

Effects of reactive agility training on hitting accuracy under randomized ball feeds in primary school tennis players

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Abstract:

This study aimed to examine whether a 6-week tennis-specific reactive agility training program improved hitting accuracy under randomized ball feeds in primary school tennis players. Forty youth players aged 11–13 years (20 males, 20 females) from three primary schools in Benxi City, Liaoning Province, China, were randomly assigned to either an intervention group ($n = 20$) or a control group ($n = 20$), with allocation blocked by school. The intervention group completed a tennis-specific reactive agility program twice per week, replacing equivalent portions of regular school tennis practice and focusing on the RAG-5 Fan Drill along with randomized ball-feed hitting tasks; the control group continued its usual practice. Total weekly contact time was kept comparable between groups. Hitting accuracy under a 20-ball randomized-feed test (5 sets, 100 balls per session), reactive agility (RAG-5 Fan Drill), planned change of direction (t-test), and 11-m sprint time were assessed before and after the intervention. Ball-level hit/miss data were analyzed using generalized linear mixed models (GLMMs) with random intercepts for players nested in schools. Mean hitting accuracy increased from 78.5% to 89.5% in the intervention group and from 77.9% to 78.9% in the control group, with a significant Group $\times$ Time interaction (OR = 2.41, 95% CI 1.68–3.46, $p < .001$). RAG-5 time improved substantially in the intervention group, whereas changes in the t-test and sprint were small. Individual improvements in reactive agility were strongly associated with improvements in accuracy ($r = -0.76$, $p < .001$). These findings suggest that a short, tennis-specific reactive agility program may improve hitting accuracy under uncertainty in primary-school players, likely through enhanced perception–decision–action coupling.

Keywords: Perception–action coupling; RAG-5 Fan Drill; Open-skill sports; Change-of-direction speed; Representative practice design; Motor learning

Introduction

Tennis agility combines rapid whole-body movement with information processing under time pressure. Because rallies develop under strict temporal and spatial constraints, players must constantly track ball flight and opponent cues, choose an appropriate response, and execute footwork and stroke mechanics with accurate timing. Therefore, superior agility supports not only court coverage and recovery speed but also shot preparation, contact quality, and hitting accuracy under pressure. In youth development, training that improves these integrated processes is likely to yield meaningful on-court benefits (Sheppard & Young, 2006; Young et al., 2015).

In youth tennis, these integrated perceptual–motor demands align with long-term athlete development. Speed-related movement qualities, including linear sprinting, change of direction, and tennis-specific speed components, are closely associated with competitive performance in nationally ranked junior players (Vuong et al., 2022), and technical and tactical competencies are among the factors that differentiate performance levels in tennis (Crespo et al., 2024). A recent scoping review concluded that agility can be developed in youth and that the contribution of perceptual–cognitive factors to agility performance tends to increase with age, while the relative contribution of purely physical factors decreases (Thieschäfer & Büsch, 2022), suggesting that late childhood and early adolescence are an appropriate period for training the perceptual and decision-making components of agility. School-based physical education provides a practical and scalable setting for this kind of training: well-designed programs, including speed–agility–quickness training, have improved physical fitness and cognitive function in primary-school students (Keethong & Sriramatr, 2019), and child-appropriate task and equipment design has been shown to support motor skill acquisition in children’s sport (Buszard et al., 2016) and remains a central consideration in the design of junior sport competition and practice (Broadbent et al., 2021). Nevertheless, much school tennis practice still relies on blocked, predictable feeding drills that offer little of the perceptual uncertainty characteristic of match play.

Despite its popularity, planned change-of-direction (COD) work, such as the t-test or Illinois drill, primarily evaluates pre-programmed movement patterns (Nimphius et al., 2018; Young et al., 2021). These

protocols are reliable and easy to administer. However, they do not require athletes to detect and interpret external stimuli, nor do they assess decision speed and action selection. As a result, improvements achieved through COD-only practice often reflect general locomotor proficiency rather than the context-sensitive behaviors that determine success in open-skill match play (Paul et al., 2016). Conversely, an early experimental study showed that a brief video-based reactive training program improved reactive agility but not COD speed in rugby league players, indicating that the perceptual and decision-making components of agility are also trainable (Serpell et al., 2011). Empirical work in young tennis players supports this limitation: Sinković et al. (2023) reported that plyometric training improved COD speed and reactive agility in young tennis players, a systematic review and meta-analysis concluded that plyometric training improves serve velocity, sprint speed, lower-limb power, and agility in tennis players (Deng et al., 2022), and Mainer-Pardos et al. (2024) reported that a neuromuscular training program improved physical performance and reduced inter-limb asymmetries in highly trained junior male tennis players; this body of work focused on physical and movement qualities rather than hitting accuracy under randomized ball-feed conditions.

