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Determining dual-task costs and exploring interindividual responsiveness to an opponent using virtual reality

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Introduction: Dual-task (DT) ability is essential in sports, where athletes must perform motor and cognitive tasks simultaneously. Virtual reality (VR), with its enhanced performance and affordability, offers a valuable tool for training and assessing these abilities. This study aimed to develop VR scenarios to measure DT costs and compare DT ability between athletes from individual (IG) and team (TG) sports using a basketball-specific scenario.

Methods: 29 participants completed two experiments to examine DT ability: a reaching and a dribbling task (DR). The reaching involved three tasks: walking a 4-m track, standing while reacting to popping balls, and a combination of both. Parameters such as step length, gait time, and reaction were measured. In DR, participants dribbled while reacting to a virtual opponent. Data on conduction time, errors, reaction time, gaze behavior (GB), and decision-making were analyzed.

Results: Significant differences were found between single and DT performances, with DT costs reaching up to 20% ($p > 0.05$). However, no significant differences were observed between IG and TG for selected parameters (F (1, 28) = 1.104, p = 0.410, partial η^2 = 0.380).

Discussion: Differences in GB and decision-making were noted and discussed. VR proved effective in assessing DT costs and providing insights into decision-making processes.

KEYWORDS

virtual reality, peripheral distractors, head-mounted display, basketball, dual-task

1 Introduction

In daily life, individuals often need to perform multiple tasks simultaneously, such as speaking while walking, where each task can influence the other. The more complex one of those tasks becomes, the more challenging it is to perform both tasks equally well compared to when each is done separately (Kunde, 2017). This phenomenon can be explained by the individual's attention span, which influences performance and is known as the Dual-Task-Paradigm (DTP). Furthermore, DTP is often defined as the simultaneous performance of a primary and secondary task (Huang and Mercer, 2001). In neuroscience, for example, the DTP is used to examine gait variability and balance in older adults or individuals with cognitive impairments (Fishbein et al., 2019). In sports science research, these DTPs typically involve a combination of cognitive and motor tasks. However, other pairings, such as multiple motor tasks (Akin et al., 2021) or multiple cognitive tasks (Kestens et al., 2024), have also been explored. Generally, the motor task is designated as the primary task, while the cognitive task is secondary. This method aims to direct participants' attention to the secondary task, thereby revealing implicit knowledge related to the primary task and assessing its impact (Hagemann et al., 2007; Pliske et al., 2016). Although the DTP can include a variety of cognitive tasks, such as speech comprehension and visual memory tasks (Kestens et al., 2024), anticipation (Loffing and Cañal-Bruland, 2017), and working memory (Buszard et al., 2017) or perceptual tasks in general (Brinkbäumer et al., 2024), motor components (or physical ones) often accompany these tasks (Ghasemzadeh and Saadat, 2023), despite the primary focus being on cognitive processes influencing each other.

A theoretical foundation of the dual task (DT) interference in simple tasks was established in a psychological context (Pashler, 1994) and later expanded to the context of sports. Pashler (1994) had already proven that reaction times and error probability increase when both tasks compete for the same cognitive resources. In this paper, the psychological refractory period (PRP) effect was described that illustrate the slowing of a person try to accomplish two speeded tasks (primary and secondary) at the same time. Normally, raw values will be subtracted from each other, so DT costs can be calculated by subtracting DT performance from single performance, while the remaining values indicate the amount of DT costs (Pashler, 1994). A further common method is to set DT costs in relation to the loss of the tasks' high-level execution, which can be determined by the change in the secondary task performance from the baseline condition in DTP (DT effect for cognitive or motor tasks: 100 × [score in DT–score in single performance]/score in single performance) (Gagné et al., 2017). In this formula, negative values indicate a performance loss when transitioning from DT to single performance, while positive values indicate the opposite transition (Plummer and Eskes, 2015). This applies only when higher values actually reflect better performance. For example, when considering the hit rate of a basketball player, a higher number of successful hits indicates better performance. According to this formula, negative values suggest that DT performance declined compared to single performance, and vice versa. For reaction times, if participants required 0.8 s in DT and 0.5 s in single performance, a positive value is obtained (in this case 60). This represents a performance loss of 60 percent in DT compared to single performance.

Especially in sports, athletes must pay attention to many relevant stimuli and may differ in their ability to handle multiple tasks simultaneously (Moreira et al., 2021). Since experts outperform novices in tasks such as cognitive-motor dual-task situations (Schaefer and Scornaienchi, 2020), it is well established that the DT effect can be reduced through training. To do so, it is trained by physical task execution, often in combination with cognitive tasks (Kimura and Matsuura, 2020). This type of training has gained increased awareness in recent years and is usually integrated with visual training, as sports involve numerous visual tasks closely linked to motor skills. In this context, attention–a cognitive process that enables individuals to focus specific information–is frequently mentioned since it is a relevant component for athletes, determining whether visually distracting stimuli can be recognized promptly (VanRullen et al., 2004), whereby auditive ones also play a vital role in those processes. Conversely, it is equally important to enhance the suppression of irrelevant stimuli that may distract from execution of the primary task (Gaspelin and Luck, 2018).

To further explore DT interferences in previously unattainable ways, Virtual Reality (VR) can be utilized to create scenarios that focus on sports-related task completion, including aspects such as perception, decision-making, and motor reactions. The advantage is to generate standardized sporting situations, allowing individuals with varying skill levels to be tested. This is highly related to the processing of visual stimuli, as VR involves their presentation through head-mounted displays (HMDs), which closely resemble real-world conditions, especially in spatial conditions (Dong et al., 2022). VR might be useful for training DT since it allows for the creation of an interactive environment, providing continuous tracking of participants' actions and tracing their paths. This enables the quantification of their behavior in ways that would be impossible through video presentations, as athletes' feedback often results in simple motoric reactions rather than sport-specific responses. This is particularly relevant for the standardized representation of specific sports situations perceivable from the first-person perspective, where not only kinematic movements can be captured, but also the head and eye movements, providing insights into the individual's perceptual cures. Richlan et al. (2023) provided a clear report on the benefits of VR compared to video training. Analyzing individuals' behavioral differences in these controlled environments can help identify the essential skills contributing to successful performance. Furthermore, training elements not part of the regular training could be incorporated, facilitating autonomous learning also ensuring higher ecological validity (Draschkow, 2022). Although the ability to perform motor tasks in VR remains limited, basic movement patterns such as stepping back, turning around, jumping or reaching are achievable. As a result, decision-making can be quantified through detailed feedback provided by VR technology components. Those responses could distinguish non-athletes from athletes (in athletes the distinction between beginners and experts) excel in visual perception by detecting peripheral distractors while simultaneously reacting appropriately (Schaefer and Scornaienchi, 2020). Besides, it is not only the skill level that determines the ability to perform multiple tasks successfully, but also the type of sport which leads to assumptions about what DTs can be performed simultaneously, for example, in team sports (Fleddermann and Zentgraf, 2018; Harris et al., 2020) or individual sports (Howell et al., 2018; Romeas et al., 2019).

