Postural balance and mental rotation in U-12 gymnasts: comparison with handball players and video gamers

Equilibrio postural y rotación mental en gimnastas U-12: comparación con balonmanistas y video jugadores

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Abstract

Introduction: Shifting from static to dynamic balance can influence cognitive performance, particularly in tasks like mental rotation.
Objective: This study investigates the impact of different postural balance conditions on visual spatial cognitive abilities, specifically mental rotation tasks involving rotated 3D cubes and human body images, in gymnasts, handball players, and video gamers under the age of twelve.
Methodology: Fifty volunteers under the age of twelve (i.e., 12 gymnasts, 18 handball players, and 20 video gamers) participated in this study. The experiment involved mental rotation tasks (i.e., object-based 3D cube and human body conditions) under four different balance conditions: without balance, static balance, dynamic frontal balance, and dynamic sagittal balance, on a stabilometric platform. Cognitive performance was assessed by measuring response time and error rate, and postural control was evaluated using center of pressure (COP) sway, acceleration, and displacement. Results: The results revealed significant immediate beneficial effects of dynamic balance on cognitive tasks. Specifically, dual tasks enhanced performance in postural control and mental rotation tasks, with reduced response time and center of pressure sway ($p<0.01$).
Discussion: Athletes demonstrated greater improvements compared to non-athletes, highlighting the positive effect of regular physical training involving postural control to enhance cognitive abilities.
Conclusions: These results suggest that participation in sports during childhood enhances sensorimotor systems, neuromuscular control and balance, which are critical for maintaining stability and developing cognitive abilities. Integrating balance training and cognitive challenges into physical training may therefore optimize both cognitive and motor performance in young athletes.

Keywords

Balance; postural control; mental rotation; gymnasts; handball players; video gamers.

Resumen

Introducción: La transición del equilibrio estático al dinámico puede influir en el rendimiento cognitivo, particularmente en tareas como la rotación mental.
Objetivo: Este estudio investiga el impacto de diferentes condiciones de equilibrio postural en las habilidades cognitivas visoespaciales, específicamente tareas de rotación mental que involucran cubos 3D rotados e imágenes del cuerpo humano, en gimnastas, balonmanistas y video jugadores menores de doce años.
Metodología: Cincuenta jóvenes voluntarios menores de doce años (12 gimnastas, 18 balonmanistas y 20 video jugadores) participaron en este estudio. El experimento incluyó tareas de rotación mental (cubos 3D y cuerpos humanos) bajo cuatro condiciones: sin equilibrio, equilibrio estático, equilibrio dinámico frontal y equilibrio dinámico sagital en una plataforma estabilométrica. l rendimiento cognitivo se evaluó mediante tiempo de respuesta y tasa de error, mientras el control postural se midió mediante oscilación, aceleración y desplazamiento del centro de presión (COP).
Resultados: Se observaron efectos beneficiosos inmediatos significativos del equilibrio dinámico en las tareas cognitivas. Las tareas duales mejoraron el rendimiento en control postural y rotación mental, con reducción del tiempo de respuesta y oscilación del COP ($p<0,01$).
Discusión: Los atletas mostraron mayores mejoras que los no atletas, destacando el efecto positivo del entrenamiento físico regular con control postural para potenciar habilidades cognitivas.
Conclusiones: Estos resultados sugieren que la práctica deportiva en la infancia mejora los sistemas sensorimotores, el control neuromuscular y el equilibrio, críticos para mantener la estabilidad y desarrollar habilidades cognitivas. Integrar entrenamiento de equilibrio y desafíos cognitivos en el entrenamiento físico podría optimizar tanto el rendimiento cognitivo como motor en jóvenes atletas.

Palabras clave

Equilibrio; control postural; rotación mental; gimnastas; balonmano; video jugadores.

Introduction

Mental rotation (MR) is a fundamental component of spatial cognition and is strongly connected to mathematical development and academic achievement (Bott et al., 2023). This cognitive skill is also closely associated with motor abilities, as motor limitations in children have been shown to affect MR performance (Krüger & Krist, 2009). Moreover, Jansen and Kellner (2015) confirmed the positive relationship between mental rotation task performance and motor ability in children aged seven to eleven . The connection between spatial cognition and motor skills is further reinforced by the link between motor competence and executive functions (Klotzbier & Schott, 2024), which are crucial for spatial problem-solving (Stuhr et al., 2020).

During early childhood, fundamental motor skills provide the foundation for more complex physical activities, while cognitive abilities such as spatial reasoning, memory, and problem-solving develop simultaneously. The under-12 (U-12) age group represents a critical developmental phase, marked by rapid maturation in both physical and cognitive domains. This period offers a valuable opportunity to explore the interaction between motor skills, particularly postural balance, and cognitive abilities like spatial cognition. These systems mutually influence and support each other during this formative stage (Diamond, 2000; Piek et al., 2008), making it an ideal time to enhance training programs and educational approaches. In a sports context, balance is a performance-limiting factor, and efficient execution of sport-specific movements depends on effective postural control (Marcolin et al., 2022). Postural control abilities are crucial in skill-oriented sports, and athletes generally exhibit superior postural control skills compared to non-athletes (Chen et al., 2023). Basically, movement and balance are intimately linked and inseparable when analyzing performance in most sports, as optimal body balance is essential for executing sports movements effectively (Paillard, 2019).

According to Winter (1995) and Rodríguez-Rubio et al. (2020),postural control refers to the capacity to sustain equilibrium within a gravitational field, ensuring that the body's center of mass remains aligned over its base of support or is quickly restored to that position, which is essential for dynamic stability. When standing without external support, humans are inherently in a state of unstable balance, as the force of gravity must constantly be counterbalanced by muscular effort.

The accurate execution of complex sports movements depends on a variety of elements, including strength, joint range of motion (ROM), and sensory information from the somatosensory, visual, and vestibular systems (Ricotti, 2011).

Additionally, athletes develop substantial sensory and motor competence over years of training and engaging in various activities and skills (Blake & Shiffrar, 2007; O'regan & Noë, 2001). This accumulated expertise results in psychological and neurophysiological adaptations across various body systems, notably the sensorimotor system, making athletes significantly different from non-athletes (Klotzbier & Schott, 2024). However, athletes must adjust both mentally and physically adaptation to shifting environmental conditions and novel motor challenges while simultaneously executing precise movements (Geisen et al., 2024). This explains why many studies have examined the relationship between physical activity, motor skills, and cognitive skills (Jansen & Kellner, 2015).

Additionally, cognitive skills are assessed through MR tasks, which were introduced by Shepard and Metzler (1971) as the ability to mentally manipulate two- or three-dimensional objects in one's mind, such as rotating, mirroring, or tilting them. The dependent variables measured are response time (RT), the duration from stimulus presentation to the participant's response (typically a button press), and accuracy (Klotzbier & Schott, 2024).

When the mental rotation (MR) paradigm is used in research studies, participants are typically asked to determine whether pairs of objects, often three-dimensional, presented in different orientations, are identical to a specific target object (Schmidt et al., 2016). Moreover, the influence of sports activities on visual-spatial skills, such as MR ability, has been extensively researched (Geisen et al., 2024; Hegarty & Waller, 2005; Jansen et al., 2011; Jansen & Lehmann, 2013; Jansen et al., 2012; Pietsch & Jansen, 2012a; Pietsch et al., 2019; Schmidt et al., 2016; Voyer & Jansen, 2017).

