing position were examined through comparisons of pre- and post-test outcomes between the experimental and control groups.

Figure 4 illustrates the percentage changes in tactical effectiveness, cognitive performance, and reaction times according to playing position and study group (experimental vs. control). For the Tactical Effectiveness Index, the experimental group exhibited marked percentage increases in the goalkeeper and pivot positions, substantially exceeding those observed in the control group. In contrast, wing and backcourt players showed smaller, although still favorable, improvements in the experimental group.

Similarly, auditory reaction time improved across all playing positions within the experimental group, whereas performance deteriorated in the control group. Regarding visual reaction time and SDMT performance, improvements were also observed in the experimental group; however, positive changes in

SDMT scores were likewise detected in the control group. Notably, goalkeepers and backcourt players demonstrated the greatest improvements in visual reaction time, suggesting a position-specific benefit of the intervention.

4 Discussion

This study developed and evaluated a hand–eye coordination training program implemented in immersive virtual reality (IVR) environments and examined its effects on reaction time, cognitive performance, and tactical effectiveness in youth handball players. Reaction time is a key indicator of an athlete's ability to detect, process, and respond to environmental stimuli rapidly and, therefore, plays a critical role in sports performance. Following an eight-week intervention consisting of a hand–eye coordination training program conducted in IVR environments, the experimental group demonstrated meaningful improvements compared with the control group. Overall, the findings revealed that the experimental group achieved significant improvements in both auditory and visual reaction times, whereas variables related to cognitive processing speed, as measured by the Symbol Digit Modalities Test (SDMT), and tactical effectiveness, as assessed by the Tactical Effectiveness Index (TEI), exhibited positive trends.

Furthermore, the results demonstrated that IVR-based training exhibited high levels of safety and acceptability, with a minimal incidence of virtual reality–related symptoms and a highly positive user experience. These findings are consistent with those reported by Rutkowski et al. (2024), who highlighted the high tolerability of immersive virtual reality devices among young athletes. Taken together, the findings suggest that virtual reality–based training programs may facilitate the integration of perception and action, which is considered a fundamental component of performance in high-speed team sports such as handball (Magnaguagno and Hossner, 2020). In addition, such programs may enhance motivation and adherence to training, both of which are key determinants of learning and long-term athletic development.

The improvements observed in visual and auditory reaction times in the experimental group, particularly under the visual condition (− 28.28 ms), indicate enhanced efficiency in perception–action coupling. These findings are consistent with recent evidence supporting the use of immersive technologies to optimize perceptual-cognitive and visuomotor performance in sport (Bernárdez-Vilaboa et al., 2026; Bonctu et al., 2026; Kittel et al., 2024). Previous studies have shown that virtual reality–based training enhances athletes' ability to detect, process, and respond more efficiently to relevant environmental stimuli (Rutkowski et al., 2024). In team sports such as handball, where game situations change continuously and decisions must be made under substantial time pressure, the speed of perception–action coupling constitutes a critical determinant of performance (Magnaguagno & Hossner, 2020).

Therefore, the reductions observed in reaction times may reflect improvements in the sensory processing and motor response selection mechanisms developed through repeated practice in virtual environments. In this regard, Bernárdez-Vilaboa et al. (2026) demonstrated that a visual training program

combining virtual reality and reaction light systems significantly improved manual reaction speed, peripheral visual awareness, and visuomotor performance in young handball players. The findings of the present study extend this evidence by demonstrating that a relatively brief intervention specifically focused on hand–eye coordination tasks is capable of eliciting significant adaptations in both visual and auditory processing.

The analysis of the program's internal variables provides complementary insights into the adaptive processes elicited during the intervention. The greatest improvements were observed in the conditions characterized by lower spatial complexity (3 × 3 and 60°), whereas the gains achieved in the 180° and 360° conditions were more modest and heterogeneous. This pattern suggests that the perceptual-motor adaptations induced by training may initially consolidate in environments with lower visual exploration and spatial processing demands before subsequently transferring to situations characterized by greater perceptual complexity.

These findings are consistent with current evidence on perceptual-cognitive learning in sport, which indicates that the acquisition of skills related to stimulus detection, attentional orientation, and response speed follows a gradual progression, with initial improvements typically emerging in more structured contexts before generalizing to more dynamic and competition-representative environments (Kittel et al., 2024; Zhu et al., 2024). Several authors have highlighted that the progressive manipulation of variables such as visual field, number of stimuli, and task spatial complexity may facilitate the development of perceptual-cognitive and visuomotor skills by enabling a gradual exposure to situations that increasingly resemble the real demands of competition (Kittel et al., 2024; Richlan et al., 2023). Therefore, these findings support the implementation of virtual reality–based training programs structured around a progressive increase in perceptual complexity in order to maximize improvements in reaction time and facilitate their transfer to sport performance.