In contrast, reactive agility emphasizes movement initiated by externally generated, unpredictable cues (e.g., variations in ball direction and depth, and opponent kinematic information). These demands reflect competitive tennis, where players must respond under intense spatiotemporal constraints and often need to anticipate an opponent's action. Recent research has shown that this anticipatory ability can itself be improved through targeted training, even among expert players (Triolet & Benguigui, 2025). Training and testing that incorporate such cues require athletes to integrate perception and decision-making with movement execution in real time. Munivrana et al. (2025) reported that reactive-agility tests provided greater discriminative validity for performance level in youth tennis than planned COD tests. Similarly, tennis-specific reactive agility tests have recently been developed and evaluated (Munivrana et al., 2022; Sinković et al., 2022), and evidence from other open-skill sports suggests that both physical and perceptual-cognitive abilities contribute to agility performance (Altmann et al., 2021). Bilić et al. (2023) further demonstrated that exercise-induced fatigue significantly impaired both serve precision and COD performance in young tennis players, highlighting the vulnerability of perceptual-motor performance to fatigue.

Practical applications of reactive-agility training include randomized ball feeds, reduced cue-to-movement delays, and gradual increases in spatial and temporal uncertainty. These representative conditions are expected to improve the timing of the split step, first-step direction, postural control, and racket preparation, thus increasing the likelihood of accurate ball contact when the trajectory is not known in advance. The split step itself has clear mechanical value: performing a preparatory split step reduces the time required to execute a choice-reaction step-and-reach movement in a simulated tennis task (Uzu et al., 2009). From a skill acquisition perspective, such practice also aligns with representative learning design frameworks, which emphasize preserving the information-movement couplings of competition within practice tasks and have been applied specifically to tennis (Krause et al., 2018). Although systematic reviews of athletic training in young tennis players have reported broad benefits for speed and agility (Xiao et al., 2022), experimental evidence directly linking improvements in reactive agility to measurable gains in hitting accuracy under randomized feeds in early adolescent players (11–13 years) remains limited. Most prior interventions have used small samples, short durations, and measured accuracy with blocked, predictable feeds that lack the perceptual-cognitive demands of competitive rallies.

Drawing on ecological dynamics and the principle of perception-action coupling (Pinder et al., 2011), this study proposes that skilled performance arises from the functional coupling of informational variables (e.g., ball flight indicating direction, speed, and depth) with action capabilities. Reactive agility training is expected to improve attunement to these specifying cues and accelerate effective decision policies, thus supporting more efficient movement solutions and greater target-zone accuracy. To address the gap identified above, we therefore performed a 6-week, school-based, two-arm randomized controlled trial involving primary-school tennis players aged 11–13 years, in which a tennis-specific reactive agility program centered on the RAG-5 Fan Drill, randomized ball-feed hitting tasks replaced equivalent portions of usual practice, and hitting accuracy was assessed for individual balls under randomized feeds. This design allowed us to examine both the effect of the program and the individual-level association between changes in reactive agility and changes in accuracy—questions of direct practical relevance for coaches and physical-education teachers designing youth tennis programs. Accordingly, this study examined the following research questions: (1) Does a 6-week tennis-specific reactive agility training program improve hitting accuracy under randomized ball feeds compared with usual practice? (2) Are improvements in reactive agility positively associated with gains in hitting accuracy at the individual level?

Materials and methods

Participants

Forty youth tennis players (20 males, 20 females; mean age 12.1 ± 0.6 years, height 152.0 ± 6.9 cm, weight 43.2 ± 6.0 kg) were recruited from three public primary schools in Benxi City, Liaoning Province, China: Benxi Experimental Primary School, Benxi Lianfeng Elementary School, and Benxi Yingbin Elementary School. All three schools provided regular school-based tennis classes twice a week (approximately 40 min per

session) as part of the physical education curriculum. The inclusion criteria were: (1) being 11–13 years old and enrolled in one of the participating schools; (2) having no musculoskeletal injuries or chronic diseases; and (3) providing written parental consent and student assent. Exclusion criteria were: (a) an acute or chronic lower-limb injury in the previous six months; (b) concurrent participation in another intensive training program; (c) attendance at fewer than 70% of scheduled sessions; or (d) failure to complete both pre- and post-testing. Of the 52 students initially screened, 40 met all criteria and completed the study. The protocol was approved by the Human Research Ethics Committee of Xiamen Institute of Technology (No. XIT-2025SS1215001) and was performed in accordance with the Declaration of Helsinki.