However, there has been limited research focusing on strategies to enhance both static and dynamic balance in children, as well as the impact of various sports on postural control strategies during early childhood (Ricotti, 2011), and the impact of postural control on cognitive abilities at this critical age. While previous research has underlined the importance of balance for athletic performance, less attention has been paid to its influence on cognitive functions such as MR during critical growing phases.

Despite findings from numerous studies indicating that by the age of six, most children can mentally rotate more complex figures (Estes, 1998), some youngsters (at 4 years of age) can already perform MR tasks with age-appropriate stimuli (Jansen & Kellner, 2015). In this line, only Rogge et al. (2017) have reported beneficial effects of balance training, as compared to relaxation training, on memory and spatial cognition. However, their study involved healthy participants aged between 18 to 65. Additionally, Amara et al. (2024b) showed a significant effect of dynamic balance on human mental rotation tasks (HMR) between two non-contact sports, comparing 20-year-old badminton and volleyball players. The same population also exhibited enhanced cognitive abilities during balance conditions and cube mental rotation task (CMR) (Amara et al., 2024a).

In addition, Jansen and Kellner (2015) and Kail et al. (1980) demonstrated that as children grow, their ability on MR becomes faster, (speed) and more accurate (hit rate) generally increase reaching adult-like proficiency during adolescence. The exploration of the relationship between motor skills and MR has been more associated with athletes over 17 years old as found by Voyer and Jansen (2017) and confirmed by Feng et al. (2019). According to these studies, sports are classified as open-skill sports, which are characterized by dynamic environments where activities are impacted by teammates, opponents and unpredictable situations. In contrast, closed-skill sports involve stable, self-paced movements requiring consistent motor control (Heilmann et al., 2022). Pietsch et al. (2019) suggested that Open-skills may enhance MR ability through visual-spatial abilities in unpredictable environments and Closed-skills may foster MR ability via precise motor control. Also, Geisen et al. (2024) noted that athletes in open-skill sports like soccer rely on extrinsic skills to position themselves and respond to moving objects. In contrast, intrinsic skills are important for preserving balance and coordination during complex movements and rotations in closed-skill sports like gymnastics. Taking all this into account, it is essential to note that the majority of our participants preferred compositional sports (such as gymnastics), which represent closed-skill sports, and game sports (such as handball), which represent open-skill sports.

Building on the scoping review by Morawietz and Muehlbauer (2021) which concluded that although there are encouraging findings showing a correlation between physical exercise and spatial abilities in children and adolescents, little is currently known about the long-term effects of motor training interventions on spatial orientation and spatial abilities in youth. Additionally, Ricotti (2011) emphasized that balance ability is influenced by changes in both the sensory and motor systems, and that these changes are most effective when introduced at appropriate developmental stages through targeted instruction. Furthermore, several studies have shown that motor skills and spatial cognition share common neural substrates, particularly within the parietal cortex (Jordan et al., 2001; Wraga et al., 2003). Subsequently, enhancing dynamic stability may, therefore, facilitate more efficient spatial information processing, leading to improved MR performance.

Accordingly, the primary objective of this research is to delve on the effect of postural balance (i.e., without balance, static balance, dynamic frontal balance, and dynamic sagittal balance) on visual-spatial cognition (i.e., MR tasks with object-based 3D cube and human body conditions) in U-12 gymnasts, handball players, and video gamers, and to compare these groups with each other.

We hypothesize that: (a) dynamic stability will have an immediate beneficial effect on the MR task in skilled U-12 athletes, specifically by reducing RTs; (b) gymnasts and handball players will demonstrate superior ability and faster RTs compared to the video gamers' group in recognizing the correct orientation of rotated 3D cube images and rotated body images; and (c) engaging in sports (i.e., gymnastics and/or handball players) during childhood will result reduced postural sway in both static and dynamic stability compared to non-athletes (i.e., video gamers).

Method

Participants

A minimum sample size of 50 participants (i.e., for 3 groups) was established using G*Power software [Version 3.1, University of Dusseldorf, Germany (Faul et al., 2007)] as an a priori statistical power analysis. The analysis (i.e., for repeated measure ANOVA between and within groups analysis) was computed with an assumed power of 0.90 with an alpha level of 0.050 and a small effect size (d = 0.40 and critical F = 1.871) (Amara et al., 2024a; Amara et al., 2024b).

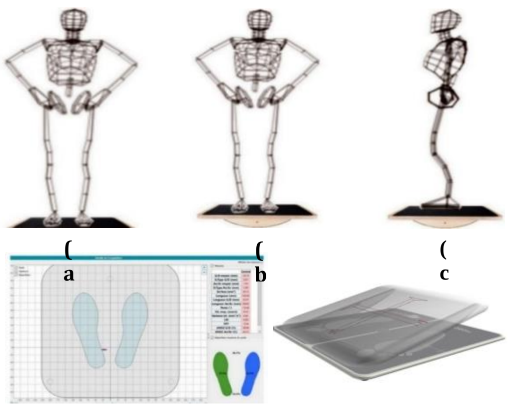
Therefore, fifty volunteer male and female U-12 participants consisting of 12 artistic gymnasts (i.e., 6 males: age at peak height velocity (APHV): M = 14.25, SD = 1.31 years; maturity offset (MO): M = -2.09, SD = 1.02 years; age: M = 12.15, SD = 0.33 years; height: M=1.50, SD = 0.09 m; body mass: M = 36.67, SD = 10.82 kg, and 6 females: APHV: M = 11.98, SD = 0.31 years ; MO M = 0.001, SD = 0.40 years; age: M = 11.98, SD = 0.33 years; height: M = 1.52, SD = 0.03 m; body mass: M = 34.83, SD = 1.17 kg), 18 handball players (i.e., 9 males: APHV: M= 12.27, SD = 1.27 years; MO: M = -0.36, SD = 1.29 years; age: M= 11.92, SD = 0.27 years; height: M = 1.66, SD = 0.11 m; body mass: M = 46.50, SD = 9.92 kg, and 9 females: APHV: M = 11.14, SD= 0.25 years; MO: M = 0.84, SD = 0.28 years; age : M = 12.98, SD = 0.22 years; height: M = 1.66, SD = 0.03 m; body mass : M = 39.13, SD = 1.81 kg), and 20 video gamers (i.e., 10 males: APHV: M = 13.51, SD = 0.97 years; MO: M = -1.29, SD = 1.04 years; Age : M = 12.22, SD = 0.23 years; height : M = 1.57, SD = 0.09 m; Body mass: M = 38.2, SD = 3.36 kg , and 10 females: APHV: M = 11.74 SD = 0.31 years; MO: M = 0.21, SD = 0.42 years; age : M = 11.95, SD = 0.28 years; Height : M = 1.56, SD = 0.04 m; Body mass : M = 37.30, SD = 2.87 kg) accepted to take part in this research.

There were no injuries or medical conditions that affected any of the participants' ability to balance. Each participant read and signed an authorization agreement to participate in the study after receiving explanations on its procedures, techniques, advantages, and any possible risks. The Local Ethical Committee of the National Observatory of Sport (ONS/UR/18JS01-2024/3) authorized the experimental procedure, which was carried out in compliance with the Declaration of Helsinki for Human Experimentation (Carlson et al., 2004).

