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Effects of Combined Cognitive-Motor Training on Agility, Decision-Making, and Match Performance in Competitive Tennis Players: A Randomized Controlled Trial

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ABSTRACT

Objective: Modern tennis performance increasingly depends on the integration of perceptual-cognitive and movement-related abilities due to the highly dynamic and unpredictable nature of competitive match play. Although combined cognitive-motor training (CCMT) has gained increasing attention in open-skill sports, evidence regarding its effectiveness in competitive tennis remains limited. Therefore, the present study aimed to investigate the effects of CCMT on reactive agility, decision-making ability, and match performance in competitive tennis players.

Materials and Methods: An assessor-blinded randomized controlled trial with a parallel-group pretest–posttest design was conducted involving 40 competitive tennis players aged 16–22 years. Participants were randomized into experimental ($n = 20$) and control groups ($n = 20$). Following two non-intervention-related withdrawals in the control group, final per-protocol analyses included 38 participants. The experimental group performed combined cognitive-motor training integrated within the regular training schedule for eight weeks, whereas the control group performed regular tennis training only. Reactive agility, tennis-specific decision-making, and match performance were evaluated before and after the intervention period. Data were analyzed using a linear mixed model ($p < 0.05$).

Findings: The experimental group demonstrated significantly greater improvements in reactive agility performance compared with the control group ($F = 18.72$, $p \leq 0.001$). Significant group $\times$ time interaction effects were also identified for decision-making accuracy ($F = 16.94$, $p \leq 0.001$) and response time ($F = 14.27$, $p \leq 0.001$). In addition, the experimental group exhibited greater improvements in match-performance indicators, including winners ($F = 11.83$, $p = 0.002$), unforced errors ($F = 13.26$, $p = 0.001$), rally success percentage ($F = 15.11$, $p \leq 0.001$), point-winning efficiency ($F = 13.02$, $p = 0.001$), and tactical efficiency index ($F = 12.48$, $p = 0.001$).

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No serious adverse events or intervention-related injuries were reported during the intervention period.

Conclusions: Combined cognitive-motor training produced greater improvements in reactive agility, tennis-specific decision-making performance, and competitive match outcomes compared with regular tennis training alone. These findings suggest that integrating cognitive challenges within representative sport-specific movement tasks may provide an effective strategy for enhancing perceptual-cognitive and movement-related performance capacities in competitive tennis players. Future studies should investigate long-term retention effects and explore the underlying mechanisms associated with cognitive-motor adaptation in sport-specific training environments.

Keywords: *Combined Cognitive-motor Ttraining; Reactive Agility; Decision-making; Tennis Performance; Perceptual-Cognitive Ttraining; Representative learning Design; Open-skill sports; Reactive Movement*

1. Introduction

Modern competitive tennis has evolved into a highly dynamic and cognitively demanding sport characterized by rapid ball exchanges, multidirectional movements, and continuous tactical adaptation under time pressure. Contemporary match play requires athletes not only to possess superior technical and physical capacities, but also to demonstrate high-level perceptual-cognitive skills, including anticipation, visual scanning, inhibitory control, and rapid decision-making. During high-intensity rallies, players are often required to process complex visual information, predict opponents' actions, and execute precise motor responses within fractions of a second. Consequently, successful tennis performance increasingly depends on the integration of cognitive and motor abilities rather than isolated physical capacities alone. Recent developments in sport science emphasize that elite performance in open-skill sports such as tennis is strongly associated with efficient perception-action coupling and adaptive decision-making mechanisms (1).

The increasing speed and intensity of modern tennis further amplify these demands. Advances in racket technology, athlete conditioning, and tactical playing styles have shortened reaction windows and increased movement complexity during rallies. Under these conditions, players frequently experience cognitive overload, especially during high-pressure situations where rapid tactical decisions are required. Inadequate cognitive processing during match play may result in delayed reactions, poor shot selection, reduced movement efficiency, and increased unforced errors. Studies in perceptual-cognitive sport science have shown that athletes with superior decision-making and anticipatory skills consistently demonstrate better tactical efficiency and competitive outcomes than athletes relying primarily on

physical abilities alone. In tennis specifically, expert players exhibit more efficient visual search behavior, faster information processing, and greater tactical anticipation compared with novice players (2).

Reactive agility has emerged as one of the most important determinants of successful tennis performance. Unlike pre-planned change-of-direction speed, reactive agility involves the ability to rapidly perceive external stimuli, process relevant information, and execute an appropriate motor response under unpredictable conditions. In the present study, reactive agility specifically refers to the ability to rapidly change movement direction in response to external stimuli involving perceptual and decision-making processes. In tennis, reactive agility is critical because players must continuously adjust footwork patterns and body positioning based on ball trajectory, opponent movement, and tactical context. Consequently, agility performance in tennis is no longer viewed solely as a physical quality, but rather as an integrated sensorimotor capability involving perceptual and cognitive components. Recent systematic evidence highlights the importance of agility-specific training approaches that incorporate perception-action coupling and sport-specific stimuli to optimize athletic adaptation (3).

Alongside reactive agility, decision-making ability is another essential component of tennis success. Tennis players are required to make rapid tactical decisions regarding shot selection, movement direction, positioning, and rally strategy under constantly changing environmental conditions. These decisions are influenced by several neurocognitive processes, including working memory, attentional control, anticipation, and inhibitory regulation. Research investigating offensive tactical decision-making in tennis demonstrated that highly skilled players possess significantly faster reaction times and superior visual

information processing strategies compared with lower-level athletes. Furthermore, visuospatial working memory capacity has been associated with more efficient visual search patterns and enhanced tactical anticipation during competitive play (2). These findings suggest that cognitive efficiency plays a central role in determining tactical effectiveness during tennis performance.