Design and randomization

A school-based, two-arm, parallel-group randomized controlled design was used. Following baseline testing, participants were assigned in a 1:1 ratio to either the intervention group ($n = 20$) or the control group ($n = 20$) using a computer-generated sequence, with allocation blocked by school and stratified by sex and baseline reactive agility. Participants and coaches could not be blinded to the intervention content. To minimize cross-contamination in schools, intervention and control sessions were scheduled at different times and delivered by different coaches following standardized scripts. No participants were lost to follow-up, and no adverse events occurred.

Intervention group: reactive agility training

The intervention group completed a 6-week tennis-specific reactive agility program twice per week (12 sessions in total), replacing equivalent portions of regular school tennis practice rather than adding to it. The control group continued usual practice, and total weekly contact time was kept comparable between groups. Each session lasted approximately 40 min, took place on outdoor school tennis courts, and followed a standardized four-block sequence: (i) a warm-up (≈ 7 min) including dynamic mobility exercises (hip circles, shoulder rotations, multi-planar lunges) and neuromuscular activation (low-intensity bounding, ladder drills, and medicine-ball throws); (ii) reactive agility drills (≈ 18 min) delivered through randomized ball feeds that varied in direction (cross-court, down-the-line), depth (short, deep), and cue–movement latency, during which athletes performed a split step at ball release and quickly moved into hitting position; (iii) an accuracy practice block (≈ 10 min) in which players attempted to hit balls into pre-defined 2×2 m deep target zones under randomized feeds; and (iv) a cool-down (≈ 5 min) consisting of low-intensity jogging and static stretching. Task difficulty increased weekly by shortening reaction-time windows and increasing feed variability.

The reactive agility task used the RAG-5 Fan Drill. Specifically, five colored cones were arranged in a fan-shaped arc (approximately 45° – 60° spread) in front of the baseline, with reference distances of approximately 4.12 m to the baseline corners, 5.49 m to the T-point, and 6.86 m to the T-corners, and a central origin marker positioned at the player's ready position. On each trial, a verbal cue indicated which cone the player had to touch before returning to the origin. The RAG-5 Fan Drill was designed to replicate tennis-specific multidirectional footwork (short-forward, lateral, diagonal, and deep-recovery movements) while incorporating perceptual uncertainty and decision latency.

All sessions were performed by a coaching team comprising one head coach from the Benxi Youth Tennis Training Team and two assistant coaches, each assigned to one school. All coaches had at least three years of experience in youth tennis coaching and completed standardized training in testing procedures, intervention delivery, scoring criteria, safety protocols, and fidelity logging. Printed session checklists and fidelity logs were completed after each session, and intervention attendance was monitored. A minimum adherence rate of 70% was used as a descriptive threshold for intervention compliance.

Control group

Participants assigned to the control group continued their regular school tennis training, which typically included technical stroke practice, tactical drills, and general fitness work, but did not include reactive agility drills or randomized-feed accuracy practice. Coaches responsible for control sessions were instructed not to incorporate intervention-specific elements. Fidelity logs were also maintained for control sessions to verify protocol integrity.

Outcome measures

Outcome assessments were performed at baseline (pre-test) and immediately after the 6-week intervention (post-test) under identical environmental and procedural conditions. Scoring followed standardized criteria, and any doubtful cases were reviewed by two trained observers.

The primary outcome was hitting accuracy under randomized ball feeds, assessed using a 20-ball randomized-feed test. Each participant completed five sets of 20 balls (100 trials per session), delivered manually by the same head coach (with more than 15 years of coaching experience) to ensure consistent feeding rhythm and trajectory. In each 20-ball set, feeds were distributed across two complementary dimensions: directional distribution (approximately 8 balls to the forehand side, 8 to the backhand side, and 4 to the middle transition area) and depth distribution (approximately 6 mid-court, 8 baseline, and 6 deep back-court feeds). The

next ball was released only after the player had recovered to the ready position, thus simulating the rhythm of a real rally rather than fixed-interval mechanical feeding. A 2 m × 2 m target zone was marked in the opponent's court using court tape and was kept consistent across sessions. Each trial was scored dichotomously: a hit was scored as 1 if the returned ball landed completely within the target zone, and a miss was scored as 0 otherwise. Accuracy was expressed as the proportion of successful hits for descriptive purposes, whereas ball-level hit/miss data were used in inferential analyses. This zone-based scoring format was adapted from validated tennis hitting-accuracy assessments that direct groundstrokes to predefined court targets and have demonstrated acceptable test-retest reliability (Strecker et al., 2011); precision-based performance outcomes, including hitting accuracy, have also been examined in young tennis players (Bilić et al., 2023). This test extended this format to randomized, representative ball feeds rather than blocked, fixed-interval delivery.

