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The effects of neurocognitive training on pain, proprioception, injury anxiety, and functional and neurocognitive performance in athletes with chronic ankle instability- randomized controlled trial

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ABSTRACT

Objectives: Considering the rapid motor-cognitive changes and increased risk of injury in preadolescent athletes, this study investigated the effects of neurocognitive training (NT) on pain, proprioception, injury-related anxiety, and functional and neurocognitive performance in athletes with chronic ankle instability (CAI).
Design: Randomized controlled trial.
Setting: Sports training facilities in Balıkesir, Türkiye.
Participants: Thirty preadolescent athletes with CAI (mean age 11.10 ± 1.06 years) were randomly assigned to an NT group ($n = 15$) or a control group ($n = 13$).
Main outcome measures: The Identification of Functional Ankle Instability (IdFAI), Cumberland Ankle Instability Tool (CAIT), pain severity, proprioception (dorsiflexion/plantarflexion), injury-related anxiety, Y Balance Test (YBT), Side Hop Test, Reactive Balance Test (RBT), and Upper Extremity Choice Reaction Time Test were evaluated pre- and post-intervention.
Results: The NT group demonstrated significant improvements in IdFAI ($p < 0.001$), CAIT ($p = 0.004$), dorsiflexion ($p = 0.003$) and plantarflexion proprioception ($p = 0.018$), injury-related anxiety ($p = 0.013$), YBT anterior reach ($p = 0.048$), RBT reaction time ($p = 0.030$), and accuracy ($p = 0.003$). The control group showed improvement only in plantarflexion proprioception ($p = 0.028$), with an increase in post-training pain ($p = 0.030$).
Conclusions: NT reduced ankle instability symptoms and injury-related anxiety while improving proprioception and neurocognitive performance. NT may enhance functional adaptation by addressing sport-specific cognitive-motor demands.

1. Introduction

Ankle sprains are among the most common lower extremity injuries, particularly in physically active individuals, and account for up to 80 % of all sports-related injuries (Herzog, Kerr, Marshall, & Wikstrom, 2019; Fong et al., 2007). These injuries often result in persistent dysfunction, recurrent sprains, and chronic ankle instability (CAI), which affects approximately 40 % of individuals after an initial sprain and may lead to postural instability, functional limitations, and even post-traumatic osteoarthritis (Hertel & Corbett, 2019). Such consequences can compromise an athlete's ability to fully participate in training and competition, underscoring the importance of effective preventive and rehabilitative strategies (Mohammadi, 2007).

Conventional interventions for CAI primarily target the peripheral nervous system, particularly ankle proprioceptors, through balance and neuromuscular training, which have been shown to improve postural control (Bleakley et al., 2019; Caldemeyer, Brown, & Mulcahey, 2020). However, studies emphasize that CAI is not restricted to peripheral mechanisms but also involves central nervous system alterations, including reduced corticospinal excitability, increased motor cortex inhibition, and microstructural changes in white matter (Hertel & Corbett, 2019; Maricot et al., 2023). These findings highlight the necessity of considering both peripheral and supraspinal mechanisms in CAI management. Evidence further suggests that individuals with CAI exhibit

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deficits in memory and attentional processes compared with healthy individuals, particularly under conditions of increased cognitive load, which negatively impacts postural stability (Rosen, McGrath, & Maerlender, 2021). Similar deficits and the benefits of motor-cognitive interventions have been observed in older adults and neurological populations, where dual-task training improved gait stability, executive functions, and working memory (Li et al., 2010; Yogev-Seligmann, Hausdorff, & Giladi, 2008; Schott, Alof, Hultsch, & Mechsner, 2016; Fritz, Cheek, & Nichols-Larsen, 2015). These findings support the integration of cognitive demands into motor rehabilitation for populations with motor control deficits. Motor-cognitive and externally focused dual-task approaches may facilitate more efficient allocation of cognitive resources, accelerate motor learning, and enhance skill retention, with associated cortical activation changes that benefit performance (Ghai, Ghai, & Effenberg, 2017; Sherman et al., 2021; Chai et al., 2024; Wang, Yu, & Chen, 2023). Neurocognitive training (NT) is distinguished from other cognitive-based interventions by its simultaneous targeting of multiple cognitive functions—such as attention, working memory, executive functions, and cognitive flexibility—while applying motor learning principles after the restoration of neuromuscular control (Walker, Brunst, Chaput, Wohl, & Grooms, 2021).

Importantly, neuromuscular control deficits observed in CAI resemble those seen in anterior cruciate ligament (ACL) injuries, where visual-motor training that combines cognitive and motor demands has been shown to promote neuroplasticity and enhance functional recovery (Grooms, Appelbaum, & Onate, 2015; Wilk, Ivey, Thomas, & Lupowitz, 2024). Although NT has been increasingly recommended and applied in ACL rehabilitation (Wilke, Vogel, & Ungricht, 2020; Wilk et al., 2024), its effects in CAI remain largely underexplored. In fact, NT has been reported only in a limited number of clinical applications (Niederer et al., 2019; Walker et al., 2021). Apart from one study that partially mimicked NT by combining balance training with stroboscopic glasses (Lee, Han, & Hopkins, 2024), no randomized controlled trials have specifically examined NT in athletes with CAI, highlighting a critical gap in the literature.

Our study specifically focused on preadolescent athletes for several reasons. This developmental stage represents a critical period of motor and cognitive maturation, characterized by rapid sensorimotor network and prefrontal executive function development, enhanced motor coordination, and heightened neuroplasticity. As a result, training programs that integrate motor and cognitive demands during preadolescence may maximize learning speed, transfer, and retention (Diamond, 2013; Best, 2010; Payne & Isaacs, 2020; Chaddock-Heyman, Hillman, Cohen, & Kramer, 2014). Moreover, this age group demonstrates a high incidence of ankle sprains due to intensive sports participation, making it a particularly relevant population for preventive and rehabilitative interventions. Early interventions in this developmental window may also mitigate the long-term adverse consequences of CAI (Doherty et al., 2014; Gribble et al., 2014). Considering its potential to address both peripheral and central mechanisms of CAI, neurocognitive training may represent a feasible approach with high ecological validity that can be readily integrated into routine sports training and rehabilitation programs to enhance functional performance and prevent injuries.

Accordingly, the present study aimed to investigate the effects of NT in preadolescent athletes with CAI. The primary outcomes were (Best, 2010): instability intensity measured by the Cumberland Ankle Instability Tool (CAIT) (Bleakley et al., 2019), functional performance assessed with the Lateral Hop Test, and (Cain, Ban, et al., 2020) neurocognitive functional performance measured with the Reactive Balance Test (RBT). Secondary outcomes included pain intensity, proprioception, fear of re-injury, additional balance performance (Y-Balance Test), and upper extremity reaction time.

2. Methods

2.1. Study design

This study was designed as a randomized controlled trial with a parallel-group design. The power analysis was based on effect size estimations from a reference study employing the side hop test (Linens, Ross, & Arnold, 2016), which indicated that a large effect size ($d = 0.8$) could be expected. Accordingly, a minimum of 26 participants (13 per group) was required to achieve 80 % power at a 95 % confidence level. Considering a potential dropout rate of 20 %, a total of 30 participants (15 per group) were recruited. Eligible volunteers were randomly assigned to either the NT or the control group using simple randomization with sealed, opaque, and consecutively numbered envelopes to ensure allocation concealment. Each group initially consisted of 15 participants. However, two participants from the control group did not attend the assessments and were therefore excluded, resulting in a final sample of 28 participants (NT: 15, Control: 13). While the intervention group received the NT program in addition to their regular training seasons, the control group continued with their regular training seasons without any additional intervention. Both groups underwent identical pre- and post-intervention assessments. To minimize bias, outcome assessors and data analysts were blinded to group allocation; however, due to the nature of the intervention, participants and physiotherapists were necessarily aware of group assignment. The randomization process and participant flow were illustrated in accordance with the CONSORT 2010 guidelines (Schulz, Altman, Moher, & CONSORT Group, 2010) (Fig. 1).