Based on the circumstances mentioned so far, a primary and a secondary objective were pursued. The primary objective was to determine whether the effects of DT are evident within VR (Experiment 1). To this end, three tasks were designed to assess the negative impact of performing multiple tasks simultaneously compared to performing them individually (single performance). The secondary objective was to develop a VR testing scenario to examine sports-specific DT ability (Experiment 2). In this scenario, the task involved dribbling a ball through pylons, while the primary task required recognizing an opponent attempting to steal the ball and reacting swiftly by stepping into the "safe zone". Studies have already shown that the DT costs differ between athletes classified in open-skills (sports involving teammates and opponents) and closed-skills (e.g., gymnastics) (Brinkbäumer et al., 2024). It is essential to determine when these differences emerge, in which situations they occur, and which relevant abilities (such as visual attention) distinguish between performance levels. For example, this could involve an appropriate response to a peripheral distractor, a common occurrence in many sports. Therefore, an additional goal was to investigate whether differences between individual and team athletes could be identified within a virtualized basketball scene, where team athletes were expected to demonstrate more effective movement patterns compared to individual athletes. Based on a previous study, we chose a basketball scene because, in this sport, cognitive and motor tasks must be accomplished simultaneously (Schaefer and Scornaienchi, 2020), which are also essential in other sports. Since this port demands so many skills, we believe that this scenario has the potential for transfer to other sports, although this still needs to be examined. In addition to the parameters relevant to the tasks–such as completion time, number of errors, and reaction time–we aimed to gain insights into the cognitive abilities of individual and team athletes by analyzing their decision-making processes and gaze behavior.

2 Materials and methods

2.1 Participants

In total, 30 participants (10 females, 20 males, mean age 25.62 ± 4.52 years) were recruited and went through the pre-and post-tests. Except for one participant, who only completed Experiment 1, all others participated in both experiments. Based on previous literature, we anticipated a high effect of DT-costs within the same sample, and the study's power was precalculated by using G*Power (version 3.1.9.7) with a 1-β error probability of 0.99 for the first experiment. Since the two experiments were conducted consecutively, we had to accept a reduction in statistical power for the analysis of the second experiment, which will be thoroughly discussed later. All participants should not have professional basketball (or comparable such as professional handball) experience to ensure an equal starting level over the groups. Before starting the experiment, the participants were asked to fill out a self-created questionnaire in which pre-experiences were queried. This also concerns VR pre-experiences that could influence participants' performances in the VR scenario itself. The participants had limited experience in terms of VR and basketball training. This was reflected in the fact that only one participant reported owning a VR device at home, while the others had only participated in short experiments. None of the participants were members of a basketball club. The majority of the individual sport athletes (n = 16) came from gymnastics or weight lifting, while most team sports athletes (n = 14) came from handball or soccer. Hereby, we carefully considered the athletes' skill levels, allowing handball and soccer experience as long as it did not exceed the district league (seventh-tier league). In both groups, the average frequency of sports activity during week was three times. 60% of the team sport and 50% of the individual sport athletes classified themselves as amateurs. Team sport athletes reported having an average of 15 years of experience in their sport, while individual sport athletes had an average of 10 years. Most participants in both groups stated that they engaged in a second sport during the week, averaging two sessions, such as jogging or swimming.

2.2 Design

The following figure shows the study design (see Figure 1). Before starting, they were asked to complete the consent form, the Simulator of Sickness Questionnaire (SSQ, pre-version) (Kennedy et al., 1993), and a self-created questionnaire about their experiences in VR, in sports, and their demographic data (see Figure 1 Q1). The SSQ is not shown in Figure 1 to maintain clarity. It was administrated to the participants before and after they completed both experiments. Since no significant differences were found in each category of the SSQ–nausea, disorientation, and oculomotor ($p > 0.05$) and no participant verbally reported any symptoms of discomfort–the phenomenon of cybersickness will not be discussed in this paper.

In general, the participants began with either the reaching or the dribbling scenario in a randomized order. After completion, the participants were asked to complete the self-made feedback questionnaire that included questions about the feasibility of each test, suggestions for improvements, and the degree of reality (see Figure 1 Q2). Test trials were implemented ensuring the comprehension of the tasks. The instructions were similar to those of the written text in this manuscript.

Since both tasks required sufficient space to be completed, the lighthouses were placed far enough apart to cover the necessary area. The VR system was calibrated by following the steps recommended by the SteamVR procedure. Participants were equipped with a wireless HMD, one controller, and two trackers. Two Unity scenes were created (reaching and dribbling scene), each being started separately. The calibration process was repeated before starting each scene to ensure sufficient tracking.

2.3 Conduction

2.3.1 Experiment 1: reaching

The reaching scenario consisted of three tasks: single ball task (SB), single gait task (SG), and the dual task (DT). For better imagination, the tasks are illustrated in Figure 2.

In the SB, the participants were instructed to stand at the starting line (see Figure 2A, green line) and to fixate on the fixation cross (5.25 m from the starting line, covering an area of 0.25 square meters) at the end of the track (see Figure 2B, yellow square with black cross). Once they indicated their readiness, the supervisor pressed "start" and a basketball (original diameter of 23 cm) appeared on the screen, moving from the bottom to the top. Participants were instructed to react as quickly as possible: once the ball entered their field of view (FoV, approximately 110° horizontal, and 100° vertical), they should move their hand to its position. The position where the ball spawned in the front of them was pseudo-randomized over the participants by reading values