Procedure

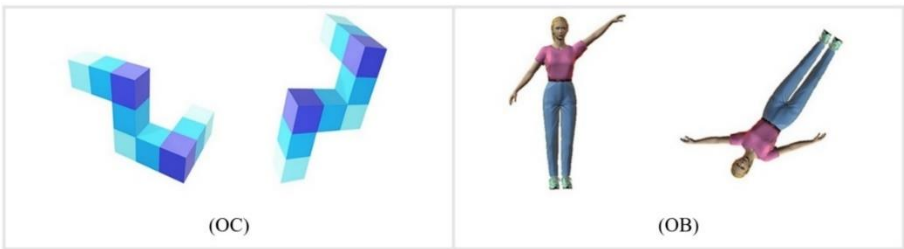
This study consisted of seven randomized assessments using a Latin Square design (Zar, 1984). Each assessment was conducted on a different consecutive day. All evaluations took place at the youth center at the same time each day (i.e., between 09:00AM and 12:00PM). Each assessment involved a MR task with 3D object-based cubes (OC) and/or human body figures (OB) under three conditions: without balance (i.e., sitting on a chair), static balance (i.e., standing position; see Figure 1a), and dynamic balance (i.e., frontal balance, Figure 1b, and sagittal balance, Figure 1c, using a single-plane balance board, i.e., Freeman tray) on a stabilometric platform [Posture-Win©, Techno Concept®, Cereste, France, frequency 40 Hz, A/D conversion 12 (Maatoug et al., 2023)]. In both MR tasks, no rotation angle appeared twice in succession, and the sequence of stimulus presentation was counterbalanced. A black fixation cross was shown in the center of each trial for 500 milliseconds, following a blank screen for 1000 milliseconds. After fixation, the test image was displayed on the screen for up to 5000 milliseconds or until a response was made. The free program OpenSesame was used to present stimuli and record response times (RT, in ms) and error rate (EP, in percentage) (Mathôt et al., 2012).

Figure 1. Posture-Win© stabilometric force platform experimental protocol: (a) Bipedal sway, standing balance; (b) Bipedal sway, frontal balance with single plane balance board; (c) Bipedal sway, sagittal balance with single plane balance board.



Seven rotation angles (i.e., 45°, 90°, 135°, 180°, 225°, 270°, and 315°) served as stimuli, with six images presented per angle in the MR task. Both OC and OB conditions featured pairs of standard and comparison images (Figure 2). The comparison image, rotated to one of the seven orientations, was positioned on the right side of the screen (Amara et al., 2024a; Amara et al., 2024b; Habacha et al., 2022; Khalfallah et al., 2021, 2022).

Figure 2. Examples of two stimuli conditions: [OC – object-based cube; OB – object-based human body (Amara et al., 2024a; Amara et al., 2024b)].



The participant performs the MR test (i.e., OC and/or OB) in front of the PC, using a wireless joystick. The left button is used to indicate matching figures (i.e., identical), while the right button indicates non-matching figures (i.e., mirror images). Participants were instructed to respond as accurately and quickly as possible to the displayed stimuli, pairs of 3D rotated OC and/or OB figures. The MR test (i.e., OC and OB) was studied under four conditions (i.e., without balance, static balance, frontal balance, and sagittal balance):

a) Without balance (WB): The participant sitting on a chair.

b) Static Balance (ST): The participant stands upright on the Posture-Win stabilometric platform.

c) Dynamic Frontal Balance (FB): The participant stands upright on the Posture-Win stabilometric platform, equipped with a Freeman try [single-plane balance board (SPBB)] positioned in the frontal plane.

d) Dynamic Sagittal balance (SB): The participant stands upright on the Posture-Win stabilometric platform, equipped with a Freeman try (SPBB) positioned in the sagittal plane.

This results in a total of 168 trials: 4 (conditions: WB, ST, FB, and SB) × 3 (groups: gymnasts, handball players and video gamers) × 2 (MR task: OC and OB) × 7 (angle display: 45°, 90°, 135°, 180°, 225°, 270°, and 315°) × 2 (responses: same or different).

In all trials, subjects were instructed to keep their body straight and their arms loosely hanging by their sides (Waer et al., 2024).

To quantify the postural sway of participants we analyzed the Center of Pressure (COP) trajectory over time. This measurement will be obtained using a Posture-Win stabilometric platform which provides precise data on the COP's movement patterns during static and dynamic balance tasks. During bipedal standing, the COP represents the point of application of vertical ground reaction forces exerted by the feet on a force plate (Winter, 1995). In a controlled stance position, the palm of the hand is oriented towards the body without making contact, while the feet are positioned narrowly on either side of a three-centimeter-wide tape. This setup ensures the heels remain aligned with another tape to maintain standardized foot placement. Such methodologies are noted to be essential in research and clinical assessments to ensure consistency in body positioning which can significantly impact balance and coordination measurements (Richer & Lajoie, 2019). Finally, we measured the left/right sway displacements (dL/R) and forward/backward sway displacements (dF/B), as well as the resultant velocity (vt) and acceleration (at) of the COP.

Data analysis

As part of statistical analysis, the SPSS 25 package (SPSS. Chicago. IL. USA) program was used for data analysis. Descriptive statistics (i.e., means ± SD) were performed for all variables. The effect size was conducted using G*Power software (Version 3.1. University of Dusseldorf. Germany). The following scale was used for the interpretation of d: < 0.2, trivial; 0.2 – 0.59, small; 0.6 – 1.19, moderate; 1.2 – 2.0, large; and > 2.0 very large (Hopkins, 2002). The normality of distribution estimated by the Kolmogorov-Smirnov test was acceptable for all variables (p>0.05). Consequently, ANOVA with repeated measures with four factors (i.e., stimulus, angles, balance, and groups) was used to benchmark different conditions. The Bonferroni test was applied in post-hoc analysis for pairwise comparisons. Additionally, effect sizes (d) were determined from ANOVA output by converting partial eta-squared to Cohen's d. A priori level less than or equal to 0.5% (p≤0.05) was used as a criterion for significance.

Results

Repeated measures ANOVA showed a significant interaction (p<0.05) in RT between balance * groups, stimulus * groups, and balance * angle (Table 1). In addition, a significant difference between conditions (i.e., WB, ST, SB, and FB, p<0.001), groups (i.e., gymnasts, handball players and video gamers, p<0.05), and angles (i.e., 45°, 90°, 135°, 180°, 225°, 270°, and 315°, p<0.001) was observed (figure 3 and 4).

Table 1. Response time, ANOVA repeated measures between conditions.

Response time (ms)	df	Mean Square	F	P value	Effect Size	Power
Stimulus	1	552994.222	0.270	0.606	0.155	0.080
Groups	2	25554471.478	3.380	0.043*	0.759	0.609
Stimulus * Groups	2	2049048.109	0.999	0.376	0.413	0.214
Balance	3	235910648.594	98.390	0.001**	2.895	1.000
Balance * Groups	6	5490404.560	2.290	0.039*	0.625	0.783
Angles	6	10161423.069	22.228	0.001**	1.375	1.000
Angles * Groups	12	319034.763	0.698	0.753	0.345	0.405
stimulus * Balance	3	2474375.462	1.879	0.136	0.397	0.479
Stimulus * Balance * Groups	6	829229.638	0.630	0.706	0.326	0.245
Stimulus * Angles	6	764539.874	2.825	0.011*	0.917	0.883
Stimulus * Angles * Groups	12	164510.746	0.608	0.835	0.320	0.351
Balance * Angles	18	468006.425	1.673	0.039*	0.752	0.950
Balance * Angles * Groups	36	315919.771	1.129	0.278	0.439	0.959
Stimulus * Balance * Angles	18	163855.315	0.606	0.897	0.229	0.455
Stimulus * Balance * Angles * Groups	36	320298.010	1.184	0.214	0.449	0.969

(*) Significant at p<0.05; (**) Significant at p<0.001.