2.2. Participants

The study included preadolescent athletes aged 10–14 years, residing in Balıkesir, who had been actively engaged in sports for at least two years and were diagnosed with CAI. The diagnosis of CAI was established according to the inclusion criteria defined by the International Ankle Consortium (Gribble et al., 2014). To determine the presence and intensity of chronic ankle instability, the Identification of Functional Ankle Instability (IDFAI) and the Cumberland Ankle Instability Tool (CAIT) were administered.

The inclusion criteria were as follows: being between 10 and 14 years of age, having participated actively in sports for at least two years, and having a history of at least one ankle sprain accompanied by a minimum of two inflammatory symptoms (e.g., pain, swelling). In addition, the most recent ankle sprain had to have occurred at least three months prior to the beginning of the study, with an IDFAI score of ≥ 11 and a CAIT score of ≤ 27. Exclusion criteria included: having undergone surgical procedures involving the hip, pelvis, knee, or ankle within the past year; a history of ankle fracture; diagnosis of any neurological disorder; a history of vestibular disorders; current use of medications that could affect balance; a diagnosis of attention deficit disorder; or color blindness. Athletes and their families who met the inclusion criteria were informed in detail about the study, and written informed consent was obtained from the legal guardians of those who voluntarily agreed to participate.

2.3. Neurocognitive training program

The NT program was specifically developed by the researchers, drawing upon the conceptual frameworks proposed by Walker et al. (2021) and Wilk et al. (2024). In its design, motor learning strategies were integrated with cognitive tasks and embedded into neuromuscular training. The cognitive tasks included rapid reaction exercises, motor–motor and motor–cognitive dual tasks, congruent/incongruent tasks, mathematical operations combined with exercises (working memory tasks), and response inhibition tasks. The program structure and progression were informed by Fitts and Posner's model of motor learning: in the cognitive phase, athletes practiced basic neuromuscular

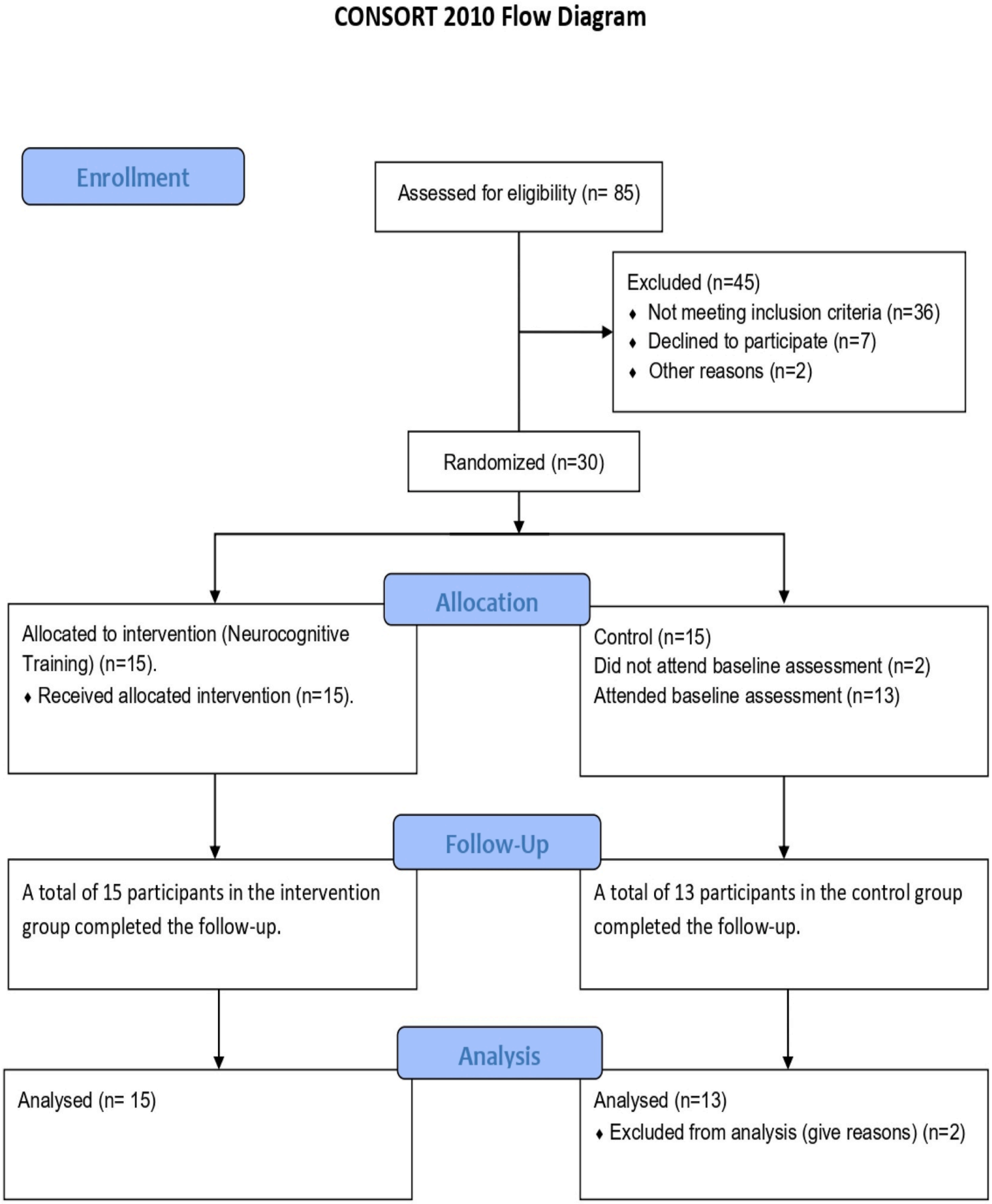

Fig. 1. Schematic representation of the study design and workflow (Schulz et al., 2010).

skills under low cognitive load; in the associative phase, neurocognitive demands were progressively increased as motor control became more consistent; and in the autonomous phase, exercises were performed under complex and competitive conditions once motor control had become automatic.

The intervention was applied progressively on different surfaces each week (flat ground, balance pad, BOSU, and inverted BOSU) to gradually increase task difficulty. The first week, performed on flat ground, served as an introductory phase during which athletes' balance and cognitive skills were evaluated and they were familiarized with the surfaces to be used in subsequent weeks. Over the following three weeks, increasingly challenging NT activities were implemented with consideration of individual differences (Fig. 2, Table 1).

The program was conducted twice weekly over four weeks, with each session lasting approximately 40 min. Sessions included a 5-min warm-up and cool-down involving free walking. To enhance ecological validity and clinical applicability, partner-based tasks and group-level cognitive challenges targeting memory and decision-making were also incorporated. In the intervention group, the NT program was administered in addition to their routine football training, whereas the control group continued only with their regular football training. The latter typically consisted of age-appropriate exercises, including warm-up drills with running and dynamic stretching, basic technical skills (passing, dribbling, shooting), coordination and agility drills (ladder runs, cone drills), and small-sided games (3v3 or 4v4). Each session lasted approximately 50–60 min and was performed twice per week. Pre- and post-test assessments were conducted simultaneously in both groups.