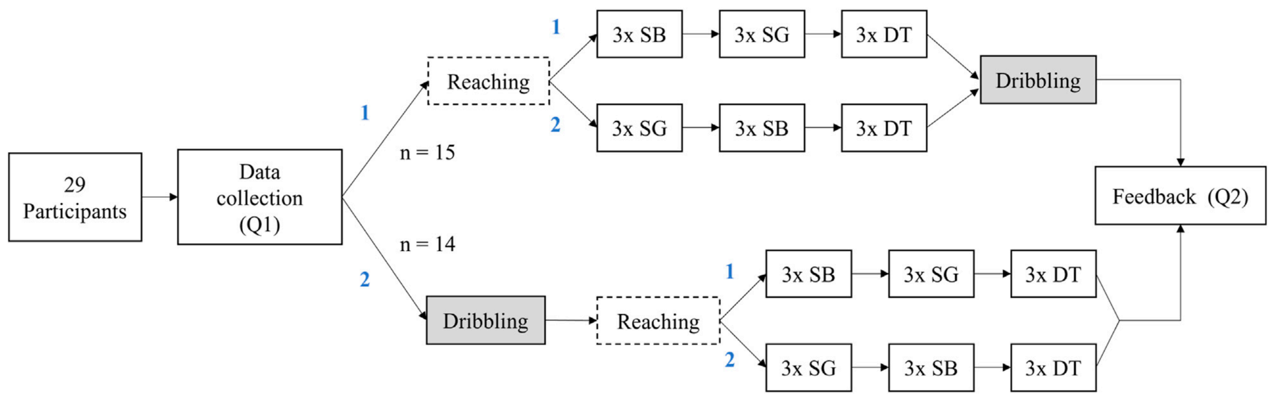

FIGURE 1
Study design. A total of 59 measurements were conducted, including both experiments (1 participant just conducted experiment 1). The reaching scenario consisted of three tasks: the Single Ball task (SB), the Single Gait task (SG), and the Dual Task, in which SB and SG were performed simultaneously. Each task was carried out three times. The Dribbling scenario was performed at least 15 times, due to the randomized order in which a disturbing opponent might appear or not. This occurred with a likelihood of 67%. The maximum number of trials that had to be carried out was 36 trials. The blue numbers indicate the second randomization. Half of the sample started with SB, while the other half started with SG. DT was always conducted at the end of the reaching scenario to avoid overload.

from a predefined list (ranging from 10, 20, or 30 cm) to ensure variety and avoid anticipatory effects. The ball disappeared when the hand virtually made contact with it. The time measured was the interval from when the ball entered the FoV to when the hand touched the ball.

In the SG (see Fig. B), the participants were asked to walk at a leisurely pace to the end of the 4-m-long track. Meanwhile, they were also instructed to fixate on the fixation cross. In total, they walked this track three times. The gait time was measured, and the raw data from the Vive trackers allowed the calculation of the step length.

In the DT scenario (see Figure 2C), participants must perform both previously described tasks simultaneously. The spawned balls are adjusted according to the body's actual position while walking along the track. The ball appeared at a range that did not influence the body postures, as was the case in SB.

2.3.2 Experiment 2: dribbling

In the second experiment, the participants were asked to dribble through a parkour slalom through pylons as quickly and accurately as possible. They started from the starting line (see Figure 3B 2 and 3, dark blue line with the green arrow above). The red circles represented the target areas (TA), where participants were required to dribble the ball. This task required a high level of concentration during execution. Once the ball touched TA, the red circle would immediately turn green, indicating that the ball had successfully hit the area (see Figure 3C). Each TA could only turn green sequentially, meaning that if the previous one was not hit, the subsequent one would not turn green either.

Participants were instructed to dribble between the pylons while ensuring they hit each TA. There were 7 TAs, so the participants were expected to dribble the ball only seven times. Any additional dribbles were counted as errors. In some of the trials, a virtual opponent appeared at one of the opponent's starting positions (mostly out of the participants' FoV, see Figure 3, number 1) and attempted to steal the ball from the participant (67% likelihood of avatar's appearance per trial). This probability was ideal for creating surprise effects from the opponent's appearance while minimizing the number of trials the participant needed to perform, as two experiments were conducted. The participant was instructed to react as quickly as possible upon recognizing the opponent by stepping or jumping out of the playing area, indicated by the right and left borders (light blue lines on the ground, see Figure 3B, numbers 4 and 5). The reaction was considered when both the left and the right foot had entirely crossed the lines. The participants were not instructed to react to a specific side; they had to choose for themselves. For instance, if the opponent approached from the right side, they were allowed to react to the ride side as well. After the opponent disappeared (in a successful trial immediately after passing one side), the participant was instructed to return to the playing area and finish the dribbling task. If the participant did not react sufficiently (i.e., did not cross the lines with both feet) or in time, the opponent would take possession of the ball, ending the task. This would be considered as error, or failed task. In that case, the participants were nevertheless asked to dribble to the end to finish the trial. The regular trial (if the opponent has not caught the ball) ended when the participant reached the end line (see Figure 3B, number 3). Footprints indicated the path the participants should take to return to the starting position. The experiment ended when the participants completed 15 trials in which the opponent appeared. Due to the randomization of the opponent's appearance, the number of trials could vary. The participants were informed and they had to complete two further questionnaires (the SSQ post, feedback questionnaire [Q2]).

Figure 4 illustrates how the participants are equipped with the components of the VR system.

2.4 Data analysis and statistics

In general, all data were examined for statistical outliers using the median absolute deviation (MAD), considered more robust than