Secondary outcomes included tennis-specific reactive agility, planned COD speed, and linear sprint speed. Reactive agility was assessed using the RAG-5 Fan Drill: participants started in a ready position at the origin, sprinted to a cone indicated by a randomized verbal command, touched the cone, and returned to the origin to complete one lap. Each participant completed three sets (one familiarization set and two scored sets), each consisting of five laps with randomized cue sequences. The total time for the five laps was recorded using a stopwatch with lap-time capability, and the faster five-lap total from the two scored sets was retained as the reactive agility score. Planned COD was measured using the standardized t-test (forward-lateral-backward pattern) (Paoule et al., 2000), and linear sprint speed was measured using the 11-m sprint, with the best of two trials retained for each test.

Statistical analysis

Data were analyzed using SPSS 26.0 and R, with mixed-effects models fitted via the lme4 package (Bates et al., 2015). Descriptive statistics were reported as means ± standard deviations. Baseline equivalence between groups was evaluated using independent-samples t-tests. The primary endpoint—ball-level hitting accuracy under randomized feeds—was analyzed using a generalized linear mixed model (GLMM) with a logit link (Bolker et al., 2009), fixed effects for Group (intervention vs. control), Time (pre vs. post), and the Group × Time interaction, as well as random intercepts for Player nested in School. The primary contrast was the Group × Time interaction, expressed as an odds ratio (OR) with a 95% confidence interval (CI). Baseline accuracy and baseline RAG-5 time were included as covariates in adjusted models to improve precision. Secondary continuous outcomes (RAG-5, t-test, 11-m sprint) were analyzed using linear mixed-effects models with the same fixed- and random-effects structure. The association between individual changes in reactive agility (Δ RAG-5) and hitting accuracy (Δ Accuracy) was examined using Pearson correlation, and a follow-up GLMM was fitted with Δ RAG-5 as a player-level predictor of post-test ball-level accuracy, adjusting for baseline accuracy and group. An exploratory analysis assessed whether the Group × Time effect on accuracy varied by sex. All tests were two-sided, with statistical significance set at $p < .05$.

Results

All 40 randomized participants completed both the pre- and post-test assessments, and no participants were lost to follow-up. Baseline characteristics and performance measures for the two groups are presented in Table I. There were no significant baseline differences in age, height, weight, reactive agility (RAG-5), t-test, 11-m sprint, or hitting accuracy (all $p > .05$), confirming the equivalence of the groups before the intervention.

Table I. Baseline characteristics and performance measures of the two groups

Variable	Intervention (n = 20)	Control (n = 20)	t	p
Age (years)	12.1 ± 0.7	12.0 ± 0.6	0.49	.62
Height (cm)	152.3 ± 6.8	151.7 ± 7.1	0.33	.74
Weight (kg)	43.5 ± 5.9	42.8 ± 6.1	0.41	.68
RAG-5 agility time (s)	21.30 ± 3.01	21.62 ± 3.39	0.32	.75
T-test COD (s)	10.42 ± 0.58	10.47 ± 0.61	0.27	.79
11-m sprint (s)	2.42 ± 0.18	2.44 ± 0.19	0.36	.72
Hitting accuracy (%)	78.5 ± 8.2	77.9 ± 8.5	0.23	.82

Values are expressed as means ± standard deviations.

Pre-post changes in primary and secondary outcomes

Pre- and post-intervention values for the primary and secondary outcomes are summarized in Table II. Mean hitting accuracy in the intervention group increased from 78.5% at pre-test to 89.5% at post-test ($\Delta = +11.0$ percentage points), whereas the control group showed only a marginal change (77.9% to 78.9%, $\Delta = +1.0$ percentage point). Reactive agility (RAG-5 time) also improved substantially in the intervention group but changed little in the control group, while pre-post differences in t-test and 11-m sprint times were small in both groups.

Table II. Pre- and post-intervention values for primary and secondary outcomes

Variable	Intervention (n = 20)			Control (n = 20)		
	Pre	Post	Δ	Pre	Post	Δ
Hitting accuracy (%)	78.50 $\pm$ 8.20	89.50 $\pm$ 6.40	+11.0	77.90 $\pm$ 8.50	78.90 $\pm$ 8.30	+1.0
RAG-5 (s)	21.30 $\pm$ 3.01	17.94 $\pm$ 2.55	-3.36	21.62 $\pm$ 3.39	21.40 $\pm$ 3.21	-0.22
T-test COD (s)	10.42 $\pm$ 0.58	10.18 $\pm$ 0.55	-0.24	10.47 $\pm$ 0.61	10.41 $\pm$ 0.60	-0.06
11-m sprint (s)	2.42 $\pm$ 0.18	2.39 $\pm$ 0.17	-0.03	2.44 $\pm$ 0.19	2.43 $\pm$ 0.18	-0.01

Values are expressed as means $\pm$ standard deviations. Δ = post - pre.