In this study, three primary outcomes were pre-specified: the CAIT score as a self-reported indicator of instability intensity, the Lateral Hop Test as an indicator of functional performance, and the Reactive Balance Test (RBT) as an indicator of neurocognitive functional performance. All other assessments were considered secondary outcomes, providing

Fig. 2. Examples of neurocognitive training exercises.

supportive information on pain, proprioception, injury anxiety, postural control, and upper-extremity reaction time.

2.4. Functional Ankle Instability identification scale (IDFAI)

The IDFAI is a self-reported assessment tool developed to identify the presence of functional instability in the ankle. It is commonly used to evaluate the frequency of sprains, intensity of symptoms, and feelings of insecurity in athletes. The total score is calculated by summing the points corresponding to responses to nine questions. The maximum total score is 37, and the higher the score, the greater the presence and intensity of instability. A score above 11 is considered indicative of instability (Simon, Donahue, & Docherty, 2012). The IDFAI has demonstrated good reliability and validity in adult and adolescent populations (Donahue et al., 2013).

2.5. Cumberland Ankle Instability Tool (CAIT)-Primary outcome

Developed in 2006, CAIT is one of the first self-report instruments based on the individual's perception to assess ankle instability (Hiller, Refshauge, Bundy, Herbert, & Kilbreath, 2006). This scale allows the subjective evaluation of instability experienced by the individual, providing a numerical representation of functional instability level. Thus, in addition to objective evaluation methods, CAIT facilitates the inclusion of sensations of imbalance and functional insufficiency perceived in daily life into the clinical decision-making process. CAIT has demonstrated high diagnostic sensitivity and specificity with an excellent intraclass correlation coefficient (ICC = 0.96). Scores range from 0 to 30 points, with lower total scores indicating severe ankle instability. In this study, a cutoff score of 27.5 was determined, yielding a sensitivity of 82.9 % and specificity of 74.7 %. Therefore, scores of 27

Table 1
Four-week neurocognitive training program for preadolescent athletes with chronic ankle instability.

Week	Motor Tasks	Motor-Cognitive Tasks	Progression Criteria
Week 1 (Familiarization)	Single-leg balance on flat surface (dominant and non-dominant leg) (2 × 30 s) Catching a ball while maintaining single-leg balance on flat surface (2 × 60 s) Passing a ball hand-to-hand clockwise or counterclockwise while standing on one leg on flat surface (2 × 30 s) Double-leg squat on flat surface while holding a stick horizontally (2 × 6 reps) Single-leg squat on flat surface (2 × 6 reps) Introduction to other surfaces, short-duration balance training	Performing simple mathematical operations (addition, subtraction, and multiplication) while maintaining single-leg balance on flat surface (2 × 30 s) Reaction training with light system on a table while standing (2 × 60 s) Running while memorizing and recalling a sequence of 4–5 numbers, depending on ability level	Reduction in sway and compensatory movements Ability to maintain motor control despite increased cognitive load
Week 2	Double-leg stance on balance pad (2 × 30 s) Single-leg stance on balance pad (2 × 30 s) Maintaining single-leg balance on balance pad while keeping a ball on a tennis racket without dropping it (2 × 30 s) Passing a ball hand-to-hand clockwise or counterclockwise while standing on one leg on balance pad (2 × 30 s) Catching a ball while maintaining single-leg balance on balance pad (2 × 60 s) Double-leg squat on balance pad while holding a stick horizontally (2 × 6 reps) Single-leg squat on balance pad while keeping a ball on a tennis racket without dropping it (2 × 6 reps)	Performing mathematical operations (addition, subtraction, and multiplication) while maintaining single-leg balance on balance pad (2 × 30 s) Performing mathematical operations (addition, subtraction, and multiplication) while doing double-leg squat on balance pad (2 × 6 reps) Standing on balance pad and extinguishing the light matching the color displayed on a phone, using the nearest foot to tap front-placed LED lights (2 × 60 s) Same as above but using both front and back lights, performed competitively against an opponent (2 × 60 s)	Maintaining motor control under cognitive load Reduced error rates in balance tasks
Week 3	Double-leg stance on BOSU (2 × 30 s) Single-leg stance on BOSU (2 × 30 s) Maintaining single-leg balance on BOSU while keeping a ball on a tennis racket without dropping it (2 × 30 s) Passing a ball hand-to-hand clockwise or counterclockwise while standing on one leg on BOSU (2 × 30 s) Catching a ball while maintaining single-leg balance on BOSU (2 × 60 s) Double-leg squat on BOSU while holding a stick horizontally (2 × 6 reps) Single-leg squat on BOSU while keeping a ball on a tennis racket without dropping it (2 × 6 reps)	Performing mathematical operations (addition, subtraction, and multiplication) while maintaining single-leg balance on BOSU (2 × 30 s) Performing mathematical operations (addition, subtraction, and multiplication) while doing double-leg squat on BOSU (2 × 6 reps) Extinguishing LED lights matching the color displayed on a phone while standing on BOSU (front placement) (2 × 60 s) Same as above with both front and back placement, performed competitively (2 × 60 s) Running on BOSU, stepping to the right on the "right" command and to the left on the "left" command (2 × 60 s) Running on BOSU, stepping opposite to the verbal command (e.g., stepping left on the "right" command) (2 × 60 s)	Completing task combinations with minimal or no errors Rapid adaptation to training surfaces
Week 4	Double-leg stance on inverted BOSU (2 × 30 s) Single-leg stance on inverted BOSU (2 × 30 s) Maintaining single-leg balance on inverted BOSU while keeping a ball on a tennis racket without dropping it (2 × 30 s) Passing a ball hand-to-hand clockwise or counterclockwise while standing on one leg on inverted BOSU (2 × 30 s) Catching a ball while maintaining single-leg balance on inverted BOSU (2 × 60 s) Double-leg squat on inverted BOSU while holding a stick horizontally (2 × 6 reps) Single-leg squat on inverted BOSU while keeping a ball on a tennis racket without dropping it (2 × 6 reps)	Performing mathematical operations (addition, subtraction, and multiplication) while maintaining single-leg balance on inverted BOSU (2 × 30 s) Performing mathematical operations (addition, subtraction, and multiplication) while doing double-leg squat on inverted BOSU (2 × 6 reps) Extinguishing wall-mounted LED lights while standing on inverted BOSU (2 × 60 s) Extinguishing table-mounted LED lights on inverted BOSU, with either concurrent or delayed recall of the light color displayed on a phone, sometimes competitively (2 × 60 s) Stepping off BOSU with one leg and extinguishing LED lights using a stick (2 × 60 s) Single-leg hopping in the opposite direction of the verbal command (e.g., jumping right on the "left" command) (2 × 15 s) Performing squats when the sum of asked numbers is even and lunges when the sum is odd (2 × 60 s)	Improved performance in reactive tasks Completing exercises within the prescribed time and repetitions with minimal errors

*A 30-s rest period was provided between exercises, and the progression criteria of the program were determined based on observations related to the attainment of motor control.

and below were interpreted as indicative of instability (Yin et al., 2022; Hiller et al., 2006). Additionally, individuals with low CAIT scores have been reported to have a higher risk of recurrent sprains (Hiller et al., 2006).

2.6. Pain İntensity assessment-secondary outcome

The Visual Analog Scale (VAS) is a 10 cm long horizontal or vertical line ranging from "No pain" to "Unbearable pain." After explaining the usage to the patients, they were asked to mark the point on the line corresponding to their perceived pain intensity. The distance in centimeters between "No pain" and the mark was measured and recorded (Gur et al., 2017). Pain intensity was evaluated exclusively in the ankle with instability symptoms, both at rest, during regular training seasons, and after training.