Figure 3. Response time of groups as a function of balance conditions.

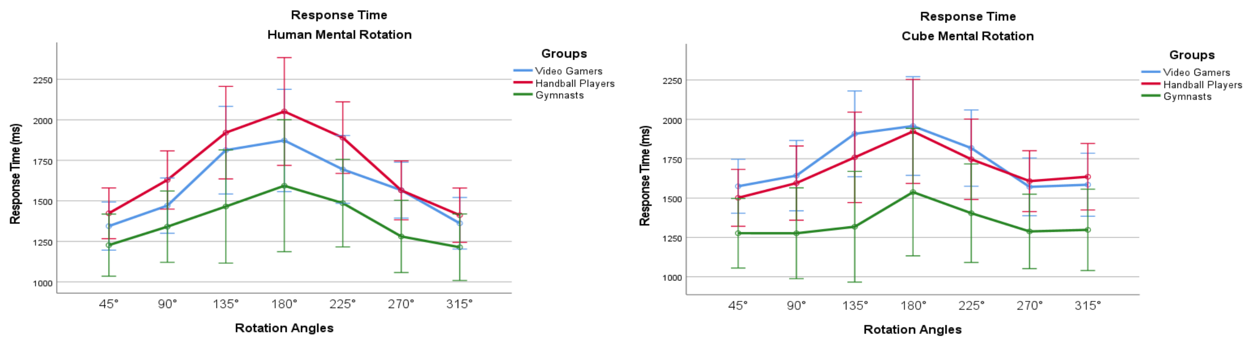
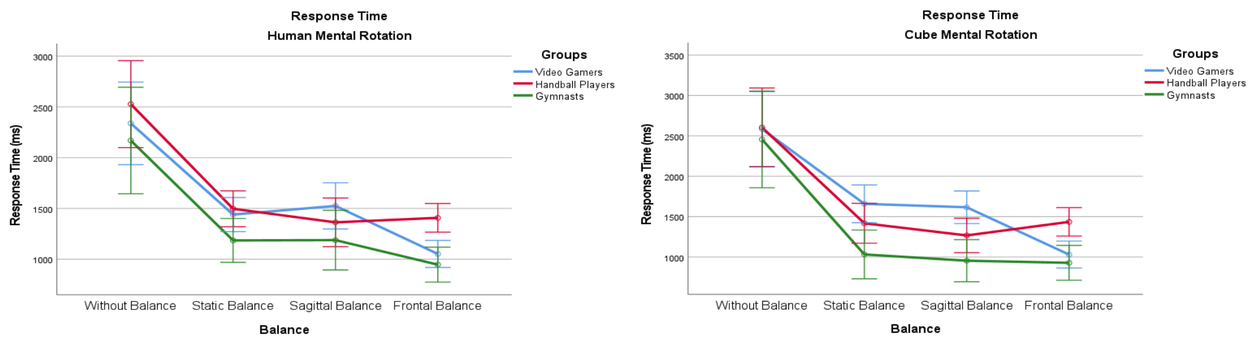


Figure 4. Response time of groups as a function of rotation angles.



The Bonferroni pairwise comparison of RT between groups (i.e., gymnasts, handball players and video gamers) indicates a significant difference (p<0.05) between gymnasts and video gamers and gymnast and handball players (table 2).

Table 2. Bonferroni pairwise comparison of response time between groups.

Groups	Mean Diff. (ms)	Std. Err. Diff. (ms)	P value	CI 95% LB	CI 95% UB	Effect Size
Gymnasts vs. Video Gamers	-298.145	134.171	0.031*	-568.063	-28.227	0.811
Gymnasts vs. Handball players	-332.466	136.938	0.019*	-607.950	-56.982	0.904
Handball players vs. Video Gamers	34.321	119.380	0.775	-205.840	274.483	0.095

(*) Significant at p<0.05

In addition, Bonferroni pairwise comparison of RT between balance conditions (i.e., WB, ST, SB, and FB) indicate a significant difference (p<0.01) between all conditions except between ST and SB (table 3).

Table 3. Bonferroni pairwise comparison of response time between balance conditions.

Balance	Mean Diff. (ms)	Std. Err. Diff. (ms)	P value	CI 95% LB	CI 95% UB	Effect Size
WB vs. ST	1074.676	97.699	0.001**	878.132	1271.221	2.694
WB vs. SB	1127.357	112.106	0.001**	901.828	1352.885	2.463
WB vs. FB	1313.008	109.782	0.001**	1092.156	1533.860	2.929
ST vs. SB	52.680	37.098	0.162	-21.951	127.312	.347
ST vs. FB	238.331	59.734	0.001**	118.163	358.500	1.387
SB vs. ST	185.651	63.436	0.005*	58.035	313.267	0.716

(WB) without balance; (ST) Static balance; (SB) Sagittal balance; (FB) Frontal balance; (*) Significant at p<0.01; (**) Significant at p<0.001.

Furthermore, pairwise comparison of RT between MR angles revealed no significant difference between following pairs angle: 45° and 315°, 90° and 270°, and 225° and 135° (table 4). Consequently, thus a quasi-similarity (p>0.05), we averaged each of these angle pairs and calculated the slope for each condition.

Table 4. Bonferroni pairwise comparison of response time between angles.

Angles	Mean Diff. (ms)	Std. Err. Diff. (ms)	P value	CI 95% LB	CI 95% UB	Effect Size
45° vs. 90°	-101.045	34.713	0.005**	-170.878	-31.212	.713
45° vs. 135°	-305.862	54.942	0.001**	-416.390	-195.334	1.363
45° vs. 180°	-431.371	64.944	0.001**	-562.021	-300.721	1.626
45° vs. 225°	-281.688	47.449	0.001**	-377.143	-186.233	1.454
45° vs. 270°	-88.323	33.295	0.011*	-155.303	-21.343	0.649
45° vs. 315°	-26.269	34.320	0.448	-95.312	42.775	0.187
90° vs. 135°	-204.817	50.591	0.001**	-306.593	-103.041	0.991
90° vs. 180°	-330.326	60.421	0.001**	-451.877	-208.775	1.339
90° vs. 225°	-180.642	34.318	0.001**	-249.682	-111.603	1.289
90° vs. 270°	12.722	34.523	0.714	-56.729	82.173	0.090
90° vs. 315°	74.777	40.921	0.074	-7.546	157.099	0.447
135° vs. 180°	-125.509	51.257	0.018*	-228.625	-22.393	0.609
135° vs. 225°	24.174	46.880	0.609	-70.137	118.485	0.126
135° vs. 270°	217.539	48.278	0.001**	120.415	314.662	1.103
135° vs. 315°	279.593	50.517	0.001**	177.966	381.220	1.355
180° vs. 225°	149.683	48.335	0.003**	52.445	246.922	0.758
180° vs. 270°	343.048	68.245	0.001**	205.757	480.339	1.231
180° vs. 315°	405.102	69.883	0.001**	264.516	545.688	5.796
225° vs. 270°	193.364	43.611	0.001**	105.630	281.099	1.086
225° vs. 315°	255.419	51.066	0.001**	152.687	358.151	1.225
270° vs. 315°	62.055	32.281	0.061	-2.886	126.995	1.626

(*) Significant at p<0.05; (**) Significant at p<0.001.