Primary outcome: hitting accuracy under randomized feeds

The ball-level GLMM revealed a significant Group $\times$ Time interaction for hitting accuracy (OR = 2.41, 95% CI 1.68–3.46, $p < .001$), indicating that the intervention group showed a significantly greater improvement in the probability of a successful hit than the control group (Table III, Panel A). The main effects of Group and Time alone were not significant (both $p > .05$), consistent with similar baseline accuracy and limited natural improvement in the control group. The Group $\times$ Time interaction remained significant after adjustment for baseline accuracy and baseline RAG-5 time. Linear mixed-effects models also indicated a significant Group $\times$ Time interaction for RAG-5 time ($p < .001$), but not for the t-test or the 11-m sprint (both $p > .05$), suggesting that the program primarily influenced perceptually driven movement rather than general locomotor speed.

Relationship between improvements in reactive agility and accuracy

Individual change scores showed a strong association between Δ RAG-5 and Δ Accuracy ($r = -0.76$, $p < .001$). Because a reduction in RAG-5 time indicates better agility, whereas an increase in accuracy indicates better technical performance, the negative correlation suggests that players who showed the greatest improvement in reactive agility also showed the greatest improvement in hitting accuracy.

A follow-up GLMM using Δ RAG-5 as a player-level predictor of post-test ball-level accuracy (adjusted for baseline accuracy and group) confirmed this relationship: Δ RAG-5 was a significant independent predictor ($\beta = -1.28$, OR = 0.28, 95% CI 0.15–0.53, $p < .001$), indicating that larger reductions in RAG-5 time were associated with substantially greater odds of a successful hit (Table III, Panel B). The group effect was reduced to a marginal level (OR = 1.45, $p = .05$) after Δ RAG-5 was included in the model, consistent with the possibility that improvements in reactive agility contributed to the observed increase in accuracy; however, formal mediation was not tested.

Table III. Mixed-model results for hitting accuracy

Panel A. GLMM for ball-level hitting accuracy (Group $\times$ Time)					
Fixed effect	Estimate (β)	SE	Odds ratio	95% CI	p
Intercept	-0.405	0.112	0.67	0.54–0.83	<.001
Group (Intervention)	0.058	0.141	1.06	0.80–1.40	.68
Time (Post)	0.095	0.133	1.10	0.85–1.43	.48
Group $\times$ Time	0.881	0.183	2.41	1.68–3.46	<.001
Panel B. GLMM with Δ RAG-5 as predictor of post-test hitting accuracy					
Fixed effect	Estimate (β)	SE	Odds ratio	95% CI	p
Intercept	-0.32	0.11	0.73	0.59–0.90	<.01
Baseline accuracy	0.41	0.15	1.51	1.12–2.05	<.01
ΔRAG-5	-1.28	0.32	0.28	0.15–0.53	<.001
Group (Intervention)	0.37	0.19	1.45	1.00–2.11	.05

Both models include random intercepts for Player nested in School. Reference categories: Group = control; Time = pre-test.

Exploratory analysis: sex

An exploratory analysis assessed whether the intervention's effect on hitting accuracy varied by sex. Boys in the intervention group improved by approximately 10 percentage points and girls by approximately 8 percentage points, whereas changes in the control group were small (+1 percentage point) for both sexes.

The three-way Sex $\times$ Group $\times$ Time interaction was not statistically significant ($p = .28$), indicating that the size of the training effect did not differ reliably between boys and girls. This finding is exploratory and should be interpreted cautiously given the limited subgroup sample size.

Discussion

This study investigated whether a 6-week tennis-specific reactive agility training program could improve hitting accuracy under randomized ball-feed conditions in primary school tennis players, and whether these improvements would co-vary with improvements in reactive agility. Three main findings emerged. First, compared with the control group, the intervention group demonstrated a substantial and statistically significant improvement in hitting accuracy under randomized feeds (Group $\times$ Time OR = 2.41, $p < .001$), corresponding to an 11-percentage-point absolute increase in mean accuracy. Second, the program led to substantial improvements in tennis-specific reactive agility (RAG-5 time) but only small, non-significant changes in planned COD (t-test) and the 11-m linear sprint, indicating a task-specific training effect rather than a broad improvement in locomotor speed. Third, individual improvements in reactive agility were strongly associated with changes in accuracy ($r = -0.76$), and Δ RAG-5 remained a significant predictor of post-test accuracy after adjusting for baseline accuracy and group, providing converging evidence that gains in accuracy were closely linked to improvements in reactive agility rather than to general physical conditioning.