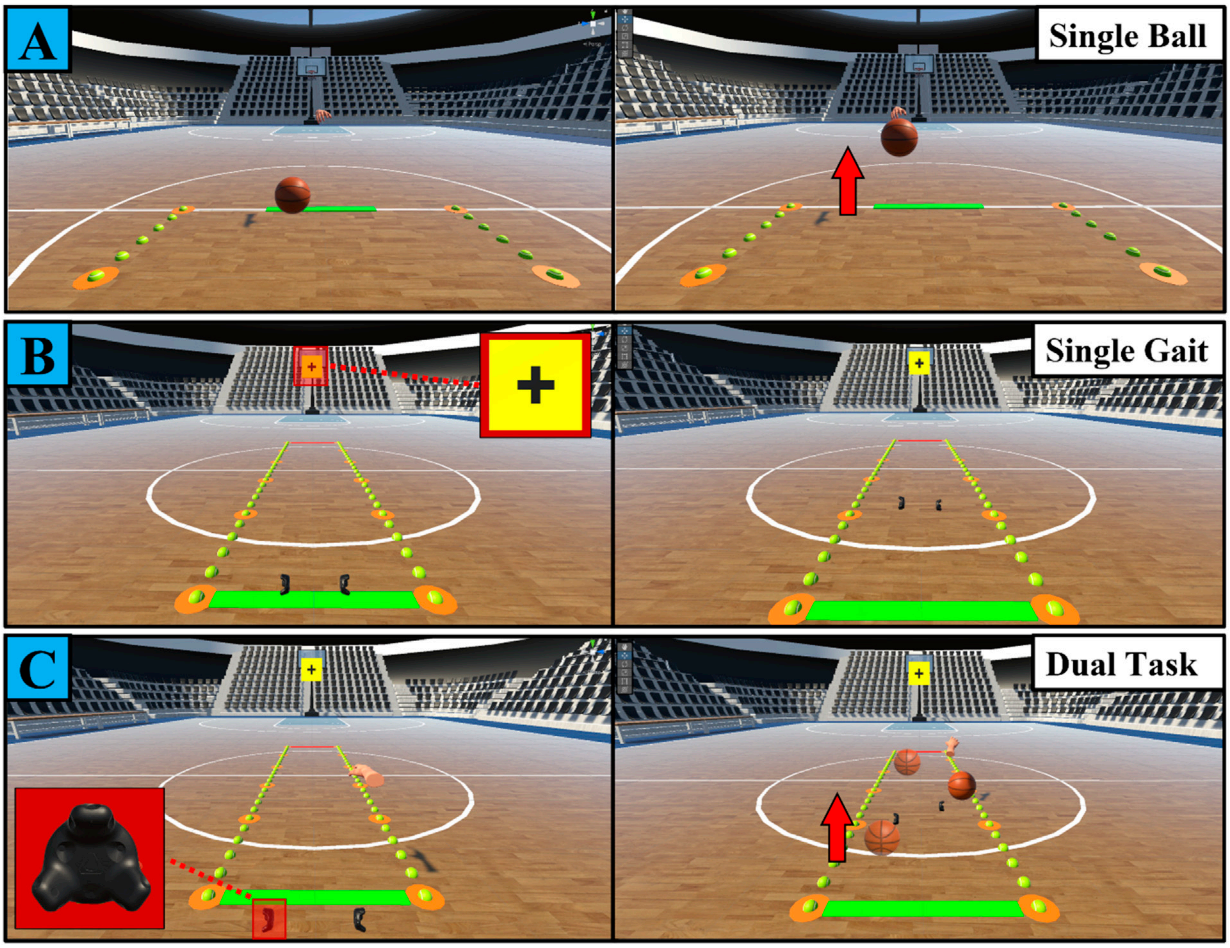

FIGURE 2
Visualization of the reaching scenario. Row **(A)** visualizes the Single Ball Task (SB), Row **(B)** the Single Gait (GT) and Row **(C)** the Dual Task (DT). In Row **(A)**, the participants stood at the starting line (green line). The ball was launched from a randomized position within the participants' reach, so no forward movement was required to react to the ball. Row **(B)** illustrates the SG, with the fixation cross highlighted. The track length was 4 m. In Row **(C)**, the DT is depicted, showing the placement of the HTC Vive trackers.

other methods (Jeong et al., 2017). The Shapiro-Wilk Test was used to assess whether the data were normally distributed, as recommended by previous examinations (Razalin and Wah, 2011). The alpha level was set at 0.05. If analysis of variance (ANOVA) was used, prerequisites were checked, and if sphericity was violated, the Greenhouse-Geisser correction was applied for interpretation. Effect sizes were indicated by using Cohen's f, small effect 0.1–0.25, moderate effect >0.25–0.4, large effect >0.4.

In the case of non-normal distributed data, we used the non-parametric statistical test instead for pairwise comparisons. In this case, the effect sizes were calculated using Pearson's correlation coefficient (Cohen, 1988), small effect 0.1–0.3, moderate effect >0.3–0.5, large effect >0.5. With the idea of using a t-test, we calculated the differences between the both data series and proved them for normal distribution and outliers. For t-tests, Cohen's d_z was used to determine the effect size, small effect 0.2–0.5, moderate effect >0.5–0.8, and large effect >0.8. If higher-level tests beyond pairwise comparisons were used, parametric tests (ANOVA) were still applied, provided that this did not predominate, as these are relatively robust against non-normally distributed data (Blanca et al., 2017) and enhance statistical power.

2.4.1 Experiment 1: reaching

To determine whether the dual-task effect also occurred in the current VR scenes, the gait time (GT), step length (SL) and RT were considered as dependent variables. The RT was compared between the SB and DT conditions using a t-test for dependent samples. GT and SL were compared between the SG and DT using a t-test for dependent samples. The DT costs were calculated using the formula from Gagné et al. (2017). Since three trials were conducted, we carefully checked for any significant differences between them using a one-way repeated measures ANOVA. When no significant difference was found, the mean of the three trials was used to represent the performance for each condition (single task [ST], dual task [DT]). If not, the best trial was used to run the analysis. The RT was calculated by measuring the time from when the participant first saw the ball (when it appeared in the FoV) until the participant reached out and hit the ball. The SL was calculated by taking the maximum difference in the position of the feet for each step