Despite the recognized importance of cognitive processes in tennis, traditional training methods continue to emphasize isolated technical drills and physical conditioning. Conventional agility and conditioning programs often rely on repetitive pre-planned movements that inadequately represent the unpredictable and information-rich nature of actual match situations. Although such approaches may improve general physical fitness, their transferability to real competitive performance remains limited. This limitation has encouraged researchers and practitioners to explore training approaches that more closely replicate the perceptual and movement demands of competitive match play. These limitations highlight the need for training approaches capable of simultaneously targeting perceptual, cognitive, and movement-related adaptations under representative sport-specific conditions.

Combined cognitive-motor training refers to training approaches that integrate cognitive challenges with sport-specific movement tasks performed simultaneously. By integrating perceptual and motor demands within the same training environment, CCMT aims to improve the transferability of training adaptations into actual competitive performance. This approach is grounded in ecological dynamics and representative learning principles, which emphasize the importance of training under competition-relevant perceptual and movement constraints. CCMT typically incorporates dual-task paradigms, reactive movement drills, visuomotor stimuli, decision-based exercises, and unpredictable environmental constraints to enhance perception-action integration. Through repeated exposure to cognitively demanding movement tasks, athletes may demonstrate enhanced perceptual-motor coordination, attentional regulation, and adaptive decision-making performance under dynamic sport-specific conditions (4).

Emerging evidence suggests that integrated cognitive-motor interventions may produce greater sport-specific adaptations than isolated physical or technical training approaches. A study involving elite basketball players reported that integrating cognitive-motor dual-task training into sprint and agility programs significantly improved agility, decision-making speed, and neural processing

efficiency compared with motor training alone (5). Similarly, investigations involving reactive agility training have shown that higher visuomotor task complexity can enhance perceptual and decision-making components of agility performance (6). In tennis-specific contexts, emerging evidence suggests that combining cognitive tasks with repeated sprint and movement training may improve tactical responsiveness and high-pressure decision-making (7). Collectively, these findings support the growing notion that integrated cognitive and physical training may provide greater sport-specific adaptation than isolated conditioning approaches.

Nevertheless, several important limitations remain within the current literature. First, many previous studies employed small sample sizes and lacked rigorous randomized controlled trial designs, reducing the strength and generalizability of their findings. Second, numerous interventions used generic cognitive assessments that were insufficiently representative of actual sport-specific demands. Third, relatively few studies have simultaneously examined reactive agility, decision-making performance, and objective competitive match outcomes within the same intervention framework. In tennis specifically, evidence regarding the effectiveness of combined cognitive-motor training remains limited, particularly among competitive athletes. Furthermore, many existing interventions lack detailed representative learning designs capable of accurately replicating the dynamic perceptual and tactical demands of tennis competition (8).

Given these limitations, there is a clear need for ecologically valid, sport-specific, and methodologically rigorous intervention studies investigating the effectiveness of combined cognitive-motor training in competitive tennis players. Understanding how integrated cognitive and movement-based training influences reactive agility, tactical decision-making, and actual match performance could provide important theoretical and practical contributions to modern tennis conditioning. From a practical perspective, CCMT may offer coaches an efficient strategy to simultaneously enhance physical and cognitive performance capacities without substantially increasing training volume. Additionally, such approaches may improve athletes' adaptability under competitive pressure and facilitate more effective transfer of training adaptations into match situations.

Therefore, the present study aimed to investigate the effects of combined cognitive-motor training on reactive agility, decision-making ability, and match performance in

competitive tennis players using a randomized controlled trial design. Specifically, this study sought to compare changes in reactive agility, tennis-specific decision-making performance, and objective match-performance indicators between an experimental group performing combined cognitive-motor training and a control group performing regular tennis training only. It was hypothesized that the combined cognitive-motor training intervention would produce significantly greater improvements in reactive agility, decision-making accuracy and response speed, as well as competitive match performance compared with conventional training alone.

2. Methods and Materials

2.1 Research Design

This study employed a assessor-blinded randomized controlled trial using a parallel-group pretest–posttest design to investigate the effects of combined cognitive-motor training (CCMT) on reactive agility, decision-making ability, and match performance in competitive tennis players. The intervention lasted for eight weeks and was conducted during the competitive preparation phase of the athletes' seasonal training program. Participants were randomly allocated into either an experimental group performing CCMT in addition to regular tennis training or a control group performing regular tennis training only.

Outcome assessors were blinded to participant group allocation throughout the study period. However, participants and coaching staff were aware of the intervention procedures because blinding was not feasible within the applied training environment.

Outcome assessments were conducted one week before and one week after the intervention period under standardized testing conditions.

The study design followed the Consolidated Standards of Reporting Trials (CONSORT) guidelines for randomized intervention studies. All procedures were approved by the Institutional Research Ethics Committee in accordance with the Declaration of Helsinki for research involving human participants. Prior to participation, all athletes and, when necessary, their guardians provided written informed consent after receiving a detailed explanation regarding study procedures, benefits, and potential risks.

