

Embodied Performance Adaptation in Precision Sport – A Multimodal Study of Cognitive, Autonomic, and Motor Integration in Refining Dexterity

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ABSTRACT

Background: Self-regulation under performance pressure is critical in precision sports such as shooting and archery. Prior research has examined cognitive, physiological, and motor processes independently, leaving limited evidence on their integrated adaptation within an embodied performance framework.

Methods: Eight trained precision sport athletes (seven men, one woman; age 31.2 ± 15.0 years) completed a longitudinal within-subject repeated-measures design with assessments at baseline, after Training Block 1 (mid-assessment), and after Training Block 2 (final assessment). Cognitive efficiency was assessed with the Automated Neuropsychological Assessment Metrics, fine motor control with the Analyser of Dynamic Parameters of Human Hand and Leg Movements, and autonomic regulation with heart rate variability (HRV). A controlled auditory pressure constraint (countdown beep) was introduced during the final assessment.

Results: From baseline to final assessment, reaction time decreased by 8.40% ($W = 36, p = .008, r_{tb} = 1.00$), motor variability decreased by 25.19% ($W = 33, p = .039, r_{tb} = 0.833$), throughput increased by 24.32% ($W = 0.0, p = .008, r_{tb} = -1.00$), maximum movement speed increased by 34.26% ($W = 0.0, p = .008, r_{tb} = -1.00$), and spatial accuracy error decreased by 11.79% ($W = 36, p = .008, r_{tb} = 1.00$). Under the auditory pressure condition, spatial accuracy improved further relative to post-training baseline ($W = 33, p = .039, r_{tb} = 0.833$) without significant HRV deterioration. Spearman's correlations linked reaction time with temporal inconsistency ($r_s = .777$), spatial accuracy with throughput ($r_s = -.802$), temporal inconsistency with HRV ($r_s = -.709$), and motor variability with shooting performance ($r_s = -.714$) (W , Wilcoxon Signed-Rank Test statistic; r_{tb} , rank-biserial correlation effect size; r_s , Spearman's rank-order correlation coefficient).

Conclusion: Multimodal training was associated with coordinated cognitive, motor, and autonomic adaptation in precision sport athletes, consistent with performance stability under externally imposed pressure and an embodied, system-level account of precision sport performance.

Keywords: Dexterity, cognition, archery, shooting, expert performance

1. INTRODUCTION

Performance in precision sports such as shooting and archery depends on an athlete's ability to produce highly stable motor output while simultaneously regulating cognitive demands and physiological arousal under pressure (Corrado et al., 2024). Even minimal deviations in posture,

trigger control in shooting, string draw and release in archery or visual alignment can substantially affect shot accuracy (Lakie, 2010), and elite performance is characterised less by the elimination of variability than by the ability to regulate and reorganise it functionally (Stergiou & Decker, 2011). Despite this