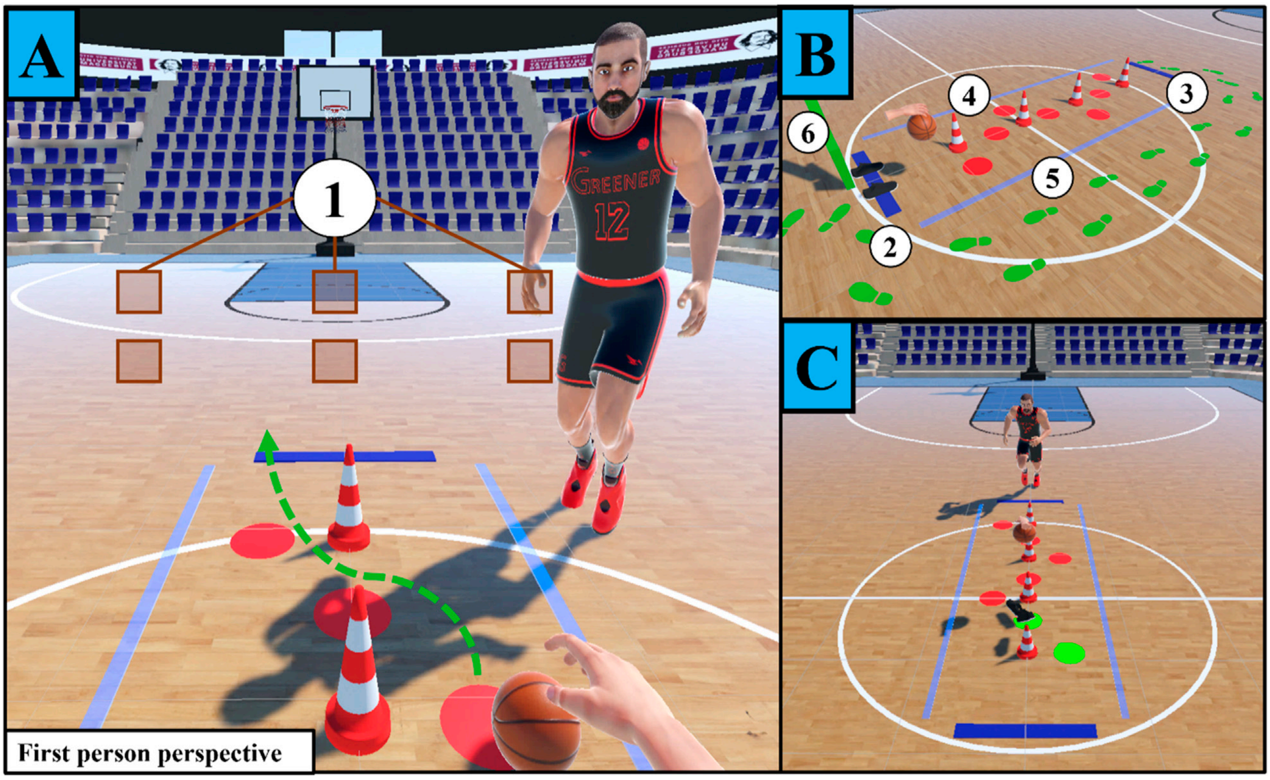

FIGURE 3
Illustration of the setup of the dribbling task. In **(A)**, the first-person perspective is shown while the participant dribbles through the pylons as the opponent attacks. This perspective was chosen solely for better illustration; normally, the participants tended to fixate the ground. The green curved arrow indicates the participants' pathway dribbling as they dribble through the pylons. The brown transparent squares [**(A)**, 1] represent the starting positions of the opponent that can spawn, varying the direction and timing of the opponent's attack on the participant. In **(B)**, the starting (2) and end line (3), as well as the left (4) and the right border (5) are shown. The green footprints and arrow (6) appear when the trial is finished, indicating that the participants should return to the starting position. In **(C)**, a scene is shown during task execution where the opponent has appeared after two targets have already been hit (turned green).

(tracker's position on the forward axis [unity's z-axis], one dimension). The GT was calculated by measuring the time from when both feet left the starting line until both feet crossed the ending line.

2.4.2 Experiment 2: dribbling

Several aspects were analyzed to provide insight into participants' performances. Metric data such as conduction time (CT), reaction time (RT), and number of dribbles (ND, all dribbles over 7 counted as error) were compared between the individuals coming from individual sports (IG) and those from team sports (TG). Furthermore, trials were compared with and without opponent's appearance, even though this is impertinent. In addition to these metrics, we also analyzed the number of decisions made, for example stepping to the left and right side when the opponent appeared on the left or right side, between both groups (IG and TG).

To further examine differences in visual attention, we analyzed the number of frames in which participants focused on each relevant object while performing the task (gaze fixated on the object). To assess the time participants fixated on each object, integer variables were created that increased frame by frame as long as the participant observed them while performing the task. This calculation belongs to the fixations made on the ball (FB), ground respectively TAs (FG), right border (FR) and left border (FL), and the opponent (FO). The manufacturer specifies a recording sample rate of 120 Hz for the eye-tracking system, and a 90 Hz rate for the HMD. Therefore, we decided to use the number of frames as fixation duration instead of the calculated time (from the moment the opponent appeared to the moment the trial ended), which depends on the recording sample rate and its consistency.

To examine the differences between IG and TG for the kinematic data and gaze behavior, we conducted a one-factor MANOVA with repeated measurements, with the between-factor group [IG, TG] and the dependent variables CT, RT, ND, FB, FG, FL, FR, FO in the trials where the opponent was present. To compare the categoric variables, we used Chi-Square tests.

2.5 Experimental apparatus

2.5.1 Hardware

The HTC Vive Pro Eye (HTC, Taiwan) was used to present the virtual environment, offering a 110° FoV (90 Hz). The integrated eye tracker (Tobii, 2001) enables the recording of the gaze behaviour and enhances scene control via gaze-controlled operation (120 Hz,

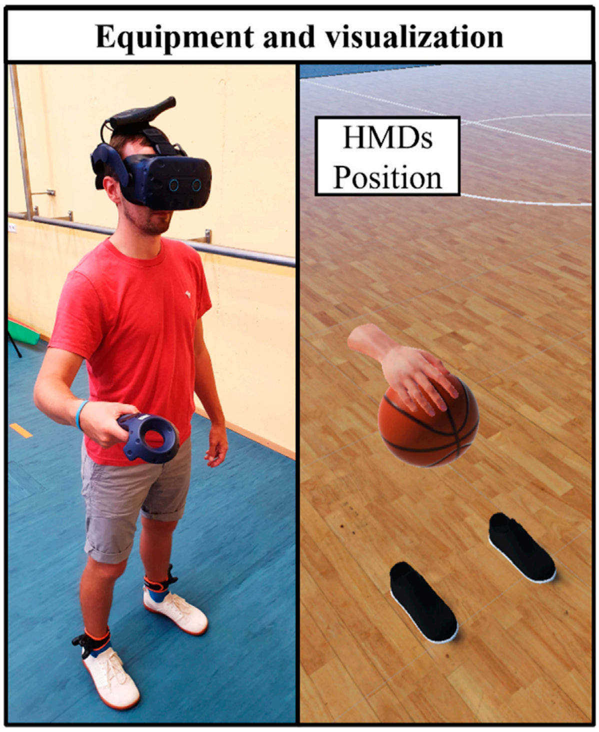

FIGURE 4
The used equipment and the resulting visualization in the virtual environment.

potentially limited by the refresh rate of the HMD). Additionally, a wireless adapter was installed to allow free movement within a fifty-square-meter area, while four basestations (HTC Vive Base Station 2.0) were placed in the laboratory (the manufacturer specifies a playing area of 100 square meters). The resolution of 1,440 × 1,600 pixels per eye ensured a clear view without pixelation. The computer consisted of the following components: Intel i7 CPU, 16 GB memory, 512 GB SSD, and NVIDIA GTX 1080 8 GB graphic card. The HTC VIVE Controller version from 2018 (equipped with 24 sensors, HTC, Taiwan) was handed over to the participants for the interactions needed to complete the required tasks. The controller was primarily used to visualize the participants' hand. Two HTC Vive Trackers 3.0 were attached to the participants' ankles to visualize their feet in VR and to capture raw kinematic data.

2.5.2 Software

The virtual environment was built with Blender (version 3.1.2) by modeling and texturing each virtual asset. The virtual scene was then imported to Unity (version 2021.3.16f1), and SteamVR (version 1.26) was integrated to include VR interactions. The functionality within the scene was realized via self-written C# scripts. The humanoid avatar was downloaded from the Unity Asset Store and was created by Code this Lab (Italy, 2009). The animations (including running and defense posture) were self-captured using Vicon Shogun (version 1.6.3) and then transferred to the humanoid avatar's skeleton. Participants' movement data and the associated timestamp data were transferred from Unity to Excel sheets, then further processed with Python (version 3.10.8), and additional statistical analysis was conducted using SPSS (version 29).