2.2 Participants

A total of 40 competitive tennis players (22 males and 18 females) voluntarily participated in this study. Participants were recruited from regional tennis academies and university tennis clubs through purposive sampling. Eligible athletes were required to meet the following inclusion criteria: (1) aged between 16 and 22 years; (2) actively competing in regional or national tennis tournaments; (3) possessing a minimum of three years of structured tennis training experience; (4) participating in regular tennis practice at least four times per week; and (5) being free from musculoskeletal injuries or neurological disorders during the previous six months. Participants were excluded if they missed more than 15% of intervention sessions or failed to complete post-intervention testing.

Sample size estimation was conducted using G*Power software version 3.1 based on repeated-measures ANOVA with an expected moderate effect size ($f = 0.25$), alpha level of 0.05, and statistical power of 0.80. The analysis indicated a minimum required sample size of 34 participants. The final sample exceeded the minimum required sample size to improve statistical precision and to account for potential participant attrition during the intervention period. To account for potential dropouts, 40 athletes were recruited.

Following baseline assessment, participants were randomly assigned into either the experimental group ($n = 20$) or control group ($n = 20$) using a computer-generated randomization procedure. Allocation concealment was performed using sealed opaque envelopes prepared by an independent researcher not involved in testing or intervention delivery. Outcome assessors were blinded to group allocation throughout the study period.

2.3 Instruments and Measurements

2.3.1 Reactive Agility Assessment

Reactive agility performance was assessed using a tennis-specific Reactive Agility Test (RAT) adapted from previously validated sport-specific agility protocols for open-skill sports. The assessment was designed to evaluate rapid movement-direction changes in response to externally presented sport-specific stimuli. The assessment was conducted on an indoor hard court to ensure environmental consistency and reduce external interference. Participants began from a central ready position and responded to randomized visual stimuli generated through a FitLight Trainer system positioned at four directional movement

zones around the court. Upon stimulus activation, athletes were required to rapidly move toward the indicated target and return to the starting position as quickly as possible.

The test consisted of three familiarization trials followed by three recorded trials with a standardized 2-minute passive recovery period between attempts. The fastest completion time was retained for statistical analysis. Movement time was measured using electronic timing gates with an accuracy of 0.01 seconds.

The reactive agility protocol demonstrated high measurement reliability in previous racket-sport investigations. Earlier validation studies reported excellent test-retest reliability with intraclass correlation coefficient (ICC) values ranging from 0.89 to 0.94 and coefficient of variation (CV) values below 5%, indicating acceptable measurement stability and consistency. Construct validity of the reactive agility assessment has also been supported through its ability to discriminate between elite and sub-elite racket sport athletes. Furthermore, the use of randomized sport-specific visual stimuli enhanced ecological validity by replicating the unpredictable movement demands commonly encountered during competitive tennis rallies.

2.3.2 Decision-Making Assessment

Decision-making ability was evaluated using a tennis-specific video-based decision-making test developed according to temporal occlusion and representative learning principles. The assessment incorporated match-based tactical scenarios recorded from a first-person competitive tennis perspective to enhance perceptual realism and task specificity. Video clips displayed offensive and defensive rally scenarios and were temporally occluded immediately before ball contact. Participants were then required to rapidly select the most appropriate tactical response from four response options presented on a touchscreen interface. The assessment consisted of 24 randomized video clips representing various offensive and defensive match situations. Each video stimulus lasted between 4 and 6 seconds and was occluded approximately 120 ms before racket-ball contact to simulate realistic anticipatory demands. Participants were required to provide their response within a 3-second response window following video occlusion. All video clips were presented in randomized order to minimize prediction bias and learning effects during assessment. Prior to formal testing, participants completed six familiarization trials to ensure procedural understanding and response consistency.

Familiarization reliability was evaluated during pilot testing and demonstrated acceptable temporal stability ($ICC = 0.87$).

Two primary variables were recorded:

1. Decision-making accuracy (%),
2. Response time (ms).

Decision-making accuracy represented the percentage of correct tactical decisions based on expert evaluation by certified tennis coaches with more than five years of competitive coaching experience. Response time represented the duration between video occlusion and participant response initiation.

Prior to formal testing, all participants completed a familiarization session to minimize learning effects and improve procedural consistency. The decision-making assessment demonstrated strong content validity because all video scenarios were developed using actual competitive match situations frequently observed in tennis competition. Three expert tennis coaches independently reviewed and validated the tactical appropriateness of each scenario before data collection. Inter-rater agreement among the expert evaluators demonstrated high consistency (Cohen's $\kappa = 0.86$), indicating acceptable agreement regarding the most appropriate tactical responses for each scenario.

Reliability analysis from previous perceptual-cognitive sport studies demonstrated acceptable internal consistency and temporal stability for video-based decision-making assessments, with ICC values ranging from 0.85 to 0.91 and Cronbach's alpha coefficients above 0.80. The temporal occlusion paradigm has also been widely recognized as a valid approach for evaluating anticipation and tactical decision-making performance in open-skill sports due to its close resemblance to real competitive conditions. Internal consistency analysis conducted in the present sample also demonstrated acceptable reliability (Cronbach's $\alpha = 0.84$).

2.3.3 Match Performance Analysis

Competitive match performance was evaluated using objective notational analysis and tactical performance analytics conducted during standardized singles matches performed before and after the intervention period. All matches were played according to official International Tennis Federation (ITF) rules on indoor hard courts and recorded using high-definition digital cameras positioned behind the baseline to capture full-court tactical movement and shot execution.