multidimensional nature of performance, research has largely examined cognitive, physiological, and motor control processes in isolation (Schaefer et al., 2025), offering a fragmented account of how these subsystems regulate, interact, prioritise, switch, share resources, and represent during real performance (Luque-Casado et al., 2013; Raab & Araújo, 2019; Voigt & Raab, 2024). From an embodied cognition perspective, performance emerges from dynamic interaction between brain, body, and environment rather than from independent subsystems (Voigt & Raab, 2024; Wilson, 2002). Cognitive processes are grounded in physiological states and motor actions, and adaptive behaviour arises through continuous system-wide regulation. Successful performers are not those who minimise variability but those who regulate it effectively (Macrine & Fugate, 2020). Cognitive efficiency, particularly reaction time and inhibitory control, supports the sustained attention and precise timing required in shooting and archery (Manci et al., 2025). Fine motor control, assessed through movement accuracy, speed, and variability, reflects the biomechanical and coordination demands of aiming and trigger release (Konttinen et al., 1998; Mononen et al., 2007). Autonomic regulation, indexed by heart rate variability (HRV), reflects the balance of sympathetic and parasympathetic activity and is linked to attentional control and stress regulation under competitive pressure (Laborde et al., 2017; Thayer & Lane, 2000). Although studies on cognitive–motor interaction within the dual-task paradigm in sports such as tennis, table tennis, and golf have offered valuable insight into resource sharing and the interaction between cognitive and motor processes and their effect on performance outcomes (Abdoli et al., 2025; Amico & Schaefer, 2022; Schaefer & Amico, 2022; Schaefer & ScornaiENCHI, 2020), research in this area has predominantly focused on open-skill sports. Moreover, a systematic review of dual-task performance in athletes demonstrated that dual-task demands influence both cognitive and motor performance across a variety of sporting contexts, while dual-task training may improve attentional control and working memory (Moreira et al., 2021). Despite these advances, precision sports such as shooting and archery remain comparatively unexplored both within the dual-task paradigm and within the embodied performance framework. Furthermore, few studies (Abdoli et al., 2025) have investigated how cognitive, motor, and autonomic systems adapt collectively over a structured training period, or whether such

adaptations contribute to performance stability under pressure-inducing environmental conditions. The aim of this study was to investigate how cognitive efficiency, autonomic regulation, and fine motor control adapt across a structured training period in precision sport athletes, and whether such training enhances performance stability under a controlled auditory pressure constraint introduced as a novel environmental demand. It was hypothesised, based on evidence, that integrated mind and body training improves cognitive–motor coupling and autonomic flexibility (Shalom et al., 2025) and that reduced motor variability is linked to more stable performance under stress (Burgum & Smith, 2021), that embodied training would enhance system-level coordination, reflected in faster and more stable cognitive performance, increased autonomic flexibility, and reduced motor variability, and that these adaptations would allow athletes to maintain functional performance under pressure.

2. METHODS

Participants

Eight trained precision sport athletes (seven men, one woman; at least three to five years of competitive experience in archery or shooting) participated. Anthropometric characteristics were (mean $\pm$ standard deviation, SD): age 31.2 ± 15.0 years, height 177 ± 6.5 cm, body mass 78 ± 19.9 kg, with an average shooting training volume of nine hours per week. *Inclusion criteria* were age 18 years or older, competitive participation in a precision sport, absence of neurological or cardiovascular disorders, no hearing impairment, no use of psychotropic substances, and normal or corrected vision. *Exclusion criteria* were acute injury at the time of testing and use of medication affecting cognition or autonomic function. Athletes abstained from alcohol and nicotine for at least 24 hours before testing and took no medication throughout the protocol. Each participant was assigned a code name to preserve confidentiality. The study was approved by the Biomedical Research Ethics Committee of Lithuanian Sports University (23/03/2026, No. MNL-SVA (M)-2026-872) and conducted in accordance with the Declaration of Helsinki; all participants provided written informed consent.