3 Results

3.1 Experiment 1: reaching

First, significant differences between the single-task and dual-task conditions were examined for all dependent variables (GT, SL, RT).

3.1.1 Gait time

In the ST condition, no significant differences between the trials were found (F (1.474, 42.742) = 1.021, p = 0.348, partial η^2 = 0.034). In the DT condition, however, a significant difference between the trials was observed (F (1.574, 37.766) = 6.409, p = 0.007, partial η^2 = 0.211). Therefore, we decided to use the trial with the shortest times in both conditions rather than the mean for comparison, noting that the differences were minor (first trial 5.64 s, second trial 5.36, third trial 5.15). The normal distribution was violated for both data series (p < 0.05). Therefore, we used the Wilcoxon signed-rank test to examine the differences between ST and DT. No statistically significant outliers were found.

The GT was significantly slower in the DT condition compared to ST, z = 4.265, p < 0.001, r = 0.85 (large effect).

3.1.2 Step length

There were significant differences between the trials in the ST condition (F (2, 54) = 9.868, p < 0.001, partial η^2 = 0.268). Therefore, we decided to use the trial with the shortest SL, although the differences were small in ST (first trial 0.63 m, second trial 0.65 m, and third trial 0.66 m). No significant differences were found within the DT condition (F (2, 54) = 3.055, p = 0.055, partial η^2 = 0.102). The normal distribution was given for both data series (p > 0.05). Therefore, the dependent t-test was used to examine the differences. No statistically significant outliers were found.

The SL was significantly shorter in the DT condition compared to the ST condition, t (27) = 7.848, p < 0.001, d = 1.49 (large effect).

3.1.3 Reaction time

There were significant differences between the trials in the ST condition (F (2, 56) = 5.405, p = 0.007, partial η^2 = 0.162). Therefore, we decided to use the trial with the lowest RT, although the differences were small in the ST (first trial 0.86 s, second trial 0.83 s, and third trial 0.83 s). The normal distribution was given between both data series (p = 0.632) and no statistically significant outliers were found.

The RT was significantly shorter in the DT condition compared to ST, t (28) = 2.498, p = 0.19, d = 0.47 (small effect).

Secondly, we calculated the DT costs (DT to ST) for each dependent variable using the formula described in the introduction.

For GT, a shorter execution time (seconds) indicates higher performance. Therefore, positive formula outcomes represent a performance loss from DT to ST. This was the case for all participants (except one) with only positive values identified ($\bar{x}$ = 19.46), indicating a performance decrease of approximately 20% in GT. For SL, longer distances (in meters) imply more security during

TABLE 1 Overview of the group comparisons of individual sports (IG) and team sports (TG). M stands for the mean and SD for the standard deviation. The individual analysis of variances (ANOVAs) from the MANOVA are listed on the right side. Although effects can be applied, these are not significant. The number of frames of the observed objects is presented in seconds for better clarity. Unity saved the data in approximately 90 Hz. Although the eye tracker captures at a higher frequency, the unity's frame rate was used instead. The gaze fixations were captured from the moment the opponent appeared in the field of view until the reaction ended.

Dependent variable (n = 29)	Group	*M*	*SD*	ANOVA effect size
Kinematic				
Conduction time (s)	IG	8.76	1.33	F (1, 28) = 0.727, p = 0.401., partial η^2 = 0.026., no effect
	TG	8.27	1.72	
Reaction time (s)	IG	2.58	1.60	F (1, 28) = 0.869, p = 0.360, partial η^2 = 0.031., no effect
	TG	2.10	0.98	
Number of dribbles (error)	IG	1.85	1.39	F (1, 28) = 0.122, p = 0.729., partial η^2 = 0.005., no effect
	TG	1.62	2.05	
Gaze behavior (number of frames)				
Fixations ball (s)	IG	1.57	0.79	F (1, 28) = 3.427, p = 0.075., partial η^2 = 0.113, no effect
	TG	1.09	0.57	
Fixations ground (s) (TAs)	IG	0.39	0.46	F (1, 28) = 0.031, p = 0.861., partial η^2 = 0.001, no effect
	TG	0.42	0.55	
Fixations right border (s)	IG	0.26	0.13	F (1, 28) = 0.739, p = 0.398., partial η^2 = 0.027, no effect
	TG	0.30	0.17	
Fixations left border (s)	IG	0.24	0.12	F (1, 28) = 1.421, p = 0.244., partial η^2 = 0.050, no effect
	TG	0.19	0.10	
Fixations on opponent (s)	IG	0.07	0.08	F (1, 28) = 0.896, p = 0.360., partial η^2 = 0.031, no effect
	TG	0.11	0.10	

walking. Therefore, adverse formula outcomes indicate a performance loss from DT to ST. This was true for all participants except one ($\bar{x}$ = −14.9). On average, SL was 15% smaller in DT compared to ST. For RT, shorter times (seconds) represent better performance. Hence, positive values indicate a performance loss from DT to ST, which was the case for 72% of the participants ($\bar{x}$ = 8.98), while 28%, showed negative values ($\bar{x}$ = −7.8, overall $\bar{x}$ = 4.92). The performance loss from DT to ST cannot be proven as strongly as for GT and SL in RT. However, for those who experienced a performance loss (the majority), their RT was approximately 9% longer in the DT condition.

3.2 Experiment 2: dribbling

First, we focused on the outcome of the MANOVA, showing the differences between the groups [IG, TG] for each dependent variable (see Table 1). The one-way MANOVA identifies no statistical difference between the groups on the dependent variables, F (1, 28) = 1.104, p = 0.455, partial η^2 = 0.402, Wilks-Lambda = 0.001. Regarding the descriptive statistic, TG needed approximately half a second less to complete the dribble task, reacted 400 m faster to the opponent, and made 0.3 fewer errors (see Tab. 1). However, these differences were not significant. Furthermore, no differences were observed in the gaze behavior.

The decision-making process of both groups (IG, TG) was analyzed from the moment the opponent appeared in the FoV, prompting a reaction from the participant (deciding to step to the left or right border). An overview of the differences is presented in Figure 5.

Furthermore, gaze behavior in the moment the opponent appeared were also compared between IG and TG in Figure 6.