Slope analysis revealed significantly steeper slopes for gymnasts (0.26 ms/°) compared to video gamers (0.14 ms/°). However, there were no significant differences between the slopes of handball players (0.21 ms/°) and video gamers, nor between gymnasts and handball players.

Regarding the error percentage (EP), repeated measures ANOVA showed no significant interaction between factors (i.e., stimulus, angles, balance, and groups). There is only a significant difference in EP between stimuli (i.e., CMR and HMR, p<0.05), groups (i.e., gymnasts, handball players, and video gamers), and angles (i.e., 45°, 90°, 135°, 180°, 225°, 270°, and 315°, p<0.001) (table 5).

Table 5. Error percentage, ANOVA repeated measures between conditions.

Error percentage (%)	df	Mean Square	F	P value	Effect Size	Power
Stimulus	1	25645.040	6.013	0.018*	0.713	0.671
Groups	2	59776.968	5.240	0.009**	0.943	0.808
Stimulus * Groups	2	463.170	0.109	0.897	0.141	0.066
Balance	3	1279.111	1.319	0.271	0.333	0.346
Balance * Groups	6	683.358	0.705	0.646	0.345	0.273
Angles	6	4319.690	13.677	.001**	1.077	1.000
Angles * Groups	12	390.513	1.236	0.257	0.458	0.698
Stimulus * Balance	3	5364.873	3.436	0.070	0.540	0.443
Stimulus * Balance * Groups	6	618.042	1.187	0.316	0.449	0.456
Stimulus * Angles	6	638.614	1.849	0.090	0.397	0.686
Stimulus * Angles * Groups	12	420.143	1.217	0.271	0.454	0.689
Balance * Angles	18	139.188	0.605	0.898	0.229	0.455
Balance * Angles * Groups	36	250.504	1.089	0.333	0.429	0.950
Stimulus * Balance * Angles	18	268.275	1.265	0.203	0.326	0.852
Stimulus * Balance * Angles * Groups	36	264.854	1.249	0.152	0.458	0.977

(*) Significant at p<0.05; (**) Significant at p<0.001.

The pairwise comparison of EP between groups showed a significant difference (p<0.01) only between handball players and video gamers (Table 6).

Table 6. Bonferroni pairwise comparison of error percentage between groups.

Groups	Mean Diff. (%)	Std. Err. Diff. (%)	P value	CI 95% LB	CI 95% UB	Effect Size
Gymnasts vs. Video Gamers	-7.564	5.212	0.153	-18.049	2.920	0.529
Gymnasts vs. Handball players	7.440	5.319	0.168	-3.260	18.141	0.521
Handball players vs. Video Gamers	-15.005	4.637	0.002*	-24.333	-5.677	1.051

(*) Significant at p<0.01.

The pairwise comparison of EP between angles showed the same kinetic aspect as that of RT (Table 7). Thus, the main effect of angle was significant (p<0.01) and supported the classical monotonic increase in error rates as a function of angle (figure 5).

Figure 5. Error percentage of groups as a function of rotation angles.

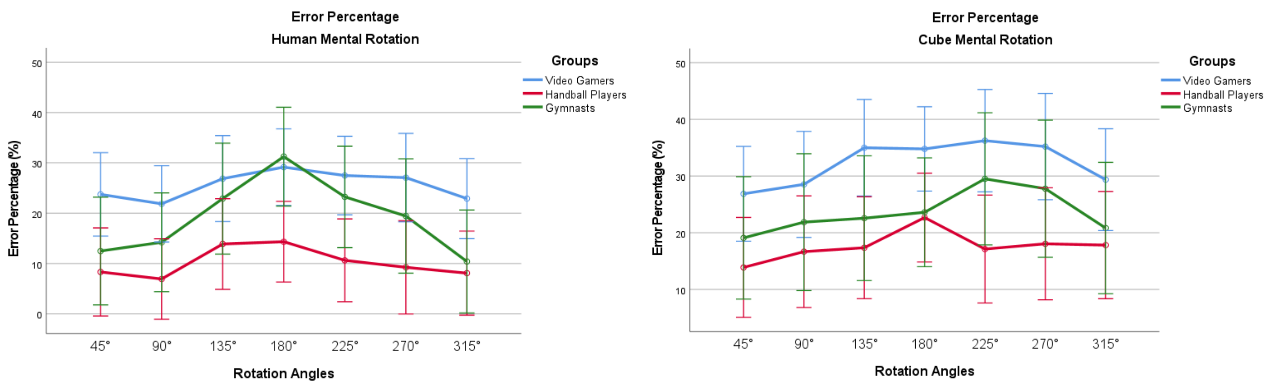


Table 7. Bonferroni pairwise comparison of error percentage between angles.

Angles	Mean Diff. (%)	Std. Err. Diff. (%)	P value	CI 95% LB	CI 95% UB	Effect Size
45° vs. 90°	-0.949	0.804	0.244	-2.567	0.669	0.289
45° vs. 135°	-5.694	1.166	0.001**	-8.040	-3.349	1.196
45° vs. 180°	-8.569	1.496	0.001**	-11.578	-5.559	1.403
45° vs. 225°	-6.643	1.481	0.001**	-9.623	-3.664	1.098
45° vs. 270°	-5.397	1.190	0.001**	-7.791	-3.004	1.110
45° vs. 315°	-0.837	1.028	0.420	-2.906	1.231	0.199
90° vs. 135°	-4.745	1.318	0.001**	-7.397	-2.094	0.881
90° vs. 180°	-7.620	1.554	0.001**	-10.746	-4.494	1.201
90° vs. 225°	-5.694	1.499	0.001**	-8.710	-2.679	0.923
90° vs. 270°	0.112	1.041	0.915	-1.982	2.206	0.026
90° vs. 315°	-4.448	1.169	0.001**	-6.800	-2.097	0.932
135° vs. 180°	-2.874	1.156	0.017*	-5.200	-0.549	0.609
135° vs. 225°	-0.949	1.199	0.433	-3.361	1.463	0.193
135° vs. 270°	0.297	1.199	0.805	-2.115	2.709	0.060
135° vs. 315°	4.857	1.420	0.001**	2.000	7.714	0.837
180° vs. 225°	1.925	1.097	0.086	-0.282	4.132	0.429
180° vs. 270°	3.171	1.306	0.019*	0.543	5.799	0.604
180° vs. 315°	7.731	1.579	0.001**	4.556	10.907	1.199
225° vs. 270°	1.246	1.152	0.285	-1.072	3.564	0.264
225° vs. 315°	5.806	1.592	0.001**	2.603	9.009	0.893
270° vs. 315°	4.560	1.244	0.001**	2.058	7.063	0.897

(*) Significant at p<0.05; (**) Significant at p<0.001.

On the other side, balance (i.e., acceleration, velocity, and sway displacement) was reduced when introducing MR tasks with OC (i.e., acceleration p<0.001, d=1.067; velocity p<0.001, d=1.478; left/right sway displacements p<0.01, d=0.925; forward/backward sway displacements p<0.01, d=0.812) and OB (i.e., acceleration p<0.01, d=0.854; velocity p<0.001, d=1.038; left/right sway displacements p<0.05, d=0.707; left/right sway displacements p<0.001, d=1.333) in balance conditions (figure 6 and 7).

Figure 6. COP sway displacements of groups as a function of balance conditions.