The following match-performance indicators were analyzed:

1. Number of winners,
2. Number of unforced errors,
3. Rally success percentage,
4. Point-winning efficiency,
5. Serve-return effectiveness.

Rally success percentage was calculated as the percentage of rallies won relative to the total number of rallies played during match analysis. Point-winning efficiency represented the percentage of total points won relative to total points contested throughout the match. All tactical-performance variables were coded according to predefined performance-analysis criteria established before data collection to ensure procedural consistency across match evaluations.

In addition to conventional match statistics, advanced performance analytics were also examined to provide a more comprehensive evaluation of tactical effectiveness during competitive play. These variables included tactical efficiency index, calculated as the ratio between successful offensive actions and total offensive attempts performed during rallies; rally duration analysis, representing the average rally duration and number of shots exchanged per point; offensive-to-defensive transition success, reflecting the percentage of successful positional recovery actions following offensive play sequences; and shot selection efficiency, defined as the percentage of tactically appropriate shot choices based on situational match context and expert performance coding. Tactical appropriateness was independently evaluated by two certified tennis analysts according to predefined performance-analysis criteria established prior to data collection. These additional indicators were included to enhance the ecological and tactical sensitivity of match-performance assessment in accordance with contemporary performance-analysis approaches in elite racket sports. Video recordings were analyzed using Dartfish motion-analysis software by two independent tennis performance analysts blinded to participant group allocation. To ensure procedural consistency, both analysts completed a standardized coding familiarization process before match evaluation.

Inter-rater reliability was assessed using intraclass correlation coefficients (ICC), which demonstrated excellent agreement across all match-performance variables (ICC = 0.88–0.95). Intra-rater reliability analysis conducted on 20% of randomly selected match footage one week after the initial analysis also demonstrated high consistency (ICC = 0.90–0.96). The notational analysis procedures used in this study

have previously demonstrated strong construct validity in tennis performance research because they objectively quantify technical and tactical effectiveness during actual match play.

Furthermore, the match-performance assessment demonstrated strong practical relevance because all performance variables were derived from competitive match situations rather than isolated laboratory-based tasks. This approach allowed the assessment of practical transfer effects from the intervention into actual tennis performance contexts.

2.3.4 Physical Load Monitoring

Training intensity during intervention sessions was monitored using the Borg Rating of Perceived Exertion (RPE) scale ranging from 6 to 20. Participants reported their perceived exertion immediately following each training session. The Borg RPE scale has been extensively validated as a reliable indicator of internal training load in athletic populations, with strong correlations reported between RPE scores and physiological markers such as heart rate and blood lactate concentration.

Previous sport-science investigations reported high reliability for session-RPE monitoring with ICC values exceeding 0.85 in intermittent sports. The use of RPE in the present study provided a practical and valid method for monitoring training intensity and ensuring comparable internal training load between the experimental and control groups throughout the intervention period. Session-RPE values were collected from both groups following all scheduled training sessions.

Attendance and training compliance were additionally recorded for all participants. Compliance percentage was calculated by dividing the number of completed sessions by the total prescribed sessions during the intervention period.

2.4 Intervention Procedures

2.4.1 Experimental Group

Participants assigned to the experimental group completed combined cognitive-motor training sessions three times weekly as part of their regular tennis training program. To maintain comparable weekly training volume between groups, portions of conventional conditioning and agility drills were replaced by CCMT sessions rather than added as additional training exposure. Each CCMT session lasted approximately 50 minutes and consisted of four primary

components: dynamic warm-up, cognitive-motor drills, reactive movement tasks, and recovery periods.

The intervention protocol was developed according to representative learning design principles to replicate the perceptual and movement demands of competitive tennis. Cognitive tasks were integrated directly into sport-specific movement patterns to stimulate simultaneous cognitive and neuromuscular adaptation.

The cognitive components included:

1. visual scanning tasks,
2. color-coded stimulus recognition,
3. inhibitory control exercises,
4. decision-based directional movement,
5. dual-task processing activities.

Meanwhile, the motor components included:

1. multidirectional sprinting,
2. reactive change-of-direction drills,

3. split-step footwork patterns,
4. acceleration and deceleration tasks,
5. tennis-specific lateral movement sequences.

Visual stimuli were delivered using FitLight technology and randomized coach commands to increase task unpredictability. Participants were required to process visual or auditory information before initiating movement responses. Drill complexity progressively increased each week by manipulating stimulus frequency, movement speed, cognitive load, and environmental unpredictability.

Table 1 presents the weekly progression model implemented throughout the combined cognitive-motor training intervention. Training progression was systematically designed to gradually increase perceptual complexity, movement unpredictability, and cognitive processing demands while preserving tennis-specific movement characteristics.

Table 1. Weekly Progression Model of the Combined Cognitive-Motor Training Intervention

Week	Cognitive Load	Movement Complexity	Stimulus Speed	Representative Task Characteristics
1–2	Low	Planned reactive movement	Low	Basic directional response and visual recognition drills
3–4	Moderate	Multidirectional movement	Moderate	Reactive footwork combined with decision-based directional tasks
5–6	High (dual-task)	Randomized movement patterns	High	Simultaneous cognitive processing and reactive agility drills
7–8	Very high	Match-simulated unpredictable movement	Maximal	Representative tennis-specific rally and tactical response scenarios

Training fidelity was monitored weekly by the principal investigator using standardized intervention checklists to ensure protocol adherence, progressive cognitive-load implementation, and participant compliance throughout the intervention period. Each session included four sets of 5-minute reactive drills separated by 90-second passive recovery intervals. Progression criteria were adjusted weekly based on movement accuracy, response time performance, and successful task completion to ensure continuous adaptation and to avoid performance plateau during the intervention period.