2.7. Proprioception assessment-secondary outcome

The joint position sense test is the most frequently used clinical test to assess proprioception of the extremities, defined as the awareness of the actual position of a joint. It is commonly applied to various joints such as the knee, elbow, ankle, hip, and spine. During the test, participants lie supine with eyes open while the relevant joint is passively positioned at a predetermined angle and held for 5 s. This procedure is repeated three times. After a 30-s rest, the participant is asked to actively reproduce the angle as closely as possible. The angle is measured and recorded using a goniometer (Chai et al., 2024). For ankles with a history of instability, dorsiflexion was set at 10° and plantarflexion at 20°. The averages of two repetitions were recorded.

Importantly, the reliability of joint position sense testing in pediatric populations has been previously demonstrated. Kunritt, Lekskulchai, and Wattananon (2021) reported high test–retest reliability (ICC = 0.82–0.91) for ankle joint proprioception in children with CAI, and Jacobs, van denBogaart, Hallemans, and Meyns (2024) confirmed acceptable reliability (ICC ranging from moderate to very good) and precision (SEM 0.8°–1.8°) for multi-joint proprioception measures in school-aged children. These findings support the validity of applying this test in our preadolescent cohort.

2.8. *Injury anxiety assessment-secondary outcome*

The Sport Injury Anxiety Scale (SIAS) was developed to measure anxiety levels in athletes following injury, with higher mean scores indicating increased injury-related anxiety (Rex & Metzler, 2016). The SIAS has demonstrated adequate reliability and validity across different athlete populations (Cassidy, 2006). Cross-cultural adaptations and psychometric evaluations, such as those conducted in Chinese collegiate athletes (Yuqiong, 2023) and Turkish student-athletes (Durmuşoğlu & Atilgan, 2023), further support its applicability in diverse contexts.

2.9. *Y Balance Test (YBT)- secondary outcome*

The YBT consists of three reach directions: anterior, posteromedial, and posterolateral. In this test, one extremity remains fixed at the composite of the reach directions while the other extremity attempts to reach toward these directions (measures were set at 135°-135°-90°). If the athlete was unable to return to the starting position in a balanced manner, shifted weight on the YBT platform, or lifted the support foot from the platform, the trial was deemed invalid and repeated. Evaluations were performed on the ankle with a history of instability. To calculate the composite balance score, lower extremity length was measured as the distance between the anterior superior iliac spine and the medial malleolus. The composite score (%) was calculated as: (sum of three reach distances)/(three times limb length) × 100 (Plisky et al., 2009). The YBT has demonstrated good reliability and validity in both adult and pediatric populations, supporting its use in preadolescent athletes (Cramer, Coburn, & St Pierre, 2017; Dobija, Wieczorek, & Wilczyński, 2021).

2.10. *Lateral hop test-primary outcome*

Studies have shown that hop-based tests capture sport-specific demands such as dynamic stability, agility, and rapid force production, all of which are frequently impaired in populations with CAI (Docherty, Arnold, Gansneder, Hurwitz, & Gieck, 2005; Hale, Hertel, & Olmsted-Kramer, 2007; Koldenhoven & Wikstrom, 2016). Furthermore, the Lateral Hop Test has demonstrated good reliability and discriminative ability in detecting functional deficits associated with ankle instability and is considered a valid indicator of return-to-sport readiness and performance-related limitations (Cain, Nicholson, Adams, & Burns, 2020). The Lateral Hop Test was selected as a primary outcome measure because it provides a sensitive and reliable assessment of functional performance in athletes with CAI. Athletes stood on the extremity diagnosed with chronic instability and performed 10 consecutive hops over two boundaries spaced 30 cm apart as quickly as possible. The time required to complete the test was recorded using a stopwatch. One practice trial was allowed prior to testing, after which the test was performed twice on the unstable extremity with a 60-s rest interval between trials. The shortest completion time was used for analysis (<link id=bib_cain_et_al_2020b>Cain, Nicholson, et al., 2020;</link>).

2.11. *Reactive Balance Test (RBT)-Primary outcome*

The RBT is a functional neurocognitive performance test that combines a smartphone application-controlled LED light system (Blazepod) with the YBT testing setup. In this test, LED lights are positioned on the YBT system to correspond to 80 % of the athlete's maximum reach distance in each direction (Fig. 3). LED targets were individually calibrated to 80 % of each participant's maximal reach distance to ensure standardized task difficulty and to account for anthropometric differences. This calibration procedure was performed prior to testing for each athlete. During the test, athletes assume the standardized starting position used in the YBT. Participants are instructed to extinguish the dark blue LED light among differently colored lights by touching it without losing balance, and to do so as quickly as possible. A total of 45 visual stimuli appear in a random sequence during the test. To eliminate anticipatory timing effects, ensure sufficient difficulty, and allow recovery to the standard position after an error, inter-stimulus intervals vary between 0.5 and 2.5 s.

The outcome measures of RBT are visuomotor reaction time (ms) and accuracy (%). Accuracy (%) is calculated as: Accuracy (%) = ((Total stimuli - (missed stimuli + required multiple attempts + decision errors))/Total stimuli) × 100.

In individuals with CAI, the RBT has demonstrated moderate test-retest reliability, good intra-rater reliability, moderate inter-rater reliability for accuracy, and good inter-rater reliability for visuomotor reaction time (Maricot et al., 2024). Furthermore, BlazePod-based reactive agility assessments have been shown to be reliable and valid in youth soccer players (Sánchez-Sánchez, Raya-González, Clemente, & Hernández, 2023). In addition, the Y-Balance Test setup, which underpins the

Fig. 3. Reactive balance test.

RBT, has demonstrated reliability in children aged 10–18 years (Cramer et al., 2017), supporting the feasibility of applying this test in preadolescent athletes. The test was conducted twice on the ankle with a history of instability, with the first trial serving as a practice attempt and the second trial's results recorded.

2.12. Choice Reaction Time Upper Extremity Test-secondary outcome

In the Choice Reaction Time Upper Extremity Test, athletes were seated on a chair and instructed to extinguish specific LED lights placed on a table using their dominant hand. At the starting position, both hands rested on the table, and four LED lights were placed 15 cm apart, calibrated to each athlete's arm length to ensure standardized task difficulty. The LED lights were illuminated in different colors at randomized intervals ranging between 0.5 and 2.5 s (Fig. 4). When the blue LED light was activated, participants were instructed to extinguish it with their dominant hand as quickly as possible. The average reaction time and the number of correctly extinguished lights within 1 min were recorded as test outcomes. Upper extremity reaction time was measured using a smartphone application-controlled LED light system (Blazepod) (Janković, Čvorović, Dopsaj, Prćić, & Kukić, 2022). The test was performed twice, with the first trial serving as practice and the second trial used for analysis. Selective attention and reaction time measured by this test were considered indicators of cognitive function (Wilke et al., 2020). Outcome assessors who recorded reaction time and accuracy were blinded to group allocation. Previous research has demonstrated that this test shows high reliability in adult athlete populations, with Blazepod-based assessments reporting excellent reliability (ICC >0.80) and low standard error of measurement (SEM ≤ 5–7 %) (Janković et al., 2022; Wilke et al., 2020).