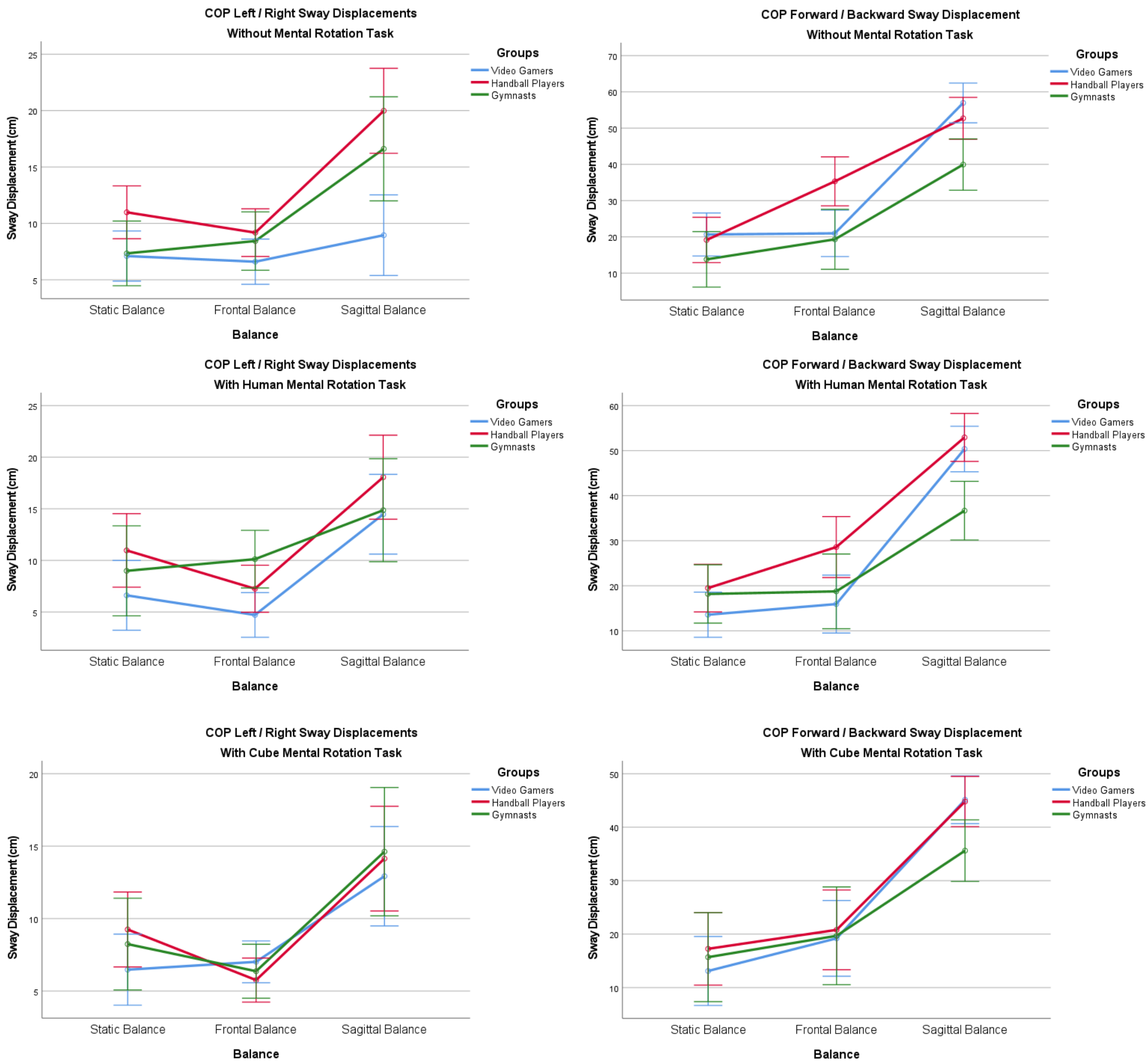
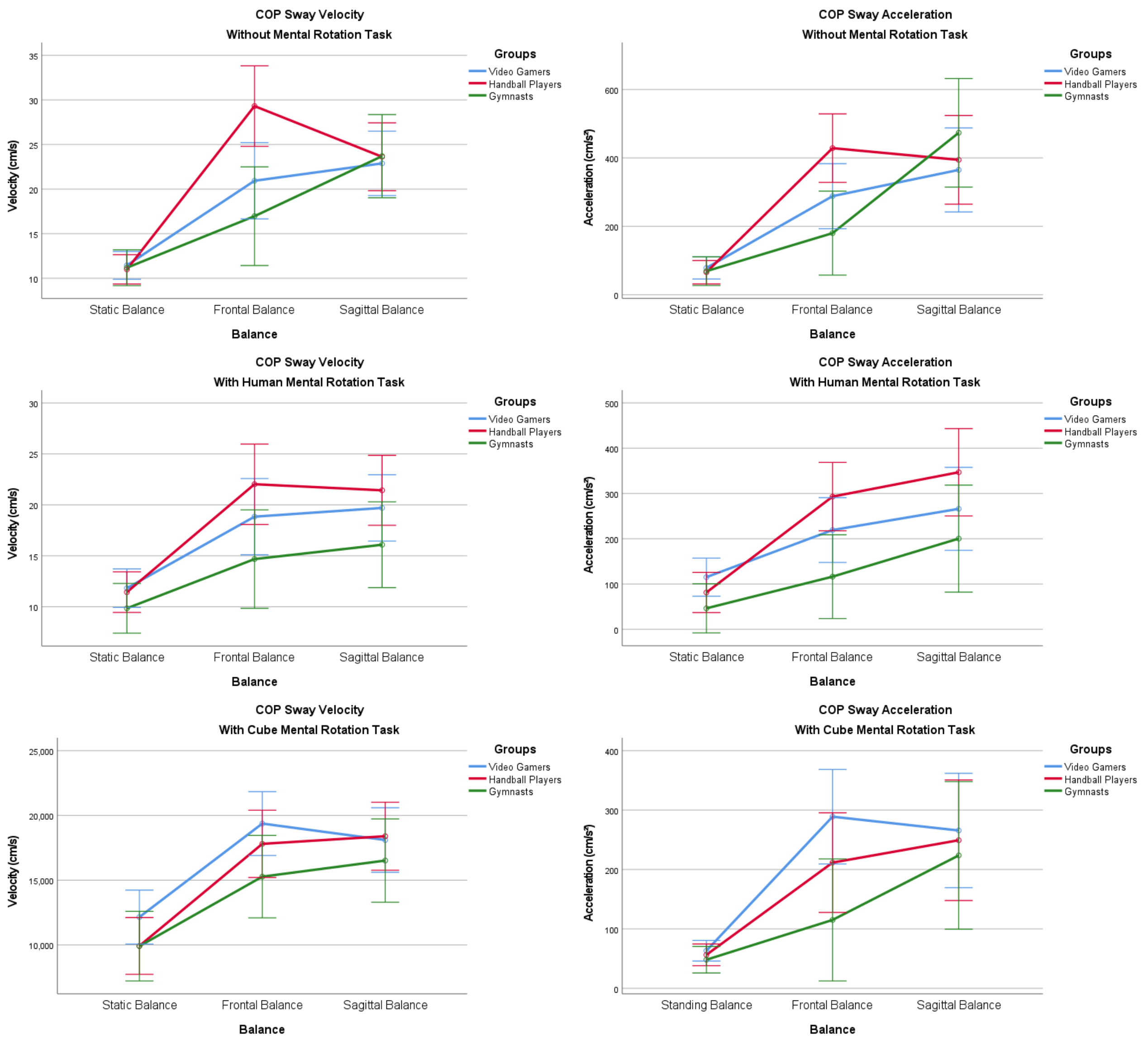


Figure 7. COP velocity and acceleration of groups as a function of balance conditions.