2.4.2 Control Group

The control group participated in five weekly tennis training sessions consisting of approximately 90–120 minutes per session. Training activities included technical stroke drills, serve-and-return practice, tactical rally exercises, aerobic and anaerobic conditioning, and supervised practice matches. Physical conditioning components primarily involved linear sprint training, general agility drills, endurance exercises, and lower-body

strength development. Training intensity was monitored by coaching staff using session duration and perceived exertion to ensure that overall weekly training load remained comparable between groups throughout the intervention period. Training frequency and overall weekly training duration were matched between groups. While the experimental group replaced portions of conventional conditioning with CCMT sessions, the control group continued performing standard conditioning and agility drills of comparable duration and perceived intensity. Additionally, total weekly training duration and overall external training exposure were standardized between groups to minimize potential confounding effects associated with unequal training volume. Where necessary, regular conditioning volume within the experimental group was adjusted by coaching staff to maintain comparable overall weekly training exposure between groups.

2.4.3 Standardization Procedures

To reduce potential bias and ensure intervention consistency, all testing and training sessions were conducted

at the same indoor tennis facility under identical environmental conditions. Participants were instructed to avoid strenuous exercise 24 hours before testing sessions and to maintain consistent sleep and nutritional habits throughout the intervention period.

All assessments were administered at the same time of day to minimize circadian variation. Attendance and compliance were recorded for every training session, and participants achieving less than 85% attendance were excluded from final analysis.

2.5 Statistical Analysis

Data analysis was performed using IBM SPSS Statistics version 26.0. Descriptive statistics were calculated and presented as mean $\pm$ standard deviation (SD). Data normality was assessed using the Shapiro–Wilk test, while homogeneity of variance was examined using Levene’s test.

A linear mixed model (LMM) analysis was performed to examine group $\times$ time interaction effects for all dependent variables. The model included group (experimental vs. control) and time (pretest vs. posttest) as fixed effects, while participant identity was treated as a random effect to account for repeated observations within subjects. Linear mixed modeling was selected because of its flexibility in handling

repeated measurements and its ability to accommodate incomplete repeated-measures data structures. However, final analyses were conducted using a per-protocol approach because participants who withdrew did not complete post-intervention assessments, resulting in insufficient outcome data for inclusion in the final analysis.

When significant interactions were identified, Bonferroni-adjusted post hoc analyses were conducted to determine pairwise differences. Effect sizes were interpreted using Cohen’s d for pairwise comparisons, alongside estimated marginal mean differences obtained from the linear mixed models. Effect sizes were interpreted as small (0.2), moderate (0.5), and large (0.8) according to Cohen’s conventional thresholds.

Statistical significance was established at $p \leq 0.05$. Additionally, 95% confidence intervals were calculated to provide further interpretation of intervention effects and practical significance.

3. Results

3.1 Participant Flow and Baseline Characteristics

Participant recruitment, allocation, follow-up, and final analysis procedures are summarized in Figure 1.

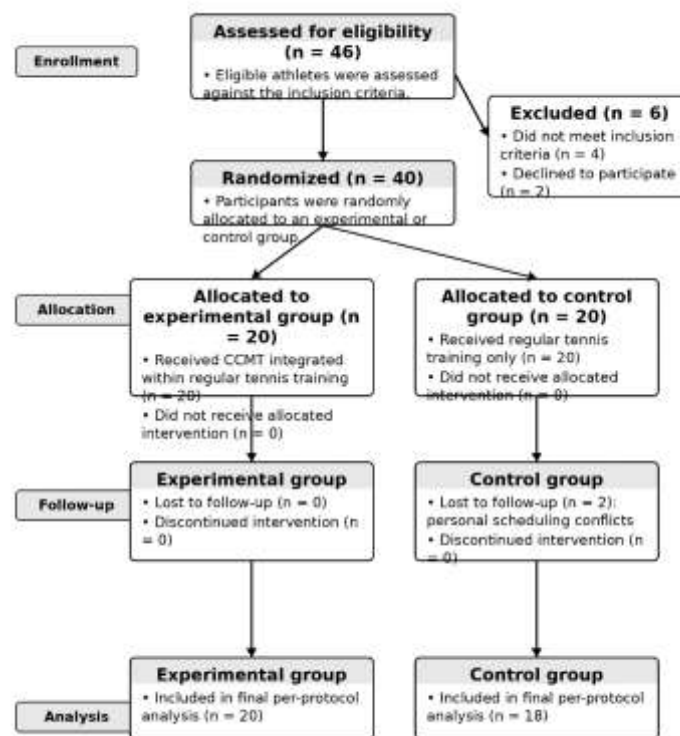


Figure 1. CONSORT flow diagram

A total of 46 athletes were assessed for eligibility. Six athletes were excluded prior to randomization because they did not meet the inclusion criteria or declined participation. Consequently, 40 competitive tennis players were randomly allocated into either the experimental group ($n = 20$) or control group ($n = 20$). During the intervention period, two participants from the control group withdrew due to personal scheduling conflicts unrelated to the study procedures. Consequently, final statistical analyses were conducted using data from 38 participants (experimental group: $n = 20$; control group: $n = 18$). Participants who withdrew during the

intervention period did not complete post-intervention assessments and were therefore excluded from the final per-protocol analysis. All participants included in the final analysis achieved a minimum attendance compliance rate of 85% throughout the intervention period.