2.13. Statistical analysis

The study data were analyzed using SPSS version 27.0 (IBM SPSS Statistics 27 software, Armonk, NY: IBM Corp.). Continuous variables are presented as mean ± standard deviation, and categorical variables as number and percentage. Normality of the data distribution was assessed using the Shapiro-Wilk test. When parametric assumptions were met, the Independent Samples *t*-test was used to compare differences between independent groups; when parametric assumptions were not met, the Mann-Whitney *U* test was applied. For examining differences within dependent groups, the Paired Samples *t*-test was used if parametric assumptions were satisfied; otherwise, the Wilcoxon Signed-Rank test was employed. Within-group changes were also compared using independent group tests. As the study included only two groups and two measurement points, and the outcomes were analyzed independently, adjustment for multiple comparisons was not considered necessary. For pairwise comparisons, effect sizes were calculated using Cohen's d. The magnitude of the effect sizes was interpreted according to Cohen's conventions: small (d = 0.20), medium (d = 0.50), and large (d ≥ 0.80). A p-value ≤0.05 was considered statistically significant in all analyses.

3. Results

The study involved 30 football players (2 females, 28 males) diagnosed with chronic ankle instability (CAI), residing in Balıkesir, with a mean age of 11.10 ± 1.06 years, an average IDFAI score of 17.56 ± 3.12, and an average CAIT score of 21.82 ± 3.50. No significant differences

Table 2
Demographic characteristics of the athletes.

Variables	NT (13 males, 2 females) X ± SS (Min/ Max)	Control (13 males) X ± SS (Min/ Max)	p**	d
Age (years)	11.14 ± 1.16 (10/14)	10.92 ± 1.03 (10/13)	0.896 (z = −0.131)	0.200
Height (cm)	145.92 ± 7.49 (135/160)	146.92 ± 10.21 (135/ 167)	0.494 (t = −0.693)	0.111
Body Weight (kg)	40.14 ± 10.31 (25/60)	40.53 ± 9.23 (30/60)	0.693 (z = −0.395)	0.039
BMI (kg/m^2)	18.61 ± 3.36 (13/26)	18.64 ± 2.86 (15/23)	0.983 (z = −0.021)	0.009
Training Age (years)	3.07 ± 1.59 (2/8)	2.53 ± 0.87 (2/5)	0.383 (z = −0.872)	0.421
Weekly Training Frequency (days)	2.57 ± 1.15 (2/5)	2.84 ± 1.34 (2/5)	0.454 (z = −0.749)	0.216

X: Arithmetic Mean; SD: Standard Deviation; NT: Neurocognitive Training Group BMI: Body Mass Index. **: Comparison between groups; t: Independent samples *t*-test; z: Mann-Whitney *U* test; d: Cohen's d effect size.

Fig. 4. Choice reaction time upper extremity test.

were observed between the study and control groups in terms of age, anthropometric data, or training experience ($p > 0.05$) (Table 2).

3.1. Primary outcomes

3.1.1. Instability Intensity

In the NT group, a significant decrease in IDFAI scores ($p < 0.001$, $d = 1.87$) and a significant increase in CAIT scores ($p = 0.004$, $d = 1.35$) were observed. No significant changes were detected in the control group ($p > 0.05$). The comparison of changes over time between groups demonstrated significant differences for both CAIT ($p = 0.009$, $d = 1.05$) and IDFAI ($p < 0.001$, $d = 1.60$) (Table 3).

3.1.2. Lateral hop test

The NT group showed a significant reduction in test completion time ($p = 0.003$, $d = 0.63$), whereas no significant changes were observed in the control group ($p > 0.05$). The comparison of changes over time between groups did not reveal significant differences ($p > 0.05$) (Table 3).

3.1.3. Reactive Balance Test

In the NT group, a significant decrease in reaction time ($p = 0.030$, $d = 0.65$) and a significant increase in accuracy percentage ($p = 0.003$, $d = 1.31$) were identified. No significant changes were observed in the control group ($p > 0.05$). The comparison of changes over time between groups showed a significant difference only for accuracy percentage ($p = 0.002$, $d = 1.15$), while reaction time and test duration did not differ significantly ($p > 0.05$) (Table 4).

3.2. Secondary outcomes

3.2.1. Proprioception

The NT group demonstrated significant improvements in dorsiflexion ($p = 0.003$, $d = 1.04$) and plantarflexion ($p = 0.018$, $d = 0.80$) joint position sense. In the control group, only plantarflexion showed significant improvement ($p = 0.028$, $d = 1.06$). The comparison of changes over time between groups did not reveal significant differences for either dorsiflexion or plantarflexion ($p > 0.05$) (Table 5).

Table 3
Results of chronic ankle instability Intensity and lateral hop test.

Variables		NT X ± SS (Min/Max)	Control X ± SS (Min/Max)	p**	d
IDFAI (score)	Pre	17.50 ± 3.32 (11/22)	17.41 ± 3.02 (13/24)	0.690 (t = 0.403)	0.028
	Post	10.92 ± 3.68 (5/17)	18.33 ± 4.31 (10/25)	**<0.001 (t=-4.381)**	1.849
	p*	**<0.001 (t=6.329)**	0.666 (t = −0.443)		
	d	1.872	0.240		
	Pre-Post difference	−6.57 ± 4.21 (−16/1)	0.91 ± 5.10 (−8/12)	**<0.001 (t=-4.280)**	1.599
CAIT (score)	Pre	21.85 ± 3.18 (17/27)	22.16 ± 4.21 (13/27)	0.724 (t = −0.356)	0.083
	Post	26.42 ± 3.58 (17/27)	22.50 ± 3.63 (16/29)	**0.012 (z=-2.513)**	1.087
	p*	**0.004 (z=-2.847)**	0.549 (t = −0.616)		
	d	1.345	0.086		
	Pre-Post difference	4.57 ± 4.70 (−5/12)	0.33 ± 3.20(−6/4)	**0.009 (t=2.825)**	1.054
Lateral Hop Test (s)	Pre	5.99 ± 2.71 (3.86/12.70)	6.80 ± 2.06 (4.66/10.29)	0.561 (z = −0.581)	0.336
	Post	4.51 ± 1.43 (2.73/9.00)	5.84 ± 1.98 (4.24/11.57)	**0.011 (z=-2.557)**	0.770
	p*	**0.003 (z=-3.010)**	0.075 (z -1.782)		
	d	0.630	0.474		
	Pre-Post difference	−1.47 ± 1.82 (−5.65/0.69)	−0.95 ± 2.13 (−5.19/2.57)	0.447 (z = −0.760)	0.262

X: Arithmetic Mean; SD: Standard Deviation; Pre-test: Pre-test; Post-test: Post-test; NT: Neurocognitive Training; IDFAI: Identification of Functional Ankle Instability; CAIT: Cumberland Ankle Instability Tool; *: Within-group comparison; **: Between-group comparison; For independent group comparisons, t: Independent Samples *t*-test, z: Mann-Whitney *U* test; For dependent group comparisons, t: Paired Samples *t*-test, z: Wilcoxon Signed-Rank test; d: Cohen's d effect size.

Table 4
Results of reactive balance test.