These results align with previous work showing that reactive-agility tests provide greater discriminative validity for performance level in youth tennis than planned COD tests (Munivara et al., 2025). The broader literature also emphasizes that reactive agility and planned COD are functionally independent skills (Young et al., 2015; Young et al., 2021), that the perceptual and decision-making components of agility can be trained in both adult and youth athletes (Serpell et al., 2011; Thieschäfer & Büsch, 2022), and that perceptual-motor performance in this population is particularly sensitive to fatigue (Bilić et al., 2023). These findings build on earlier intervention studies and evidence syntheses in young tennis players (Deng et al., 2022; Sinković et al., 2023; Mainer-Pardos et al., 2024), which have reported improvements in COD speed, reactive agility, physical performance, and inter-limb symmetry but have not evaluated hitting accuracy under randomized feeds. By demonstrating, in a school-based, individually randomized trial involving 11–13-year-old players, that gains in reactive agility were accompanied by measurable improvements in hitting accuracy under representative randomized-feed conditions, this study addresses a gap identified in prior systematic reviews of athletic training in young tennis players (Xiao et al., 2022). The design does not support strong causal claims about the mechanism, but the pattern of effects is consistent with an interpretation based on perception-action coupling. From the perspective of ecological dynamics, the randomized-feed and RAG-5 fan-drill tasks introduced informational variability that required participants to attune to specifying cues (ball flight direction, depth, and timing) and to couple perception with action under representative time constraints. Repeated exposure to such constraints is believed to strengthen the functional coupling between informational variables and action capabilities, thus supporting more timely split steps, more accurate first-step directionality, and better positioning at ball contact. The disconnect between large gains in reactive agility and only minor changes in t-test and sprint times is consistent with this interpretation: the program emphasized the perceptual-decision components of agility rather than its purely locomotor components. This pattern also aligns with evidence that the transfer of perceptual-cognitive training depends on preserving the information-movement couplings of competition in practice tasks (Pinder et al., 2011; Krause et al., 2018).

The strong correlation between Δ RAG-5 and Δ Accuracy, along with the significant independent contribution of Δ RAG-5 to post-test accuracy in the mixed model, suggests that improvements in reactive agility and hitting accuracy were closely associated. This pattern aligns with the perception-action coupling hypothesis: better attunement to specifying information should be reflected both in faster, more accurate movement responses (reactive agility) and in improved hitting outcomes under uncertainty (accuracy). The observed accuracy gains (≈ 11 percentage points) are practically meaningful for school-based tennis development, consistent with evidence that structured speed-agility-quickness training is feasible and beneficial for primary school students (Keethong & Sriramatr, 2019) and that well-designed training programs can improve agility and related physical qualities in other sports (Lamangtong et al., 2025). The exploratory subgroup analysis indicated generally similar benefits for boys and girls, with no significant three-way interaction, supporting the use of mixed-sex reactive agility training in school settings; however, this should be confirmed in larger samples. Several limitations should be noted. The sample was drawn from three primary schools in a single city, which may limit the generalizability of the findings to other regional and competitive contexts. The age range (11–13 years) was relatively narrow. Thus, the results should not be extrapolated to younger children or elite junior players without further study. The intervention duration (6 weeks, 12 sessions) was short by competitive training standards, and longer-term retention and effects on match performance still need to be examined. Participants and coaches could not be blinded to the intervention content. Future research should examine longer interventions, broader age ranges, and effects on match-play outcomes, and should determine whether combining reactive agility training with technical or tactical instruction produces additional benefits.

Conclusions

A 6-week tennis-specific reactive agility training program, delivered twice a week in a school-based setting and replacing equivalent portions of regular tennis practice, was associated with substantial improvements in hitting accuracy under randomized ball-feed conditions in primary school tennis players, with an 11-percentage-point absolute gain in mean accuracy and a Group $\times$ Time OR of 2.41 ($p < .001$). The program

also considerably improved tennis-specific reactive agility but had minimal effects on planned COD and linear sprint speed, indicating task-specific transfer. Individual improvements in reactive agility were strongly and independently associated with improvements in hitting accuracy, supporting an interpretation based on enhanced perception–decision–action coupling. The findings suggest that coaches and physical education teachers may benefit from incorporating randomized-feed hitting drills and reactive-agility tasks such as the RAG-5 Fan Drill into school-based youth tennis programs to help develop accuracy under match-like uncertainty.

Beyond the primary effect, the pattern of results has theoretical and methodological significance. The clear dissociation between substantial improvements in reactive agility and negligible changes in planned COD and linear sprint performance indicates that the program trained not generic locomotor speed, but the coupling of perception, decision-making, and action under uncertainty. The strong individual-level association between gains in reactive agility and gains in hitting accuracy reinforces this interpretation and suggests that, in this age group, reactive agility should be treated as a skill with substantial perceptual–cognitive content rather than as a purely physical capacity. Methodologically, the study shows that hitting accuracy can be evaluated under randomized, representative ball feeds and analyzed at the level of individual balls using GLMMs—an approach that increases statistical sensitivity and better captures the probabilistic nature of stroke success than aggregate percentage scores alone, and that can be applied in future studies of technical performance under uncertainty.