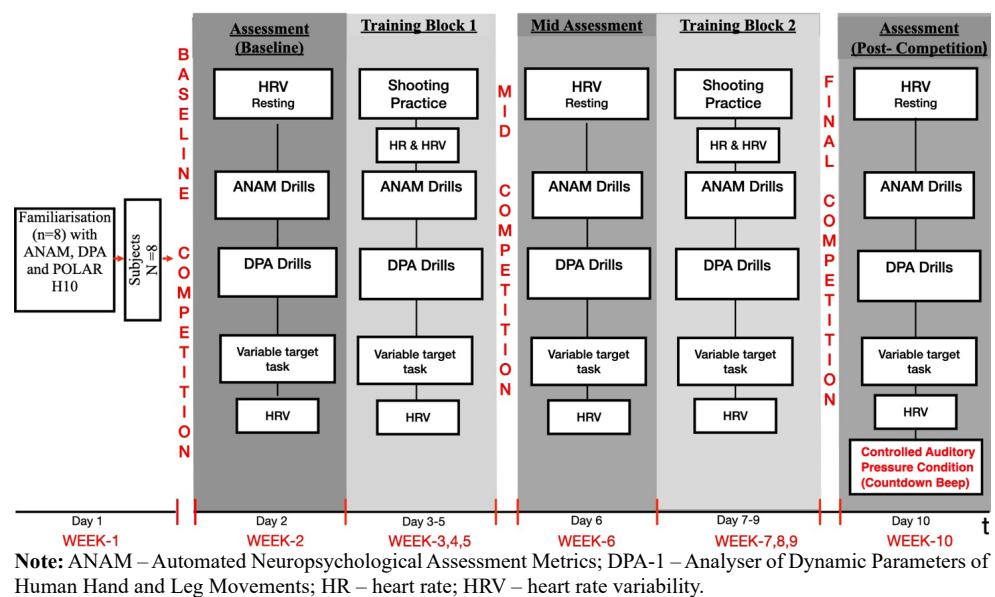
Design and procedure

Longitudinal within-subject repeated-measures design was used across ten weeks. Following a familiarisation week, baseline assessment was

conducted in week two. Training Block 1 (two sessions, weeks three to five) was followed by a national federation competition and a mid-assessment in week six. Training Block 2 (two sessions, weeks seven to nine), each session comprising approximately 60–90 minutes of structured precision sport practice that combined athlete's habitual shooting and archery training with supervised cognitive–motor tasks targeting sustained attention, inhibitory control, and fine motor precision under progressive accuracy demands, supplementary to their regular nine-hours-per-week training schedule was

followed by a national championship and a final assessment conducted within 24 hours of competition, replicating the baseline protocol (Figure 1). During the final assessment only, a controlled auditory pressure constraint, a countdown beep delivered through noise-cancelling headphones (*Soundbrenner Metronome* application, 175–215 beats per minute), was introduced during the variable target task to evaluate adaptive robustness following training. All testing was conducted in the Institute of Sport Science and Innovations Laboratory of Lithuanian Sports University (21°C, 29% humidity).

Figure 1. Protocol visualisation of testing procedure



Instruments and measures

Cognitive efficiency was assessed with the Automated Neuropsychological Assessment Metrics (*ANAM, version 4.3.0.1, VISTA Life Sciences, Parker, CO, USA*), using two-choice and simple reaction time, Go/No-Go, spatial processing, and finger-tapping tasks to derive reaction time (RT, ms), throughput (TP, bits/s), and movement variability (ms) (Cernich et al., 2007). Fine motor control was assessed with the Analyser of Dynamic Parameters of Human Hand and Leg Movements (*DPA-1, Lithuanian Sports University, Kaunas, Lithuania*), using constant- and variable-target tracing and maximum-speed tasks to derive spatial accuracy (SA, mm), temporal inconsistency (TC, s), and maximum speed (mm/s) (Solianik et al., 2018). Autonomic regulation was assessed via heart rate variability using a Polar H10 chest sensor (*Polar Electro Oy, Kempele, Finland*) and the Elite HRV application (*version 5.5.8, Elite HRV Inc., Asheville, NC, USA*),

with the time-domain root mean square of successive differences (RMSSD, ms) recorded at rest, during shooting training, and during the variable target task. HRV shift was calculated as task RMSSD minus resting RMSSD. Body mass and height were measured with a body composition analyser (*TBF-300, Tanita Arlington Heights, IL, USA*) and a stadiometer. For controlled auditory pressure condition, a countdown beep delivered through Apple AirPods Pro (*version 8B39, Apple Inc., Cupertino, CA, USA*) with active noise cancellation, using the Soundbrenner Metronome application (*version 1.42.5, Soundbrenner Limited, Hong Kong, China*) with beats per minute (BPM) at 175–215, was used.