Despite the improvements observed in reaction times, the Tactical Effectiveness Index did not reveal statistically significant differences between groups. This finding may be explained by the multifactorial nature of tactical performance, which encompasses not only perceptual-cognitive abilities but also technical, physical, strategic, and contextual components inherent to invasion sports (Wagner et al., 2014). In this regard, although faster information processing may facilitate more rapid decision-making, it does not necessarily guarantee immediate improvements in global indicators of competitive performance. Consistent with this interpretation, recent evidence on virtual reality–based training indicates that such interventions primarily produce improvements in specific perceptual-motor variables, such as reaction time and accuracy, whereas transfer to overall performance in real-game situations tends to be more limited (Paludo et al., 2026).

Regarding cognitive performance, participants in the experimental group showed improvements in SDMT scores, although no significant differences were observed compared with the control group. These findings are consistent with those reported by Lachowicz et al. (2024), who found that the effects of virtual reality interventions tended to be concentrated in cognitive skills directly related to the

demands of the trained task, such as attention, visuomotor coordination, and processing speed, with more limited transfer to general measures of cognitive performance. Similarly, recent reviews on the use of immersive technologies in sport have suggested that these tools hold greater potential for enhancing specific perceptual-cognitive skills, including anticipation, decision-making, and information processing in representative sport contexts, than for improving general cognitive abilities assessed through conventional neuropsychological tests (Kittel et al., 2024; Richlan et al., 2023). Therefore, it is possible that the cognitive improvements induced by the intervention were not fully captured by a general measure such as the SDMT, which may be less sensitive to the specific adaptations elicited by perceptual-cognitive training in sport settings.

Overall, the findings of the present study indicate that the intervention had a positive effect, as significant improvements in reaction time and favorable changes in tactical effectiveness were observed in the experimental group compared with the control group. Therefore, the hand–eye coordination program implemented in immersive virtual reality environments appears to be a promising alternative for improving reaction time and enhancing tactical effectiveness in youth handball players during their developmental stages.

Several limitations of the present study should be acknowledged. First, the duration of the intervention may have limited the magnitude of the observed adaptations. Although the program lasted eight weeks, a longer intervention period may be necessary to detect more substantial changes in perceptual-cognitive and performance-related outcomes. Second, the duration of the exergame sessions may also represent a limitation, as longer exposure times could potentially produce more pronounced training effects. Finally, the relatively small sample size constitutes another limitation. Future studies should include larger samples and participants from different educational or competitive levels to improve the generalizability of the findings.

5 Conclusions

The findings of the present study suggest that an immersive virtual reality (IVR)-based hand–eye coordination training program can effectively enhance reaction time and promote positive adaptations in tactical effectiveness among youth handball players, while demonstrating high levels of safety and acceptability without inducing adverse effects. Furthermore, the proposed training protocol, in terms of frequency, duration, intensity, and exergame design, proved to be feasible and appropriate for implementation in this population. Collectively, these findings support the use of immersive virtual reality–based hand–eye coordination training as a promising and ecologically valid approach for fostering perceptual-motor development and optimizing performance-related outcomes during the developmental stages of handball players.

Declarations

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Author contributions: conceived of the study. X.R., J.C., A.L. and P.L. designed by X.R. and J.C. worked out the Virtual Reality technical implementation. X.R. performed data analyses. J.C wrote the manuscript X.R., A.L., P.L. and J.C. All authors commented and contributed to the final manuscript.

Ethical approval. All subjects signed informed consents prior to the participation in the study and were given verbal and written descriptions of the experimental protocols. The study was approved by Ethical approval was obtained from the local ethics committee of the University of Vigo (CP-220126-14) in accordance with the Declaration of Helsinki on the use of human subjects in research.

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Conflict of interest The authors declare that they have no competing interests.