From a practical standpoint, several recommendations emerge. First, coaches and physical education teachers working with players aged 11–13 years can incorporate reactive-agility tasks such as the RAG-5 Fan Drill and randomized-feed hitting blocks into existing lessons without increasing total contact time because this program replaced rather than added to usual practice. Second, progression should be structured around perceptual demands—shortening cue-to-movement latencies and increasing feed variability—rather than training volume alone. Third, because boys and girls benefited to a broadly similar extent, mixed-sex delivery appears appropriate in school settings, although this should be confirmed in larger samples. Fourth, planned COD and sprint training alone should not be expected to improve performance under match-like uncertainty. Future research should investigate longer interventions, the retention of gains, transfer to competitive match play, and the combination of reactive-agility training with technical and tactical instruction. Until such evidence accumulates, these findings support randomized-feed, reactive-agility practice as a low-cost, scalable way to develop hitting accuracy under uncertainty in school-based youth tennis programs.

Conflicts of interest

The authors declare no potential conflicts of interest.

Declaration of generative AI and AI-assisted technologies used in the writing process

During the preparation of this work, the authors used Claude (Anthropic) and ChatGPT (OpenAI) to improve the language and readability of the manuscript and to check formatting consistency with the journal template. After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

- Altmann, S., Neumann, R., Härtel, S., Kurz, G., Stein, T., & Woll, A. (2021). Agility testing in amateur soccer: A pilot study of selected physical and perceptual-cognitive contributions. *PLOS ONE*, 16(6), e0253819. <https://doi.org/10.1371/journal.pone.0253819>
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Bilić, Z., Sinković, F., Barbaros, P., Novak, D., & Zemkova, E. (2023). Exercise-induced fatigue impairs change of direction performance and serve precision among young male tennis players. *Sports*, 11(6), 111. <https://doi.org/10.3390/sports11060111>
- Bolker, B. M., Brooks, M. E., Clark, C. J., Geange, S. W., Poulsen, J. R., Stevens, M. H. H., & White, J.-S. S. (2009). Generalized linear mixed models: A practical guide for ecology and evolution. *Trends in Ecology & Evolution*, 24(3), 127–135. <https://doi.org/10.1016/j.tree.2008.10.008>
- Broadbent, N., Buszard, T., Farrow, D., & Reid, M. (2021). Scaling junior sport competition: A body-scaling approach? *Journal of Sports Sciences*, 39(23), 2746–2754. <https://doi.org/10.1080/02640414.2021.1956217>
- Buszard, T., Reid, M., Masters, R., & Farrow, D. (2016). Scaling the equipment and play area in children's sport to improve motor skill acquisition: A systematic review. *Sports Medicine*, 46(6), 829–843. <https://doi.org/10.1007/s40279-015-0452-2>
- Crespo, M., Martínez-Gallego, R., & Filipic, A. (2024). Determining the tactical and technical level of competitive tennis players using a competency model: A systematic review. *Frontiers in Sports and Active Living*, 6, 1406846. <https://doi.org/10.3389/fspor.2024.1406846>
- Deng, N., Soh, K. G., Huang, D., Abdullah, B., Luo, S., & Rattanakoses, W. (2022). Effects of plyometric training on skill and physical performance in healthy tennis players: A systematic review and meta-analysis. *Frontiers in Physiology*, 13, 1024418. <https://doi.org/10.3389/fphys.2022.1024418>