Discussion

The purpose of this study was to compare MR performances (i.e., OC and OB) in various upright conditions (i.e., WB, ST, FB, and SB) among three groups (i.e., gymnasts, handball players, and video gamers) of young people U-12 years old.

The results of our study provided a significant interaction in RT between balance and groups, stimulus and groups, and balance and angle. Thus, a notable distinction between conditions (i.e., WB, ST, SB, and FB, $p<0.001$), groups (i.e., gymnasts, handball players, and video gamers, $p<0.05$), and angles (i.e., 45°, 90°, 135°, 180°, 225°, 270°, and 315°, $p<0.001$) was observed.

These findings align with previous studies that have demonstrated the influence of balance conditions on cognitive performance, particularly in MR tasks. For instance, Amara et al. (2024b) found that dynamic stability has an immediate beneficial effect on MR tasks, reducing RTs for skilled athletes. This further supports the idea that postural control and cognitive processes are closely connected, with bidirectional improvements between the two domains. Similarly, Woollacott and Shumway-Cook (2002) emphasized the common neural substrates involved in maintaining balance and executing cognitive tasks, supporting the idea that balance conditions can modulate cognitive performance. Furthermore, Bonferroni pairwise comparison between balance conditions (i.e., WB, ST, SB, and FB) revealed a significant difference (p<0.01) across all conditions, except between ST and SB.

This notable decrease in RTs during dynamic balance conditions (SB, FB) compared to the static balance (ST) condition suggests that unstable equilibrium positions, may enhance cognitive processing abilities, allowing participants to complete (MR) tasks more quickly. Pairwise comparisons between MR conditions showed significant differences in RT across all angles of rotation (45°, 90°, 135°, 180°, 225°, 270°, and 315°) under all balance conditions (WB, ST, SB, and FB), but no significant difference was observed between ST and SB.

These findings align with Kawasaki and Higuchi (2013), who demonstrated that MR interventions have immediate beneficial effects when performed under dynamic balance conditions. They suggested that mentally imagining foot movements is closely related to postural stability, particularly during challenging postural tasks. Similarly, Bigelow and Agrawal (2015) showed that vestibular function links the cognitive regions responsible for visuospatial skills (such as mental rotation, spatial memory, and navigation) with motor performance, reinforcing the idea that both processes share common neural substrates. In this line also, Rogge et al. (2017) found that manipulating the vestibular system during balance training causes modifications in certain parts of the brain associated with spatial processing, such as the hippocampus and parietal cortex. These changes may mediate the observed improvements in spatial cognition. Taking together, the results of these studies corroborate with our findings in accordance with hypothesis (a) that dynamic stability will have an immediate beneficial effect on the MR task in skilled U-12 athletes, specifically by reducing RTs.

In addition, significant differences were observed also between balance conditions (i.e., WB, ST, SB, and FB), groups (i.e., gymnasts, handball players, and video gamers), and angles of rotation (i.e., 45°, 90°, 135°, 180°, 225°, 270°, and 315°). Bonferroni pairwise comparisons indicated significant differences between gymnasts and video gamers, as well as between gymnasts and handball players, but there was no significant difference between handball players and video gamers.

Since the RTs increase from 45° to 180° and then decrease to 315°, and there are no significant differences between the following RT angle pairs: 45° and 315°, 90° and 270°, and 135° and 225°, we averaged these angles and observed a linear increase in slope (Habacha et al., 2014). In fact, the monotonic increase in RTs with increasing angles of rotation up to 180° is consistent with classical findings in MR research (Shepard & Metzler, 1971). This linear relationship reflects the progressive complexity of the task as the angle of rotation increases, requiring greater cognitive resources for accurate judgment. Additionally, numerous studies on mental rotation have confirmed a linear increase in response time with the degree of rotation as well as a reduction in accuracy as the angular disparity between figures increase (Armitage et al., 2020; Cheung et al., 2009) . Specifically, response time increased approximately linearly with the angle of rotation up to 180°, after which it begins to decrease. This decline is attributed to participants mentally rotating in the opposite direction ,resulting in a concave upward pattern (Cooper & Shepard, 1973). Likewise, figures with a big angular difference may become more comparable than those with a lesser rotation (Cheung et al., 2009).

Furthermore, the significant differences between groups suggest that sport-specific training plays a critical role in shaping cognitive-motor integration during development. These results corroborate findings from Voyer and Jansen (2017), who reported that athletes outperform non-athletes in MR tasks due to enhanced visuospatial skills developed through regular physical activity. Likewise, motor competences seem to be involved in MR processes because motor specialists outperform non-motor experts in the MR test (Jansen et al., 2011; Jansen et al., 2012; Pietsch & Jansen, 2012a, 2012b; Steggemann et al., 2011; Voyer & Jansen, 2017) and motor training has positive effects on MR ability in children (Blüchel et al., 2013; Jansen et al., 2011; Pietsch et al., 2017). As a result, gymnasts' superior performance aligns with studies showing that closed-skill sports foster advanced motor-cognitive integration, particularly for tasks involving body-centered spatial processing (Geisen et al., 2024).

Additionally, their superior performance compared to handball players, and video gamers supports the notion that closed-skill sports enhance precise visuospatial processing, particularly for body-related stimuli (Moreau et al., 2011). Moreover, Jansen and Lehmann (2013) demonstrated that, regardless of the type of stimulus, gymnasts have higher mental rotation performance attributed to their extensive practice of rotational movements around the three axes. In contrast, handball players' intermediate performance underscores their adaptability to dynamic environments, which may prioritize rapid decision-making over fine-grained spatial precision (Chen et al., 2023). Our result seems to be as the interpretation of Hofmann et al. (2024) when analyzed the relationship between the visuospatial ability MR and motor function by the finding of Wohlschläger and Wohlschläger (1998) who assumed that motor and MR share common processes. Moreover, Bonferroni pairwise comparison of RT between groups (i.e., gymnasts, handball players and video gamers) indicate a significant difference ($p<0.05$) between gymnasts and video gamers and gymnast and handball players. The superior performance of gymnasts compared to handball players, and video gamers supports previous research showing that closed-skill sports like gymnastics foster advanced spatial cognition and body awareness. For example, Pietsch et al. (2019) and Schmidt et al. (2016) highlighted that athletes engaged in precise, controlled movements develop enhanced visuospatial skills, particularly for body-related stimuli. Handball players, on the other hand, demonstrated intermediate performance, likely due to their experience with unpredictable environments requiring rapid decision-making. Their performance between those of gymnasts and video gamers, reflecting the adaptability characteristic of open-skill sports. This finding is consistent with Moreau et al. (2011), who argued that open-skill athletes prioritize adaptability over absolute precision. This result is consistent with our hypothesis (b) about gymnasts and handball players compared to the video gamers' group in terms of correctly detecting the orientation of rotated 3D OC and OB images. More specifically the lack of significant difference between handball players and video gamers in RT ($p>0.05$) is fascinating. It can be explained by the fact that both groups operate in dynamic and unpredictable contexts, where cognitive efficiency relies more on rapid processing mechanisms rather than on the fine-tuning of attentional resources. While our results show that video gamers performed worse than handball players in MR tasks, especially under dynamic balance conditions, this does not contradict with Bediou et al. (2023) findings. Instead, it highlights a critical distinction that the cognitive advantages gained through video gaming may not fully translate into motor-cognitive integration required for physical tasks. Video gamers excel in virtual environments where spatial navigation and quick reactions are prioritized, but they lack the embodied experience and sensorimotor training provided by sports. To investigated the influence of video game on cognition Powers et al. (2013) demonstrated that training with a first-person shooter video game improved perceptual processing and spatial imagery, but not motor skills or executive functions . This suggests that while gaming enhances certain aspects of spatial cognition, it does not foster the same level of adaptability in dynamic, real-world contexts as athletic training does.