4 Discussion

The primary goal of the current study was to investigate whether the DT effect can be observed in VR sports scenarios. To achieve this, we developed DT scenarios closely related to sports. Three VR scenes were designed; two of them involved single tasks—walking a 4-m track and reaching to balls that appeared while standing still—and the third one was a DT scenario where participants performed both single tasks simultaneously. The secondary objective was to create a more specific VR scenario with a basketball DT-scenario, allowing for the investigation of potential differences between individual and team sports athletes in a common team sport situation–reacting adequately to an opponent. We sought to determine if the motor tasks in VR closely resemble real-world conditions, enabling the detection of measurable effects between both groups. Additionally, we utilized

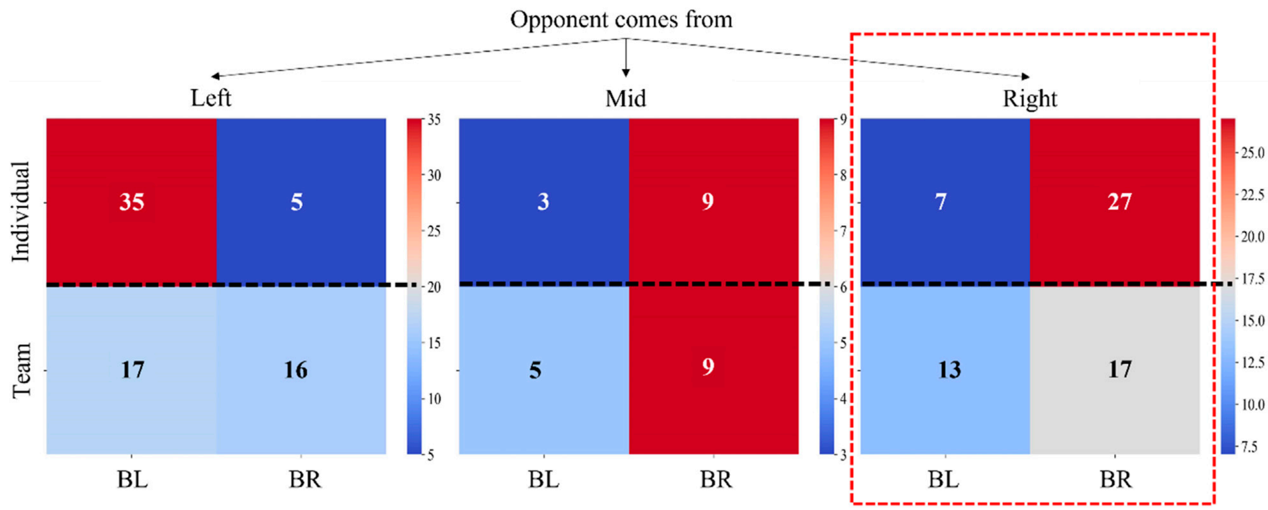

FIGURE 5
This figure highlights the differences between athletes assigned to individual sports and team sports. The opponent appeared in six different positions (see Figure 3A, brown transparent squares), and it started to attack the participants. The graphic showcases the three positions that are the most distant to the player's area. The percentage of decisions made from each condition (where the opponent approaches from a specific direction) is displayed, indicating whether the participant reacted to either the left border (BL) or the right border (BR). Since the three positions from the last row were chosen, the percentages could not add up to 100%. For example, in the red dashed square on the right side, when the opponent started from the right side, 27% of athletes with an individual sports background reacted to the ride side, while athletes from the team sports displayed a more balanced reaction.

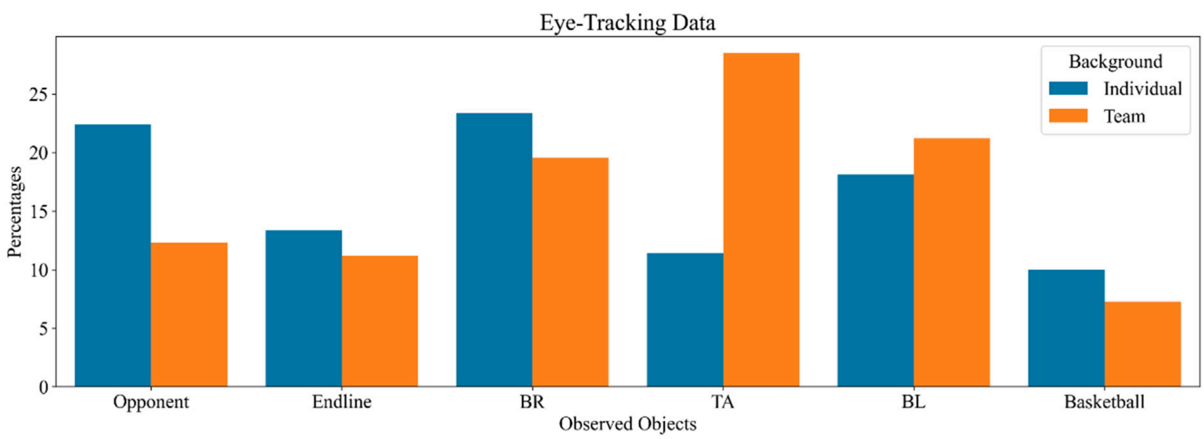

FIGURE 6
Illustration of the observed objects for both groups at the moment the opponent enters the FoV while attempting to catch the ball. It highlights the traceability of visual attention at this specific time point. "BR" represents the right border, "TA" indicates the target areas (red circles on the ground that the ball needs to hit), and "BL" denotes the left border.

VR to collect data on cognitive abilities essential for optimal athletic performance, including decision-making and visual attention. This study could serve as a pioneering step in data curation and analysis for future VR applications.

An overview of current research on DT performance shows that performance declines are often studied in individuals with various health conditions (Yun et al., 2023; Kayabinar et al., 2021; Galperin et al., 2023). The first experiment's result demonstrate that VR can effectively be used to assess DT costs in a sports-related context (with athletes). To emphasize the decline in performance when both tasks are performed simultaneously, we compared each task under both ST and DT. The GT was significantly longer in DT to ST, step lengths were significant lower in DT to ST, and the RT was significantly slower during DT as well. These findings align with previous research, which has similarly reported increased uncertainty in gait, e.g., shorter RT under DT conditions (Kaur et al., 2014). Another study also observed constraints in gait parameters during DT, although the quality of gait itself was not negatively affected (Ito et al., 2023). Many studies already indicate that VR can be a useful for training both physical and cognitive tasks (Liao et al., 2019). They reported even greater benefits for the VR group compared to those who trained in the real-world. Yun et al. (2023) shared this opinion and also used VR exergames as a training tool. They stated a significant improvement for executive function and balance (Yun et al., 2023). The scenarios developed in this study are not yet suitable for training, as certain parameters need to be adjusted. Instead, they are primarily intended to identify the costs associated with digital transformation and to determine their sources. Training concepts can then be developed based on these findings.

The participants' performance was determined using the lowest value of the three trials in the first experiment. To obtain a more accurate measure of performance, additional trials would have been needed to calculate the mean or median. By excluding outliers (such as significantly faster or smaller values), we minimized the influence of any "luck hits" in the data. However, having more trials would have provided a more stable representation of participants' performance. Since both experiments were conducted on the same day, we were unable to extend the duration of each experiment, which affected the data quality during this phase.