- Keethong, V., & Sriramatr, S. (2019). The effects of 2 type SAQ training on primary school students' physical fitness and cognitive function. In *Proceedings of the 5th International Conference on Physical Education, Sport, and Health (ACPES 2019)* (pp. 225–228). Atlantis Press.
- Krause, L., Farrow, D., Reid, M., Buszard, T., & Pinder, R. (2018). Helping coaches apply the principles of representative learning design: Validation of a tennis specific practice assessment tool. *Journal of Sports Sciences*, 36(11), 1277–1286. <https://doi.org/10.1080/02640414.2017.1374684>
- Lamangtong, N., Maphong, R., & Sriramatr, S. (2025). Effects of concurrent and mixed-methods training on physical performance in futsal athletes. *Retos*, 71, 239–249. <https://doi.org/10.47197/retos.v71.116244>
- Mainer-Pardos, E., Villavicencio Álvarez, V. E., Moreno-Apellaniz, N., Gutiérrez-Logroño, A., & Calero-Morales, S. (2024). Effects of a neuromuscular training program on the performance and inter-limb asymmetries in highly trained junior male tennis players. *Heliyon*, 10(5), e27081. <https://doi.org/10.1016/j.heliyon.2024.e27081>
- Munivrana, G., Jelaska, I., & Tomljanović, M. (2022). Design and validation of a new tennis-specific reactive agility test—A pilot study. *International Journal of Environmental Research and Public Health*, 19(16), 10039. <https://doi.org/10.3390/ijerph191610039>
- Munivrana, G., Jelaska, G., & Tomljanović, M. (2025). Performance level discriminative validity of agility tests in youth tennis players. *Frontiers in Sports and Active Living*, 7, 1486777. <https://doi.org/10.3389/fspor.2025.1486777>
- Nimphius, S., Callaghan, S. J., Bezodis, N. E., & Lockie, R. G. (2018). Change of direction and agility tests: Challenging our current measures of performance. *Strength and Conditioning Journal*, 40(1), 26–38. <https://doi.org/10.1519/SSC.0000000000000309>
- Paul, D. J., Gabbett, T. J., & Nassis, G. P. (2016). Agility in team sports: Testing, training and factors affecting performance. *Sports Medicine*, 46(3), 421–442. <https://doi.org/10.1007/s40279-015-0428-2>
- Pauole, K., Madole, K., Garhammer, J., Lacourse, M., & Rozenek, R. (2000). Reliability and validity of the T-test as a measure of agility, leg power, and leg speed in college-aged men and women. *Journal of Strength and Conditioning Research*, 14(4), 443–450.
- Pinder, R. A., Davids, K., Renshaw, I., & Araújo, D. (2011). Representative learning design and functionality of research and practice in sport. *Journal of Sport and Exercise Psychology*, 33(1), 146–155. <https://doi.org/10.1123/jsep.33.1.146>
- Serpell, B. G., Young, W. B., & Ford, M. (2011). Are the perceptual and decision-making components of agility trainable? A preliminary investigation. *Journal of Strength and Conditioning Research*, 25(5), 1240–1248. <https://doi.org/10.1519/JSC.0b013e3181d682e6>
- Sheppard, J. M., & Young, W. B. (2006). Agility literature review: Classifications, training and testing. *Journal of Sports Sciences*, 24(9), 919–932. <https://doi.org/10.1080/02640410500457109>
- Sinković, F., Foretić, N., & Novak, D. (2022). Reliability, validity and sensitivity of newly developed tennis-specific reactive agility tests. *Sustainability*, 14(20), 13321. <https://doi.org/10.3390/su142013321>
- Sinković, F., Novak, D., Foretić, N., Kim, J., & Subramanian, S. V. (2023). The plyometric treatment effects on change of direction speed and reactive agility in young tennis players: A randomized controlled trial. *Frontiers in Physiology*, 14, 1226831. <https://doi.org/10.3389/fphys.2023.1226831>
- Strecker, E., Foster, E. B., & Pascoe, D. D. (2011). Test–retest reliability for hitting accuracy tennis test. *Journal of Strength and Conditioning Research*, 25(12), 3501–3505. <https://doi.org/10.1519/JSC.0b013e318215fde6>
- Thieschäfer, L., & Büsch, D. (2022). Development and trainability of agility in youth: A systematic scoping review. *Frontiers in Sports and Active Living*, 4, 952779. <https://doi.org/10.3389/fspor.2022.952779>
- Triolet, C., & Benguigui, N. (2025). Anticipation training for expert tennis players when facing a specific player. *Frontiers in Psychology*, 15, 1508627. <https://doi.org/10.3389/fpsyg.2024.1508627>
- Uzu, R., Shinya, M., & Oda, S. (2009). A split-step shortens the time to perform a choice reaction step-and-reach movement in a simulated tennis task. *Journal of Sports Sciences*, 27(12), 1233–1240. <https://doi.org/10.1080/02640410903233222>
- Vuong, J.-L., Fett, J., Ulbricht, A., & Ferrauti, A. (2022). Physical determinants, intercorrelations, and relevance of movement speed components in elite junior tennis players. *European Journal of Sport Science*, 22(12), 1805–1815. <https://doi.org/10.1080/17461391.2021.2005150>
- Xiao, W., Soh, K. G., Bai, X., Bu, T., Norjali Wazir, M. R., Talib, O., Liu, W., & Zhan, C. (2022). Effect of exercise training on physical fitness among young tennis players: A systematic review. *Frontiers in Public Health*, 10, 843021. <https://doi.org/10.3389/fpubh.2022.843021>
- Young, W. B., Dawson, B., & Henry, G. J. (2015). Agility and change-of-direction speed are independent skills: Implications for training for agility in invasion sports. *International Journal of Sports Science & Coaching*, 10(1), 159–169. <https://doi.org/10.1260/1747-9541.10.1.159>
- Young, W., Rayner, R., & Talpey, S. (2021). It's time to change direction on agility research: A call to action. *Sports Medicine - Open*, 7(1), 12. <https://doi.org/10.1186/s40798-021-00304-y>