The interaction between stimulus type (i.e., OC and OB) and groups (i.e., gymnasts, handball players, and video gamers) highlights the importance of sport-specific demands in shaping cognitive abilities. These results align closely with Ozel et al. (2004) findings when examined the relationship between motor skills and cognitive abilities in athletes from different sports disciplines. They found that gymnasts, due to their specialized training in precise body control and spatial awareness, demonstrated superior performance in tasks requiring MR and visuospatial processing compared to athletes from open-skill sports. Ozel et al. (2004) attributed this advantage to the closed-skill nature of gymnastics, which emphasizes pre-planned movements and fine-grained spatial precision may them exhibit superior performance in body-related spatial tasks. Conversely, open-skill athletes like handball players may show greater adaptability in dynamic environments, which could explain their intermediate performance compared to gymnasts and video gamers.

Regarding the EP, repeated measures ANOVA showed no significant interaction between factors (i.e., stimuli, angles, balance, and groups). However, there is a significant difference between only stimuli (i.e., CMR and HMR, $p<0.05$), groups (i.e., gymnasts, handball players, and video gamers), and angles (i.e., 45°, 90°, 135°, 180°, 225°, 270°, and 315°, $p<0.001$). These data support the idea that MR performance is modulated by motor expertise and the intrinsic/extrinsic spatial abilities developed through different sports specialties (Klotzbier & Schott, 2024; Pietsch et al., 2019). Furthermore, team sports like soccer which rely on extrinsic and dynamic abilities enhance MR skills (Matos & Godinho, 2006). Consistent with embodied cognition, sensorimotor integration may explain both the superior MR performance of athletes and the selective effects of motor expertise (Habacha et al., 2014). This advantage is particularly evident in sports requiring dynamic spatial transformations, were athletes distinct judgment for both cube and body related stimuli (Feng et al., 2017).

More specifically, the pairwise comparison between angles and EP of OB exhibited the same kinetic pattern as that of RT. Thus, the main effect of angle was significant (p<0.01) and supporting the classical monotonic increase in error rates as a function of angle. This observation is associated with Cooper and Shepard (1973) studies, who were the first to document the linear relationship between angular disparity and task difficulty. The concave upward relationship between angular disparity and error percentage (EP) near 180° orientation mirrored the pattern observed for reaction time (RT)(Cooper & Shepard, 1973). Moreover Jost and Jansen (2024) supported the result that accuracy decreases (increasing EP) with angular disparity, which is interpreted as the involvement of MR ability. Correspondingly, Jola and Mast (2005) confirmed that egocentric MR tasks represent faster RT than object-based MR tasks and verified an increase of RT with increasing angular disparity. Moreover, Jost and Jansen (2022) demonstrated that numerous studies have shown an increase in RT and EP with increasing angular disparity. They also highlighted that faster reaction times and fewer errors triggered the importance of motor processes and the link between motor preparation and MR. Likewise Zwierko et al. (2022) affirmed that motor expertise from specific sports specialties may influence cognitive functioning. Thus, the performance of handball players showed the same concave upward relationship between rotated angles and EP for both OC and OB, (Figure 5). This pattern can be attributed to the influence of their specialty which involve manipulating objects (i.e., ball) which supported by the suggestion of Heppe et al. (2016) that physical exercise may positively influence the cognitive performance of athletes. Which also proved by our results that although gamers demonstrated reaction times (RT) comparable to those of handball players, this similarity did not translate into greater accuracy or precision. The significant difference observed in error percentage (EP) between gamers and handball players highlights the distinct impact of real-world physical activity and sports participation on cognitive and motor performance. However, gymnasts and gamers showed an increase in EP with greater rotation angle in (OC) indicating that accuracy decreases with angular disparity increases. This highlights the easier discrimination of human figures compared to objects cube. These findings align with (Jansen et al., 2020; Kaltner & Jansen, 2014) results demonstrated the superior MR performance for OB over OC, with OC stimuli exhibiting higher EP than OB stimuli.

On the other side, balance (i.e., acceleration, velocity, and displacement) was reduced when introducing MR tasks with object-based cube (i.e., acceleration p<0.001, d=1.067; velocity p<0.001, d=1.478; horizontal displacement p<0.01, d=0.925; vertical displacement p<0.01, d=0.812) and object-based human (i.e., acceleration p<0.01, d=0.854; velocity p<0.001, d=1.038; horizontal displacement p<0.05, d=0.707; vertical displacement p<0.001, d=1.333) in balance conditions. Our findings align with recent studies involving both adults and children have demonstrated that maintaining or regaining stability demands attentional resources (Amara et al., 2024b; Beauchet et al., 2005; Broglio et al., 2005; Hofmann et al., 2023; Huxhold et al., 2006; Mujdeci et al., 2016; Schmid et al., 2007; Woollacott & Shumway-Cook, 2002). Moreover, Bigelow and Agrawal (2015) suggest that balance requires significant cognitive resources and is not merely a reflexive process. Interestingly, balance as measured by sway velocity, did not deteriorate when attention-demanding tasks were introduced. This finding indicates that the brain prioritizes maintaining balance, often at the expense of performing cognitive tasks. Moreover Lacroix et al. (2021) affirmed that previous studies have demonstrated a strong relation between cognitive functions and the vestibular system. The significant difference observed between groups and balance condition along with the superior performance of gymnasts underscore the beneficial effects of sport activities. This finding is supported by Andreeva et al. (2021), who demonstrated that practicing any kind of sport was associated with increased postural stability in normal bipedal stance. Additionally, proprioceptive reweighting processes can be improved by gymnastic training during childhood, leading to similar control and coordination of posture as adults (Busquets et al., 2021). These results demonstrated that athletes often exhibit superior postural control compared to non-athletes affirm our third hypothesis that (c) engaging in sports (i.e., gymnastics and/or handball) during childhood will result in reduced postural sway in both static and dynamic stability compared to non-athletes (i.e., video gamers).

The present exploration offers a new perspective on the link between cognitive abilities and postural stability. Nevertheless, this study has certain limitations that should be recognized. First, our experimental sample was comprised of athletes from single sport discipline (i.e., handball) for open skill – sport and (i.e., gymnastic) for closed-skill sport. These suggest to other populations of different sport disciplines should be addressed in future investigations.

However, it would be interesting to evaluate more athletes and sedentary individuals and exclude the video gaming addiction to conclude the real effect of sports on mental rotation and postural control.

Conclusions

This study clearly provides evidence that balance has an immediate effect on MR performance in young athletes. The approach of dual tasks could improve postural control and MR abilities by engaging sensorimotor systems, enhancing cognitive processing and developing spatial skills. The significant difference between gymnastics, handball players and video gamers in dual tasks performance and MR tasks may support the potential of sports training to optimize both motor and cognitive development. Integrating age-appropriate balance training optimizes sensorimotor maturation, supporting athletic excellence and overall motor competence. By understanding how postural control integrates both physical and cognitive demands, educators and coaches can better tailor interventions that strengthen this bidirectional relationship, particularly during the U-12 developmental window.

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