Baseline demographic and training characteristics for both groups are presented in Table 2. No significant between-group differences were identified at baseline for age, body mass, height, training experience, or weekly training frequency ($p > 0.05$), indicating acceptable group homogeneity prior to intervention.

Table 2. Baseline Characteristics of Participants

Variable	Experimental Group ($n = 20$)	Control Group ($n = 18$)	p-value
Age (years)	18.4 ± 1.7	18.1 ± 1.9	0.642
Height (cm)	171.8 ± 7.5	170.9 ± 6.9	0.731
Body Mass (kg)	64.3 ± 8.2	63.7 ± 7.8	0.814
Training Experience (years)	6.2 ± 1.9	6.0 ± 2.1	0.768
Weekly Training Frequency (sessions/week)	5.4 ± 0.7	5.2 ± 0.8	0.489
Male/Female	11/9	11/9	1.000
Dominant Hand (Right/Left)	17/3	16/2	0.801
Competitive Level (Regional/National)	13/7	12/6	0.944

The results presented in Table 2 demonstrate that both groups exhibited comparable baseline physical and training characteristics before the intervention period. All participants regularly competed in regional and national tennis tournaments during the competitive season, and both groups demonstrated comparable distributions of sex, dominant playing hand, and competitive level at baseline.

3.2 Assumption Testing

Prior to inferential analysis, assumption testing was performed to examine data normality and homogeneity across all dependent variables. Shapiro–Wilk analysis indicated that all variables were normally distributed ($p > 0.05$), whereas Levene’s test confirmed homogeneity of variance between groups for all baseline measures ($p > 0.05$).

Table 3. Results of Normality and Homogeneity Testing

Variable	Shapiro–Wilk p-value	Levene’s Test p-value
Reactive Agility	0.217	0.384
Decision-Making Accuracy	0.192	0.411
Decision-Making Response Time	0.156	0.337
Rally Success Percentage	0.238	0.429
Point-Winning Efficiency	0.201	0.365
Winners	0.184	0.392
Unforced Errors	0.227	0.401
Tactical Efficiency Index	0.173	0.356

The reported Shapiro–Wilk and Levene tests did not indicate statistically significant departures from normality or homogeneity for the variables examined.

3.3 Reactive Agility Performance

Changes in reactive agility performance before and after the intervention period are presented in Table 4. Both groups demonstrated improvements following the intervention;

however, the magnitude of improvement was greater in the experimental group compared with the control group.

Table 4. Reactive Agility Performance Before and After the Intervention

Variable	Group	Pretest	Posttest	Mean Difference	<i>p</i>	Cohen's <i>d</i>
Reactive Agility (s)	Experimental	8.41 ± 0.52	7.63 ± 0.47	-0.78	<0.001	1.49
	Control	8.36 ± 0.55	8.12 ± 0.51	-0.24	0.041	0.43

Linear mixed model analysis revealed a significant group × time interaction effect for reactive agility performance ($F = 18.72$, $p < 0.001$, 95% CI [-0.92, -0.51]). Post hoc analysis demonstrated that the experimental group exhibited significantly greater reductions in reactive agility completion time compared with the control group during posttest assessment.

3.4 Decision-Making Performance

Table 5 summarizes post-intervention changes in tennis-specific decision-making performance. Improvements were observed in both groups; however, greater changes in decision-making accuracy and response time were identified in the experimental group.

Table 5. Decision-Making Performance Before and After the Intervention

Variable	Group	Pretest	Posttest	Mean Difference	<i>p</i>	Cohen's <i>d</i>
Decision-Making Accuracy (%)	Experimental	71.5 ± 6.4	82.8 ± 5.9	+11.3	<0.001	1.76
	Control	72.1 ± 5.8	75.4 ± 6.1	+3.3	0.048	0.54
Response Time (ms)	Experimental	842 ± 76	731 ± 68	-111	<0.001	1.52
	Control	836 ± 81	801 ± 74	-35	0.067	0.36

Linear mixed model analysis demonstrated significant group × time interaction effects for both decision-making accuracy ($F = 16.94$, $p \leq 0.001$, 95% CI [7.14, 12.85]) and response time ($F = 14.27$, $p \leq 0.001$, 95% CI [-128.42, -54.77]). Estimated marginal mean comparisons indicated greater improvements in tennis-specific decision-making

performance within the experimental group relative to the control condition.

3.5 Match Performance Outcomes

Changes in competitive match-performance indicators before and after the intervention are presented in Table 6.