Variables		NT X ± SS (Min/Max)	Control X ± SS (Min/Max)	p**	d
RBT Reaction Time (s)	Pre	1.20 ± 0.19 (0.83/1.62)	1.24 ± 0.22 (0.92/1.76)	0.827 (z = −0.218)	0.194
	Post	1.09 ± 0.13 (0.90/1.48)	1.25 ± 0.24 (1.01/1.68)	0.076 (z = −1.774)	0.829
	p*	**0.030 (z=-2.166)**	0.944 (z = −0.070)		
	d	0.653	0.043		
	Pre-Post difference	−0.11 ± 0.19 (−0.62/0.21)	0.01 ± 0.24 (−0.44/0.39)	0.171 (t = −1.408)	0.554
RBT Accuracy (%)	Pre	91.58 ± 4.62 (82.22/100)	92.58 ± 4.95 (84.44/100)	0.501 (t = −0.681)	0.208
	Post	96.82 ± 2.57 (91.11/100)	92.21 ± 4.78 (82.22/97.77)	**0.002 (z=-3.056)**	1.201
	p*	**0.003 (z=-2.947)**	0.679 (t = 0.424)		
	d	1.306	0.076		
	Pre-Post difference	5.23 ± 5.20 (−2.23/15.55)	−0.37 ± 4.52 (−4.44/13.33)	**0.002 (z=-3.068)**	1.149
RBT Test Duration (s)	Pre	126.14 ± 10.32 (104/140)	127.91 ± 13.15 (110/161)	0.963 (z = −0.046)	0.149
	Post	121.14 ± 6.76 (113/138)	130.25 ± 15.34 (112/158)	**0.048 (t=-2.079)**	0.768
	p*	**0.040 (t=2.284)**	0.700 (z = 0.385)		
	d	0.550	0.162		
	Pre-Post difference	−5.00 ± 8.19 (−18/9)	2.33 ± 12.57 (−13/22)	0.133 (t = −1.554)	0.690

X: Arithmetic Mean; SD: Standard Deviation; Pre-test: Pre-test; Post-test: Post-test; RBT: Reactive Balance Test; NT: Neurocognitive Training; *: Within-group comparison; **: Between-group comparison; For independent group comparisons, t: Independent Samples *t*-test, z: Mann-Whitney *U* test; For dependent group comparisons, t: Paired Samples *t*-test, z: Wilcoxon Signed-Rank test; d: Cohen's d effect size.

Table 5
Results of proprioception and sport injury anxiety scale.

Variables		NT X ± SS (Min/Max)	Control X ± SS (Min/Max)	p**	d
Proprioception Dorsiflexion (degrees °)	Pre	2.62 ± 1.86 (1/8)	3.08 ± 2.06 (1/7)	0.966 (z = −0.043)	0.234
	Post	0.90 ± 0.57 (0/2.20)	2.33 ± 1.92 (0/7)	**0.015 (z=-2.432)**	1.009
	p*	**0.003 (z=-2.977)**	0.188 (z = −1.316)		
	d	1.042	0.376		
	Pre-Post difference	−1.62 ± 2.08 (−7/0.20)	−0.75 ± 2.70 (−5/6)	0.428 (z = −0.792)	0.360
Proprioception Plantar Flexion (degrees °)	Pre	3.20 ± 2.78 (1/11)	2.87 ± 1.41 (1/6)	0.733 (z = −0.341)	0.149
	Post	1.24 ± 0.95 (0.20/4.00)	1.58 ± 0.66 (1/3)	0.071 (z = −1.805)	0.415
	p*	**0.018 (z=-2.358)**	**0.028 (z=-2.195)**		
	d	0.800	1.055		
	Pre-Post difference	−1.45 ± 2.25 (−6/3)	−1.29 ± 1.25 (−4/0.00)	0.558 (z = −0.586)	0.087
SIAS (score)	Pre	39.64 ± 18.57 (19/76)	44.16 ± 15.82 (22/76)	0.666 (t = −0.437)	0.262
	Post	30.42 ± 19.27 (19/76)	39.25 ± 15.41 (21/76)	0.069 (z = −1.819)	0.506
	p*	**0.013 (z=-2.482)**	0.285 (z = −1.070)		
	d	0.487	0.890		
	Pre-Post difference	−9.21 ± 13.06 (−27/18)	−4.91 ± 19.02 (−32/28)	0.352 (t = −0.947)	0.263

X: Arithmetic Mean; SD: Standard Deviation; Pre-test: Pre-test; Post-test: Post-test; NT: Neurocognitive Training; SIAS: Sport Injury Anxiety Scale; *: Within-group comparison; **: Between-group comparison; For independent group comparisons, t: Independent Samples *t*-test, z: Mann-Whitney *U* test; For dependent group comparisons, t: Paired Samples *t*-test, z: Wilcoxon Signed-Rank test; d: Cohen's d effect size.

3.2.2. Injury anxiety assessment

A significant reduction in SIAS scores was observed in the NT group ($p = 0.013$, $d = 0.49$), whereas no significant changes were detected in the control group ($p > 0.05$). The comparison of changes over time between groups did not indicate significant differences ($p > 0.05$) (Table 5).

3.2.3. Y Balance Test

In the NT group, a significant decrease was found only in the anterior reach distance ($p = 0.048$, $d = 0.52$). No significant changes were observed in other parameters or in the control group ($p > 0.05$). The comparison of changes over time between groups did not demonstrate significant differences ($p > 0.05$) (Table 6).

3.2.4. Choice reaction time – upper extremity test

The NT group exhibited a significant reduction in upper extremity reaction time ($p < 0.001$, $d = 1.00$), whereas no significant changes were observed in the control group ($p > 0.05$). The comparison of changes over time between groups demonstrated a significant difference favoring the NT group ($p = 0.016$, $d = 1.11$) (Table 7).

3.2.5. Pain İntensity

In the NT group, no significant change was observed in pain intensity between pre- and post-training assessments ($p > 0.05$), whereas the control group exhibited a significant increase in pain following their regular training sessions ($p = 0.030$, $d = 0.746$). Between-group comparisons further confirmed these findings, with both post-training scores ($p = 0.034$, $d = 0.998$) and pre-to-post differences ($p = 0.024$, $d = 0.944$) favoring the NT group) (Fig. 5).

Post-hoc power analyses were conducted using GPower 3.1.9.7. The effect size for reaction time was $dz = 0.65$ with an achieved power of 78 %. The Lateral Hop Test yielded an effect size of $dz = 0.63$ and a power of 75 %. The instability intensity score showed a very large effect size ($dz = 1.34$) with nearly perfect power (>99 %).

4. Discussion

In this study, following a 4-week NT program applied to athletes with CAI, a reduction in instability intensity, improvement in proprioception, and a decrease in injury-related anxiety were observed. Additionally, significant decreases were found in the lateral hop test time and anterior sway. Neurocognitive performance measures showed reductions in RBT reaction time and upper extremity reaction time, along with an increase in accuracy percentage. In the control group, significant increases were only noted in plantar flexion proprioception and post regular training seasons pain intensity.

When reviewing studies targeting cognitive function enhancement in individuals with CAI, interventions such as dual-task training, reaction time training using cognitive tools, exergaming, exercises with stroboscopic glasses, and NFT have been reported (Chai et al., 2024; Sepasgozar et al., 2024; Lee et al., 2024; Yalfani, Azizian, & Gholami-Borujeni, 2024). In this context, findings related to the effects of cognitive training interventions in the literature are discussed in detail below. When evaluating functional performance outcomes, the study by Kwak and Choi (2016) found that dual-task training enhanced jump performance. Similarly, Chai et al. (2024) compared balance training alone with combined balance-cognitive training in individuals with CAI and reported improvements in proprioception in both groups. In our study, the improvement observed in plantar flexion proprioception in the control group may be attributed to the effects of regular training. Although dual-task training shares certain similarities with NT, most dual-task interventions involve a single cognitive task and lack the multi-sensory attentional demands present in NT.

NT, in contrast, comprises complex task-environment interactions and multifaceted components that closely mimic real-life sport-specific conditions. It includes elements such as card-based instructions, complex motor-cognitive integration, and reaction time measurement using LED systems, providing a more ecologically valid training model. The only study in the literature with a training intensity and structure comparable to ours is the one by Niederer et al. (2019), which was conducted in healthy and physically active individuals. However, their 4-week motor-cognitive dual-task intervention did not yield significant improvements in motor or cognitive outcomes. Unlike their findings, our study revealed significant improvements in both domains, likely due to the inclusion of athletes with CAI, a population known to exhibit central neuroplasticity alterations (Maricot et al., 2023), thereby necessitating cognitively driven rehabilitation strategies.