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Figures

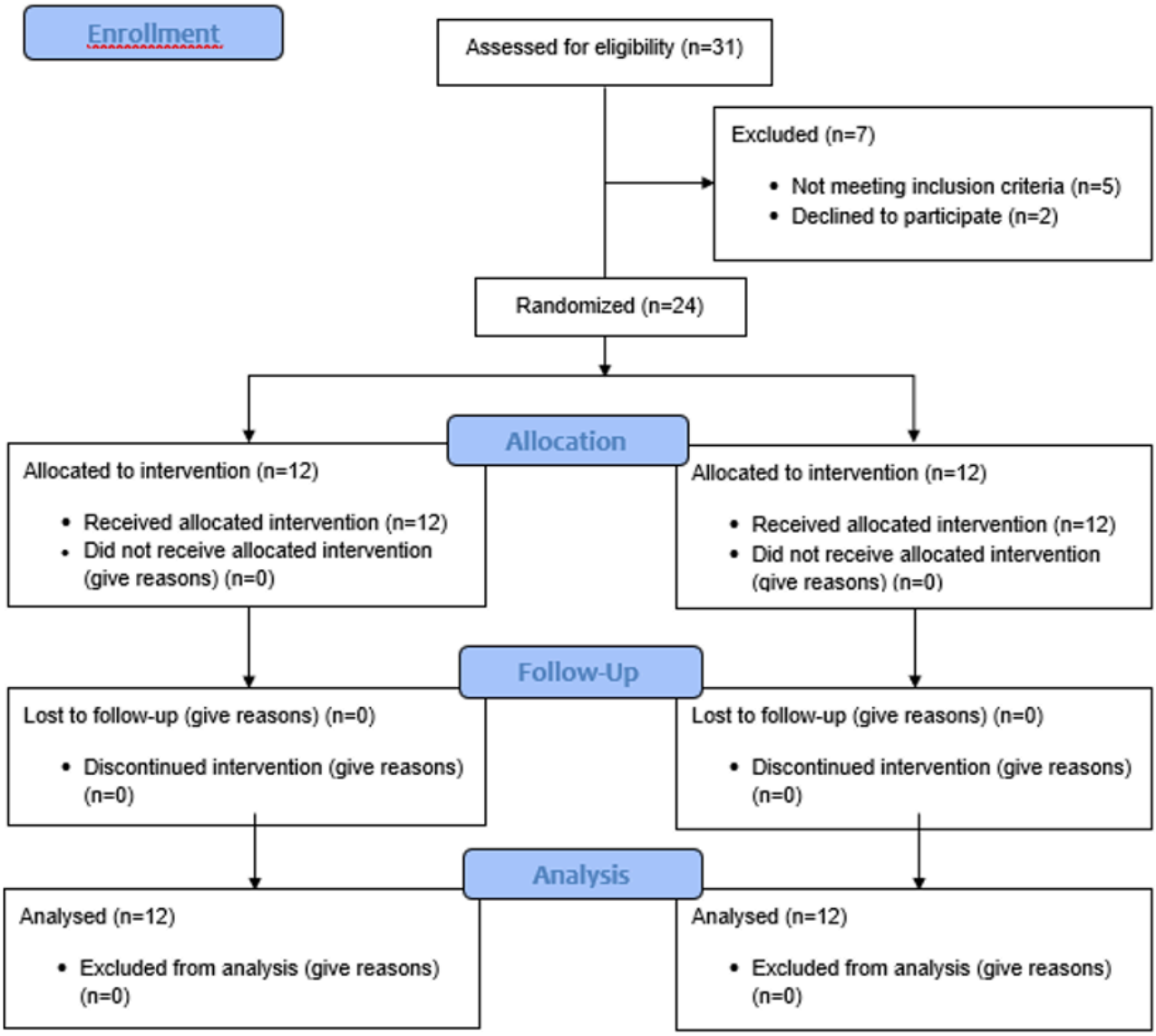

Figure 1

CONSORT Flow chart of enrolment process

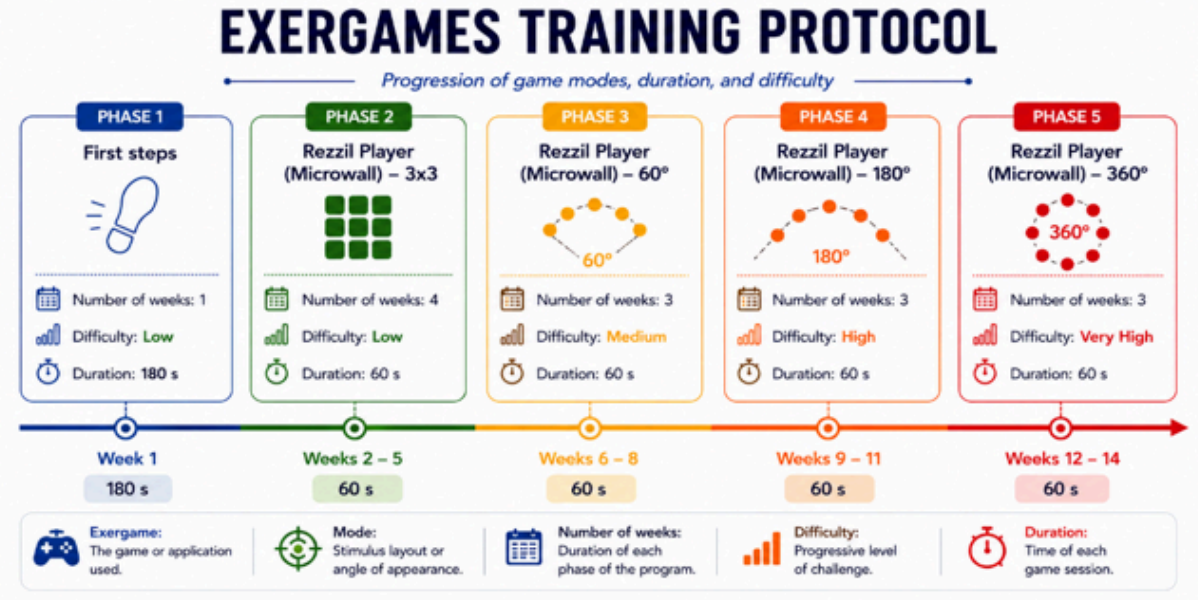

Figure 2

Timeline and characteristics of the immersive virtual reality–based eye–hand coordination training program