Table 6. Match Performance Outcomes Before and After the Intervention

Variable	Group	Pretest	Posttest	Mean Difference	<i>p</i>	Cohen's <i>d</i>
Winners (n)	Experimental	12.4 ± 2.8	16.1 ± 3.1	+3.7	<0.001	1.24
	Control	12.7 ± 2.6	13.5 ± 2.9	+0.8	0.114	0.29
Unforced Errors (n)	Experimental	18.6 ± 3.5	14.2 ± 3.1	-4.4	<0.001	1.33
	Control	18.1 ± 3.7	17.2 ± 3.3	-0.9	0.173	0.25
Rally Success (%)	Experimental	47.8 ± 5.4	56.9 ± 5.7	+9.1	<0.001	1.62
	Control	48.1 ± 5.7	50.4 ± 5.9	+2.3	0.081	0.39
Point-Winning Efficiency (%)	Experimental	51.3 ± 4.9	59.8 ± 5.2	+8.5	<0.001	1.67
	Control	51.0 ± 5.1	53.2 ± 5.4	+2.2	0.089	0.41
Tactical Efficiency Index	Experimental	0.58 ± 0.08	0.71 ± 0.09	+0.13	<0.001	1.53
	Control	0.57 ± 0.09	0.61 ± 0.08	+0.04	0.093	0.45

Linear mixed model analysis identified significant group × time interaction effects for winners ($F = 11.83$, $p = 0.002$, 95% CI [1.82, 4.91]), unforced errors ($F = 13.26$, $p = 0.001$, 95% CI [-5.32, -2.11]), rally success percentage ($F = 15.11$,

$p < 0.001$, 95% CI [5.12, 10.48]), point-winning efficiency ($F = 13.02$, $p = 0.001$, 95% CI [4.37, 9.26]), and tactical efficiency index ($F = 12.48$, $p = 0.001$, 95% CI [0.07, 0.16]). Larger changes across most match-performance indicators

were observed in the experimental group compared with the control group.

Additional match-performance variables, including serve-return effectiveness, rally duration analysis, offensive-to-defensive transition success, and shot selection efficiency, demonstrated small-to-moderate favorable changes in the experimental group compared with the control group; however, these differences did not reach statistical significance during posttest assessment ($p > 0.05$). Consequently, these secondary outcomes were not interpreted further within the primary analysis framework of the study.

3.6 Training Compliance and Internal Load Monitoring

Training attendance compliance remained high throughout the intervention period for both groups. Mean attendance compliance reached 93.6% in the experimental group and 91.8% in the control group. No significant between-group differences in training attendance compliance were observed. Session-RPE monitoring demonstrated that average training intensity remained within the planned “hard” to “very hard” range in both groups throughout the intervention period (experimental group: RPE = 15–17; control group: RPE = 14–16), indicating generally comparable internal training loads between groups.

No serious adverse events, intervention-related injuries, or participant withdrawals associated with the training procedures were reported during the study.

4. Discussion

The present study investigated the effects of combined cognitive-motor training (CCMT) on reactive agility, decision-making ability, and match performance in competitive tennis players using a randomized controlled trial design. The primary findings demonstrated that the experimental group performing CCMT exhibited significantly greater improvements in reactive agility, decision-making accuracy, response time, and several match-performance indicators compared with the control group performing regular tennis training alone. These findings support the hypothesis that integrating cognitive and movement-related demands within representative sport-specific environments may enhance tennis performance more effectively than conventional training approaches focused primarily on isolated technical or physical components.

One of the most important findings of the present study was the significant improvement in reactive agility performance following the CCMT intervention. Tennis is characterized by unpredictable movement demands that require athletes to rapidly perceive environmental information and execute appropriate movement responses under severe time constraints. Unlike pre-planned agility tasks, reactive agility involves perceptual and decision-making processes closely associated with perception–action coupling and sensorimotor adaptation (9). The larger reductions in reactive agility completion time observed in the experimental group suggest that repeated exposure to cognitively demanding movement tasks may improve the efficiency of stimulus processing and movement-response coordination during sport-specific activities. These findings are consistent with previous investigations demonstrating that agility performance in open-skill sports is strongly influenced by perceptual-cognitive processing rather than physical capacity alone (10, 11).

The present findings also align with previous reactive agility research reporting that training programs incorporating visuomotor stimuli and decision-based movement tasks produce greater sport-specific adaptations than traditional change-of-direction drills (12). In the current study, athletes were required to process randomized visual and auditory stimuli before initiating movement responses, which may have enhanced anticipatory processing and movement adaptability under unpredictable conditions. The representative learning characteristics incorporated within the intervention may therefore have contributed to improved transferability between training tasks and competitive match situations (13).

Another important outcome of the present study was the significant improvement in tennis-specific decision-making performance observed in the experimental group. Athletes performing CCMT demonstrated greater increases in decision-making accuracy alongside faster response times compared with the control group. Tennis performance requires rapid tactical decisions involving shot selection, movement positioning, and anticipation of opponent behavior under continuously changing environmental conditions (14). The integration of cognitive tasks within movement-based training may therefore have enhanced athletes' ability to process relevant perceptual information while simultaneously executing appropriate motor responses.

These findings are consistent with previous perceptual-cognitive sport research demonstrating that expert athletes

exhibit superior visual search strategies, faster information-processing speed, and greater anticipatory capabilities than lower-level performers (15). Similar improvements in tactical decision-making have been reported in studies involving cognitive-motor dual-task interventions in basketball, soccer, and racket sports (16). The present results extend these findings specifically to competitive tennis players by demonstrating that ecologically valid cognitive-motor training may improve both decision-making accuracy and response efficiency within sport-specific contexts.

Importantly, the improvements observed in the present study may be associated with enhanced perceptual-motor coordination and attentional regulation developed through repeated exposure to representative tennis-specific situations. However, the present study did not directly evaluate neurophysiological adaptations such as cortical activation, neural efficiency, or electrophysiological responses. Therefore, mechanistic interpretations regarding neural adaptation should be considered cautiously and remain speculative. Future investigations incorporating neurophysiological assessments such as electroencephalography (EEG) or functional neuroimaging may help clarify the underlying mechanisms associated with cognitive-motor adaptation during sport-specific training (17).