Other studies utilizing different cognitive training modalities have reported findings consistent with ours. For instance, Sepasgozar et al. (2024) found that an exercise program using Nintendo Wii Fit Plus in recreational athletes with CAI led to reductions in instability intensity and injury-related anxiety, along with improvements in balance and lateral hop test performance. Similarly, Lee et al. (2024) showed that four weeks of balance training with stroboscopic glasses in individuals

Table 6
Results of Y balance test.

Variables		NT X ± SS (Min/Max)	Control X ± SS (Min/Max)	p**	d
YBT Anterior (cm)	Pre	73.64 ± 7.52 (60/84)	75.04 ± 9.15 (61/91)	0.851 (t = −0.190)	0.167
	Post	69.28 ± 9.20 (55/88)	70.37 ± 6.23 (57/81.50)	0.387 (t = −0.880)	0.138
	p*	**0.048 (t=2.164)**	0.102 (t = 1.770)		
	d	0.515	0.576		
	Pre-Post difference	−4.35 ± 9.10 (−16/11.50)	−4.66 ± 7.99 (−19/6.50)	0.420 (z = −0.807)	0.036
YBT Posteromedial (cm)	Pre	70.75 ± 10.48 (56/95)	72.08 ± 11.30 (52/87)	0.733 (t = −0.345)	0.122
	Post	68.47 ± 13.08 (49/92)	67.62 ± 7.48 (56/78)	0.966 (t = −0.043)	0.079
	p*	0.481 (t = 0.723)	0.204 (t = 1.342)		
	d	0.190	0.447		
	Pre-Post difference	−2.27 ± 14.66 (−24/21)	−4.45 ± 12.18 (−26/12)	0.736 (t = 0.341)	0.161
YBT Posterolateral (cm)	Pre	66.57 ± 10.83 (49/86)	62.66 ± 10.47 (42/79)	0.434 (t = 0.794)	0.367
	Post	62.82 ± 11.27 (40/83)	59.12 ± 8.02 (47/69)	0.453 (t = 0.762)	0.378
	p*	0.104 (t = 1.737)	0.192 (t = 1.382)		
	d	0.339	0.373		
	Pre-Post difference	−3.75 ± 9.43 (−18/14.50)	−3.54 ± 10.59 (−18/23)	0.955 (t = −0.057)	
YBT Composite (score)	Pre	91.50 ± 12.15 (75/113.02)	91.92 ± 9.34 (70.94/103.50)	0.959 (t = −0.052)	0.038
	Post	88.42 ± 11.01 (61.17/107.40)	87.66 ± 4.91 (77.14/95.55)	0.998 (t = 0.003)	0.089
	p*	0.317 (t = 1.038)	0.149 (t = 1.543)		
	d	0.265	0.526		
	Pre-Post difference	−2.38 ± 12.48 (−20.13/14.20)	−4.25 ± 9.86 (−16.22/18.38)	0.877 (t = 0.157)	0.166

X: Arithmetic Mean; SD: Standard Deviation; Pre-test: Pre-test; Post-test: Post-test; NT: Neurocognitive Training; YBT: Y Balance Test; *: Within-group comparison; **: Between-group comparison; For independent group comparisons, t: Independent Samples *t*-test, z: Mann-Whitney *U* test; For dependent group comparisons, t: Paired Samples *t*-test, z: Wilcoxon Signed-Rank test; d: Cohen's d effect size.

Table 7
Results of choice reaction time upper extremity test.

Variables		NT X ± SS (Min/Max)	Control X ± SS (Min/Max)	p**	d
Upper Extremity Reaction Time (s)	Pre	0.63 ± 0.06 (0.49/0.73)	0.66 ± 0.12 (0.53/1.03)	0.663 (z = −0.436)	0.316
	Post	0.57 ± 0.06 (0.46/0.68)	0.68 ± 0.17 (0.50/1.17)	**0.040 (z=-2.050)**	0.862
	p*	**<0.001 (t=4.262)**	0.972 (z = −0.035)		
	d	1.000	0.132		
	Pre-Post difference	−0.05 ± 0.04 (−0.12/0.03)	0.02 ± 0.08 (−0.06/0.16)	**0.016 (z=-2.419)**	1.106
Correctly Extinguished Lights	Pre	24.21 ± 1.42 (22/27)	23.41 ± 2.60 (16/26)	0.485 (z = −0.699)	0.381
	Post	24.28 ± 0.91 (23/26)	23.16 ± 2.94 (15/26)	0.586 (z = −0.545)	0.514
	p*	0.882 (t = 0.151)	0.719 (z = −0.360)		
	d	0.056	0.089		
	Pre-Post difference	0.07 ± 1.68 (−4/2)	−0.25 ± 1.71 (−3/3)	0.893 (t = 0.136)	0.188

X: Arithmetic Mean; SD: Standard Deviation; Pre-test: Pre-test; Post-test: Post-test; NT: Neurocognitive Training; *: Within-group comparison; **: Between-group comparison; For independent group comparisons, t: Independent Samples *t*-test, z: Mann-Whitney *U* test; For dependent group comparisons, t: Paired Samples *t*-test, z: Wilcoxon Signed-Rank test.

with CAI increased ankle muscle activation and promoted safer landing mechanics. In our study, the NT program involved the use of the ReactionX LED light system, emphasizing visual stimuli. Despite the differing approaches—sensory input limitation via stroboscopic glasses versus visual input enhancement via LED systems—both protocols resulted in improved functional performance. These findings suggest that different sensory modulation strategies can enhance motor learning and performance through distinct but effective mechanisms. Yalfani et al. (2024) reported that neurofeedback training (NFT), when added to neuromuscular training in athletes with CAI, improved balance, proprioception, and psychological well-being. While NFT directly targets cortical activity, NT achieves cognitive stimulation through external environmental cues, yet both result in comparable functional outcomes. Integrating neurofeedback or neurocognitive-based approaches into neuromuscular rehabilitation protocols may contribute to the development of more comprehensive and effective strategies.

Interestingly, our study revealed a decrease in the anterior reach component of the Y-Balance Test. This finding may indicate a shift in motor control strategy. Neurocognitive training is known to enhance attention, reaction time, and decision-making processes (Wilk et al., 2024), which may be particularly advantageous in reactive balance tasks requiring rapid responses to external stimuli. In contrast, proactive balance involves preplanned motor responses (Wulf & Lewthwaite, 2016). The NT program may have increased athletes' reliance on reactive strategies while attenuating proactive motor planning due to cognitive interference. However, the reduction in anterior reach could also be attributed to measurement variability or to the athletes' deliberate adoption of more conservative strategies aimed at optimizing performance in the RBT. Future studies should clarify whether this decrease represents a genuine trade-off between proactive and reactive balance control or merely reflects methodological or strategy-related artifacts. The improvements in upper extremity choice reaction time observed in our study suggest enhancements in cognitive functions such as attention, reaction time, and visual scanning. Moreover, the reduction in reaction time during the Reactive Balance Test may indicate that increased cognitive load during training activates higher-order processing. These findings align with previous literature supporting the role of NT in enhancing both motor and cognitive performance (Walker et al., 2021; Wilk et al., 2024). Thus, even a short-term NT intervention appears capable of improving not only lower extremity motor skills but also cognitive domains like attention, decision-making, and reaction speed.