Statistical analysis

Descriptive statistics (mean $\pm$ SD) were calculated for all variables. Normality was assessed with the Shapiro–Wilk Test; because reaction time, motor variability, and HRV shift deviated from

normality, a uniform non-parametric approach was adopted. Wilcoxon Signed-Rank Test (exact method throughout) compared baseline and final assessment, and post-training and pressure-condition values, with rank-biserial correlation (r_{rb}) as the effect size (small ≥ 0.1 , moderate ≥ 0.3 , large ≥ 0.5) (Fiel Peres, 2026). Spearman's rank-order correlation (r_s) assessed multimodal associations among cognitive, motor, autonomic, and shooting-performance variables. Given the small sample, individual adaptation trajectories were additionally examined descriptively. Analyses were performed in jamovi (version 2.7.24.0), with significance set at $p < .05$.

3. RESULTS

From baseline to final assessment, athletes showed coordinated improvements across cognitive, motor, and shooting-performance domains

(Table 1). Reaction time decreased by 8.40% ($W = 36, p = .008, r_{rb} = 1.00$), and motor variability by 25.19% ($W = 33, p = .039, r_{rb} = 0.833$). Throughput increased by 24.32% ($W = 0.0, p = .008, r_{rb} = -1.00$), and maximum movement speed increased by 34.26% ($W = 0.0, p = .008, r_{rb} = -1.00$). Spatial accuracy error decreased by 11.79% ($W = 36, p = .008, r_{rb} = 1.00$). Conversely, there were no significant changes in temporal inconsistency ($W = 18, p = 1.000, r_{rb} = 0.000$) and HRV shift as it moved from negative to positive ($W = 12, p = .441, r_{rb} = -0.333$), representing a positive directional change of 9.70 ms towards improved autonomic regulation. While HRV during task showed a 9.19% decrease ($W = 28, p = .183, r_{rb} = 0.556$). Although shooting performance increased by 1.85%, this change was not statistically significant ($W = 7, p = .148, r_{rb} = -0.611$).

Table 1. Wilcoxon Signed-Rank Test results and percentage change for embodied performance variables from baseline to final assessment ($N = 8$)

Variable	Baseline (M $\pm$ SD)	Final (M $\pm$ SD)	Significance	% change
Reaction time (ms)	702 $\pm$ 125	643 $\pm$ 62	$W = 36, p = .008,$ $r_{rb} = 1.00$	-8.40%
Motor variability (ms)	26.2 $\pm$ 20.4	19.6 $\pm$ 18.0	$W = 33, p = .039,$ $r_{rb} = 0.833$	-25.19%
Throughput (bits/s)	32.9 $\pm$ 6.86	40.9 $\pm$ 6.61	$W = 0.0, p = .008,$ $r_{rb} = -1.00$	+24.32%
Maximum speed (mm/s)	1,515 $\pm$ 309	2,034 $\pm$ 78	$W = 0.0, p = .008,$ $r_{rb} = -1.00$	+34.26%
Spatial accuracy (mm)	2.63 $\pm$ 0.13	2.32 $\pm$ 0.24	$W = 36, p = .008,$ $r_{rb} = 1.00$	-11.79%
Temporal inconsistency (s)	2.29 $\pm$ 0.16	2.35 $\pm$ 0.33	$W = 18, p = 1.00,$ $r_{rb} = 0.00$	+2.62%
HRV – RMS- SD (ms)	38.1 $\pm$ 3.7	34.6 $\pm$ 6.5	$W = 28, p = .183,$ $r_{rb} = 0.556$	-9.19%
HRV shift (ms)	-5.67 $\pm$ 15.8	4.03 $\pm$ 11.8	$W = 12, p = .441,$ $r_{rb} = -0.333$	+9.7 ms (absolute change)
Shooting performance (pts)	542 $\pm$ 53	552 $\pm$ 38	$W = 7, p = .148,$ $r_{rb} = -0.611$	+1.85%

Note: Where tied differences were present, the exact p-value was computed by enumeration rather than normal approximation.