The second experiment demonstrates how future sports-related VR scenarios can be designed to assess adequate reactions to an opponent by filtering the sensory input. However, in real-world conditions, more complex situations may arise, such as having less space to react, or needing to choose between passing, throwing, dribbling, or other actions. The key challenge often lies in determining the "right decision" in a given situation. Therefore, it could be valuable to investigate the differences between experts (in this case, the team sports athletes) and novices (in this case the individual sports athletes) to define better what constitutes the "right decision". The lack of deficits between the groups could also be explained by the categorization of open- and closed-skills athletes (Heilmann et al., 2022; Yongtawee et al., 2022), where differences may become apparent only after reaching a specific performance level (Vaughan and Laborde, 2021). We assume that an increased performance level, whether in the team sports group nor the individual athletes group, would increase the differences between them. Brinkbäumer et al. (2024) discussed various approaches for obtaining such information, including the "expert performance approach", which highlights differences in decision-making or visual scanning among athletes. However, these differences can be influenced by athletes' procedural and declarative knowledge (that could also have happened in the current study), prompting consideration of additional approaches. Given this, further comparisons, incorporating concepts from the "cognitive component approach" (Brinkbäumer et al., 2024), could provide valuable insights into differences between sports. This could include factors such as multiple tracking (Qiu et al., 2018), executive functions (Verburgh et al., 2014) and further aspects. The ability to create more VR scenarios that replicate specific sports situations could help highlight the differences between open and closed-skill athletes, while recognizing that this distinction is not the same as that between individual and team sport athletes. Distinguishing between individual and team sport athletes might also be influential, since there are individual sports, such as tennis or fencing, that also require high-level DT abilities compared to weightlifting, as a few participants of the current studies were involved.

The statistical analysis of the selected parameters–CT, RT, ND–revealed no significant differences between the groups IG and TG. There could be several reasons for this lack of distinction. First of all, the lack of haptic feedback, and thus the absence of transfer from in real-world adapted skills to VR, could mean that no specific ball sports skills were required to complete the task adequately. Visual and auditory feedback are predominantly provided by today's VR applications (Gibbs et al., 2022). Gibbs et al. (2022) reported on an experiment where participants experienced a virtual ball bouncing on a stick held in their hands. The results showed that this increased presence and haptics alone were more effective than vision alone (Gibbs et al., 2022). Such a device could be important for sport-specific VR DT scenarios to detect the differences between the two groups accurately. With the VR technology used in this study, it remains a challenge to design motor tasks in a way that effectively identifies the interference between motor and cognitive tasks. These investigations should be kept in mind and integrated into future applications listed in previous reviews (Borgmann, 2018; Caeiro-Rodríguez et al., 2021).

Additional parameters, such as the viewing angle when the opponent was first seen and the distance between the opponent and the participant, were analyzed but ultimately deemed irrelevant for specific reasons. The FoV of the HMD is limited, particularly in the vertical direction. As a result, the viewing angle did not extend beyond 5° range, preventing the inclusion of reaction times across different eccentricities (Schiefer et al., 2001). The distance to the opponent was also excluded, as the varying starting positions only influenced when the opponent appeared within the FoV, ensuring a high level of variability across trials.

A significant portion of the lack of significant effects observed in the selected parameters in the dribbling task can be attributed to the limited statistical power (Experiment 2), which addressed the secondary goal ($n = 29$). With only 29 participants collected, the MANOVA with the between-subject factor group (IG and TG) was only able to detect an effect size of 0.38, which may already suggest the presence of a small effect. Small but significant effects, that are also recognizable by the observation of descriptive data, could be obscured by the marginal power in this context. A sample size of at least 81 participants is needed to increase statistical power and reliably detect significant effects. Since the ET data and the decision-making revealed differences in the participant's behavior and tendencies, which are also reflected in the selected parameters, more data should be collected.

The decisions made reveal notable differences between the IG and TG groups regarding which side participants chose to evade the opponent. When the opponent attacked from left or right, TG responded more balanced, while IG tended to evade the side from which the opponent attacked. This could be considered as disadvantage, as in a typical context, participants would likely aim to shield the ball from the attack rather than evading in the direction of the opponent's approach.

This may also occur in the gaze behavior, although the empirical evidence for sophisticated gaze behavior for experts compared to novices decreased in the last years (Klostermann and Moeinirad, 2020). Experts were assumed to outperform novices through optimal linkage of perception-action, with gaze behavior playing a more supporting role. In this context, it is important to note that we did not collect visual perception data of both groups, such as parameters like fixations and saccades (Pastel, 2021). Instead, we only recorded the number of frames during which objects were viewed at specific points in time. The most noticeable differences between IG and TG were observed in the objects they focused on when the opponent appeared in the FoV. IG seemed more distracted, as they spent more time observing the opponent compared to the TG group. In contrast, TG demonstrated greater task focus, directing more attention to the task-related cues, particularly the TAs, indicating a higher level of visual attention to relevant information, that is congruent to previous findings (Carmichael et al., 2010). Nevertheless, it is important to clarify what the appropriate reaction would be in this case, as fixated gaze positions may vary in terms of where attention is focused (Schooler et al., 2011). Therefore, they are not always an accurate indicator of good performance.

5 Conclusion

In conclusion, VR is a valuable tool for effectively determining DT costs in sports sufficiently. This can be observed through the decline in performance during the DT condition compared to the single-task condition. Furthermore, the behavior of athletes from various sports can be tested and analyzed in standardized situations using VR technology. This approach facilitates the evaluation of not only kinematics but also decision-making and gaze behavior. However, to better understand the variations in DT capabilities across different sports, additional tests are needed to uncover the unique strengths of athletes from each discipline, or to include a group of basketball experts to gain insight into their intuitive behavior compared to the other groups. Given that, it will also be a challenge to develop a training framework building on the differences between novices and experts with VR, since today's technological limitations restrict the realism of motor tasks. Despite this, we see significant potential for VR applications in DT training, particular in perception, decision-making, visual memory, and anticipation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Otto-von-Guericke University at the Medical Faculty and University of Hospital Magdeburg (139/22). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SP: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. AS: Investigation, Software, Writing–review and editing. AK: Investigation, Writing–review and editing. KA: Investigation, Writing–review and editing. DB: Conceptualization, Methodology, Writing–review and editing. FH: Methodology, Writing–review and editing. KW: Conceptualization, Funding acquisition, Methodology, Supervision, Writing–review and editing.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2025.1523022/full#supplementary-material

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