Additionally, the change in the Cumberland Ankle Instability Tool (CAIT) score in the NT group exceeded the minimal clinically important

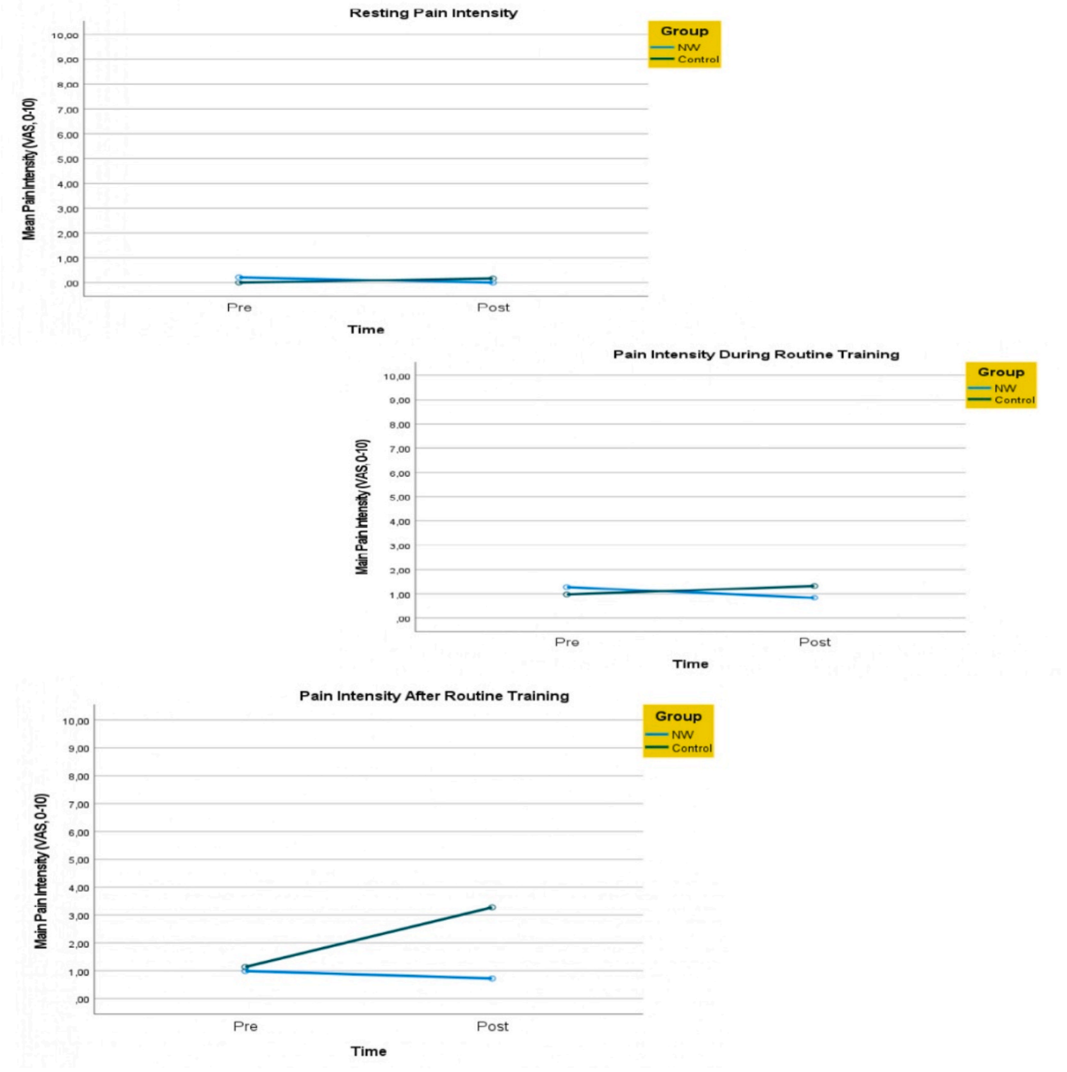

Fig. 5. Results of pain Intensity (VAS).

difference (MCID) of ≥3 points reported in the literature (Wright, Linens, & Cain, 2017), with a mean improvement of 4.57 points. Given the known relationship between ankle instability and performance or injury risk (Hiller et al., 2006), this clinically meaningful improvement highlights the potential of NT to reduce reinjury risk in athletes. Notably, while pain intensity remained unchanged in the NT group, an increase was observed in the control group following regular training seasons, which may be due to uncontrolled loading during training and competition, stemming from unresolved CAI symptoms. Importantly, by exceeding the threshold for clinical significance, NT may contribute not only to symptom reduction but also to maintaining athletic performance and supporting long-term sport participation. Therefore, NT may support both performance enhancement and symptom management.

4.1. Limitations of the study

This study has certain limitations that should be taken into account when interpreting the findings. The absence of long-term follow-up limits the ability to determine whether the observed effects are sustained over time. Moreover, although outcome assessors and data analysts were blinded, participants and trainers were necessarily aware of group allocation due to the nature of the intervention, which may have introduced bias. In addition, despite the neurocognitive focus of the intervention, no objective neural measures such as EEG, fNIRS, or fMRI were included, restricting the capacity to directly associate the improvements with underlying neural mechanisms. Finally, the relatively young age of the sample (mean age ~11 years) constrains the generalizability of the results to older adolescent or adult athletes. Although the RBT has demonstrated reliability in individuals with CAI (Maricot et al., 2024), direct reliability data in preadolescent populations are limited. In the post-hoc power analyses, reaction time (78 %) and hop performance (75 %) were slightly below the conventional threshold of 80 %, yet still support the reliability of these results despite the small sample size. The instability intensity score demonstrated a very large effect with nearly perfect power (>99 %). A limitation of the study is that, due to non-normal data distribution, nonparametric tests were applied, which do not allow direct estimation of interaction effects as in ANOVA or mixed models.

Future studies should therefore incorporate long-term follow-up assessments to evaluate the persistence of training effects, include objective neuroimaging methods to clarify the underlying neural mechanisms, and recruit larger and more diverse samples across different age groups. Such efforts will strengthen the evidence base and provide broader clinical implications for the application of neurocognitive training in athletes with CAI.

4.2. Strengths of the study

This study represents the first randomized controlled trial to investigate the effects of neurocognitive training in adolescent athletes with CAI. Methodological rigor was maintained through the use of randomization, an a priori power analysis, and validated outcome measures. The training program was specifically designed by the researchers to match both the sport context and the age group, thereby enhancing ecological validity. Furthermore, full adherence to the training program was achieved, which strengthens the reliability of the study findings.

5. Conclusion

Our findings demonstrate that NT supports not only physical but also cognitive functioning, making it an effective approach in the management of CAI. By targeting both physical and cognitive components, NT contributes to the growing body of evidence supporting multidimensional rehabilitation strategies. Enhancing athletes' cognitive capacities through NT may strengthen sport-specific skills such as decision-making and on-field reactions. Moreover, improvements in performance outcomes associated with injury risk (e.g., reactive balance, reaction time) suggest that incorporating NT into injury prevention programs may help reduce injury incidence.

CRediT authorship contribution statement

Ebru Tekin: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Fatma Unver:** Writing – review & editing, Validation, Supervision, Software, Resources, Funding acquisition.

Use of generative AI tools

During the preparation of the supplementary materials (appendices), the authors used OpenAI's ChatGPT to assist in drafting figures and explanatory texts. After using this tool, the authors carefully reviewed, revised, and edited the content as needed, and take full responsibility for the final version of the material.

Ethical approval

The study was conducted in accordance with the latest revision of the Declaration of Helsinki and the approved Pamukkale University Non-Interventional Clinical Research Ethics Committee (E−60116787-020-408611). All participants were informed about the study and tests and their written consent was obtained.

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Declaration of competing interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2025.10.001.

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