The present study also demonstrated significant improvements in several competitive match-performance indicators, including winners, rally success percentage, point-winning efficiency, and tactical efficiency index. Furthermore, reductions in unforced errors were greater in the experimental group than in the control group. These findings suggest that the adaptations induced by CCMT may transfer beyond isolated laboratory-based assessments into actual competitive performance contexts. This practical transfer effect is particularly important because one of the major criticisms of traditional conditioning approaches is their limited ecological relevance and poor transferability into real-match situations (18).

The observed improvements in tactical performance may be explained by the representative learning design used throughout the intervention. Training tasks were specifically designed to replicate the perceptual, cognitive, and movement-related constraints commonly encountered during competitive tennis rallies. According to ecological dynamics theory, athletic adaptation is optimized when training environments closely resemble the informational and movement demands of actual competition (19). Consequently, athletes exposed to representative sport-

specific stimuli may develop more effective perception-action coupling and improved adaptability under dynamic match conditions (20).

The present findings are also consistent with contemporary research emphasizing the importance of integrated training approaches in open-skill sports. Previous studies involving soccer and basketball athletes demonstrated that combining perceptual-cognitive challenges with reactive movement drills improved tactical responsiveness and competitive decision-making more effectively than isolated physical conditioning programs (21). Similarly, investigations involving tennis players reported that training interventions integrating anticipation and movement-response tasks may improve competitive performance under high-pressure situations (22). The present study further supports the growing evidence that combined cognitive-motor approaches may provide meaningful sport-specific benefits in competitive tennis environments.

From a practical perspective, the findings of the present study may have important implications for coaches, strength and conditioning specialists, and sport-performance practitioners. Traditional tennis conditioning programs frequently emphasize repetitive technical drills and isolated physical development. However, the current findings suggest that integrating cognitive challenges directly within movement-based training may provide a more representative and competition-relevant approach to performance development. CCMT may therefore represent an efficient strategy for simultaneously targeting perceptual, cognitive, and movement-related capacities without substantially increasing overall training volume.

Several limitations of the present study should be acknowledged. First, although overall weekly training exposure and internal training load were monitored and standardized as closely as possible between groups, the experimental group received a combined cognitive-motor intervention that may have introduced residual differences in training stimulus and participant motivation. Second, the present study used a per-protocol analytical approach because participants who withdrew during the intervention period did not complete post-intervention assessments. Although linear mixed modeling was implemented to improve robustness against missing observations, future studies may benefit from intention-to-treat approaches to further strengthen randomized controlled trial methodology. Third, complete participant blinding was not feasible because of the applied nature of the intervention, which may

have introduced expectancy-related influences. Fourth, although match-performance assessments were conducted under standardized competitive conditions, contextual factors inherent to tennis performance, including opponent behavior and situational tactical variability, could not be fully controlled. Finally, several secondary match-performance outcomes demonstrated non-significant trends and were therefore not interpreted extensively within the primary analysis framework. Future investigations involving larger sample sizes, longer intervention durations, retention testing, and more comprehensive sport-performance monitoring may further clarify the long-term transfer effects of combined cognitive-motor training in competitive tennis athletes.

Overall, the findings of the present study indicate that combined cognitive-motor training may represent an effective training strategy for improving reactive agility, tennis-specific decision-making performance, and competitive match outcomes in competitive tennis players. The integration of cognitive and movement demands within representative training environments appears to provide greater sport-specific adaptation than conventional training approaches emphasizing isolated physical or technical development alone.

5. Conclusions

The present study investigated the effects of combined cognitive-motor training (CCMT) on reactive agility, decision-making ability, and competitive match performance in competitive tennis players using a randomized controlled trial design. The findings demonstrated that athletes performing CCMT exhibited greater improvements in reactive agility, decision-making accuracy, response time, and several match-performance indicators compared with athletes performing regular tennis training alone. These results support the effectiveness of integrating cognitive and movement-related demands within representative sport-specific training environments.

The improvements observed in the experimental group suggest that combining perceptual-cognitive challenges with reactive movement tasks may enhance athletes' adaptability during dynamic tennis situations requiring rapid information processing and movement execution. In addition, the positive changes identified in match-performance variables indicate that the benefits of CCMT may extend beyond isolated testing conditions into actual competitive performance contexts.

From a practical perspective, the findings of this study highlight the potential value of incorporating cognitively demanding and representative training tasks within modern tennis conditioning programs. Coaches and sport-performance practitioners may consider using CCMT as an alternative or complementary training strategy to simultaneously develop perceptual, cognitive, and movement-related capacities relevant to competitive tennis performance.

Future studies are encouraged to investigate the long-term retention effects of CCMT and to further examine the underlying perceptual-cognitive and physiological mechanisms associated with sport-specific cognitive-motor adaptation.

Authors' Contributions

M.A. contributed to the study design, data collection, statistical analysis, manuscript preparation, and funding acquisition. F.I. contributed to the study design, manuscript preparation, and funding acquisition. U.N. contributed to the study design, statistical analysis, and manuscript preparation. I. contributed to the study design, statistical analysis, manuscript preparation, and funding acquisition. The contributions of Z.K. and B.E.O. were not specified. All authors have read and approved the final version of the manuscript.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants.

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