Figure 3

IVR training program with the SD Teucro youth team (U12/U13 category).

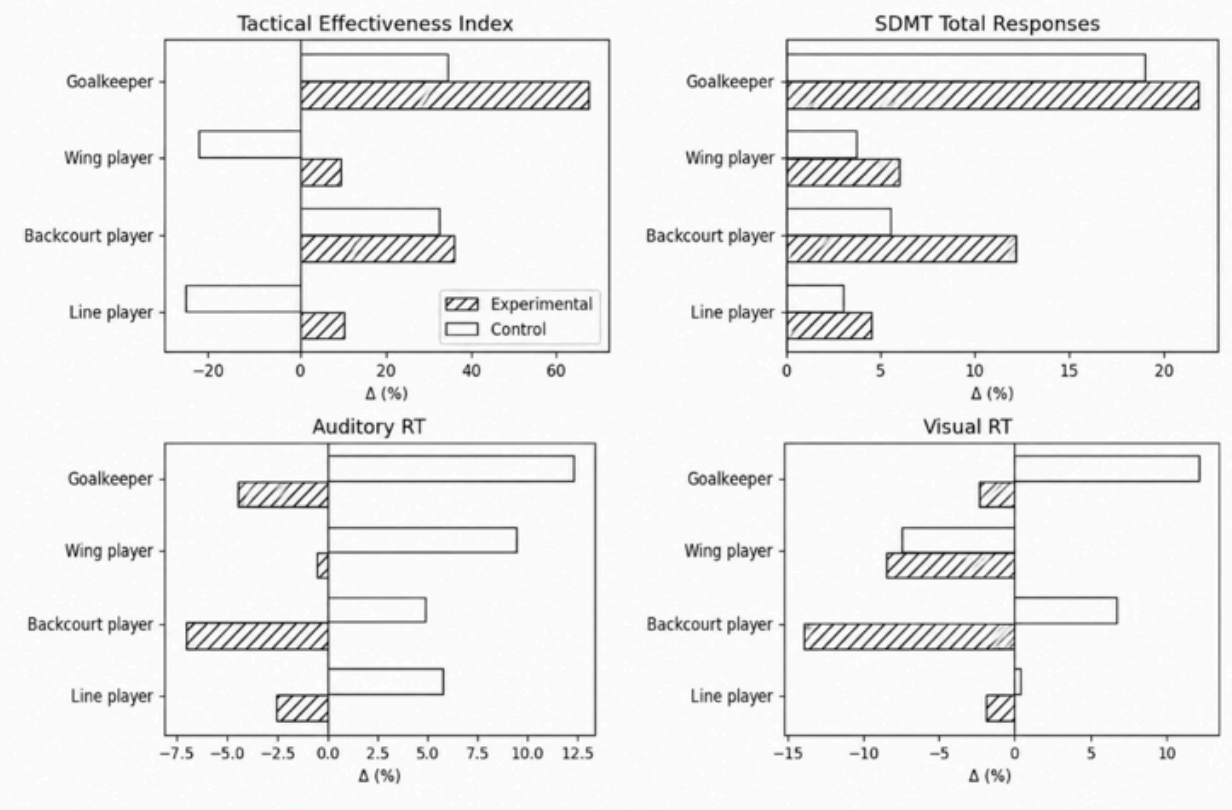

Figure 4

Percentage changes in tactical effectiveness, cognitive performance, and reaction times according to playing position