Multimodal integrations

Spearman's correlations revealed meaningful cross-domain associations (Table 2). Reaction time correlated positively with temporal inconsistency ($r_s = .777$, $p = .023$), spatial accuracy correlated negatively with throughput ($r_s = -.802$, $p = .017$),

temporal inconsistency correlated negatively with HRV ($r_s = -.709$, $p = .049$), and motor variability correlated negatively with shooting performance ($r_s = -.714$, $p = .042$). A borderline association was found between HRV shift and throughput ($r_s = .707$, $p = .050$).

Table 2. Spearman's rank-order correlations among multimodal performance variables ($N = 8$)

Variable Pair	r_s	p
Reaction time ↔ Temporal inconsistency	.777	.023
Spatial accuracy ↔ Throughput	-.802	.017
Temporal inconsistency ↔ HRV	-.709	.049
Motor variability ↔ Shooting performance	-.714	.042
HRV shift ↔ Throughput	.707	.050

Pressure conditions

Under the controlled auditory pressure condition (Table 3), spatial accuracy improved further relative to post-training baseline (1.50 ± 0.24 mm to 1.26 ± 0.14 mm; $W = 33$, $p = .039$, $r_{rb} = 0.833$). Task

HRV decreased from 34.1 ± 9.02 ms to 29.6 ± 9.61 ms, but this reduction was not significant ($W = 27$, $p = .233$, $r_{rb} = 0.500$), indicating that the introduction of pressure did not compromise either motor accuracy or autonomic regulation.

Table 3. Wilcoxon Signed-Rank Test result for spatial accuracy and heart rate variability under auditory pressure condition relative to post-training baseline ($N = 8$)

Variable	Post (Mean $\pm$ SD)	Pressure (Mean $\pm$ SD)	Significance (p-value)
Spatial accuracy	1.50 ± 0.24	1.26 ± 0.14	$W = 33$, $p = .039$, $r_{rb} = 0.833$
Autonomic regulation	34.1 ± 9.02	29.6 ± 9.61	$W = 27$, $p = .233$, $r_{rb} = 0.500$

Individual adaptations

Individual trajectories revealed heterogeneous adaptation profiles: two athletes improved across all measured domains, two showed consistent, balanced improvement, two showed mixed responses with gains in some domains but not others, one showed high autonomic variability despite cognitive and motor gains, and one athlete demonstrated broad cognitive and motor improvements, while shooting performance remained relatively stable and autonomic regulation showed some fluctuation across assessment points.

4. DISCUSSION

The findings broadly support the hypothesis that coordinated improvements in cognitive efficiency, motor precision, and autonomic regulation reflect an integrated, embodied adaptation process,

and that this adaptation supports performance stability under externally imposed pressure.

Cognitive and motor adaptation

The significant reductions in reaction time and motor variability, together with increased throughput and maximum speed, indicate improved efficiency in both cognitive processing and motor execution. This is consistent with evidence that elite shooters exhibit lower movement variability and more stable motor patterns than novices (Konttinen et al., 1998; Mononen et al., 2007; Schaefer & Scornaienchi, 2020) and supports the view that expert performance reflects efficient coordination of speed and accuracy rather than in isolation (Schmidt & Lee, 2011). From an embodied cognition perspective, these joint gains suggest enhanced coupling between perception, cognition, and action (Wilson, 2002).

Autonomic regulation

The moderate reduction in HRV during task performance is consistent with functional sympathetic engagement supporting task execution rather than maladaptive stress (Laborde et al., 2017), paralleling controlled HRV reductions reported before shot execution in elite shooters (Konttinen et al., 1998). The shift in HRV from negative to positive values, although not statistically significant, suggests improved autonomic flexibility consistent with the neurovisceral integration model (Thayer & Lane, 2000).

Performance under pressure

A central finding was that spatial accuracy improved, rather than deteriorated, under the auditory pressure constraint, while HRV showed only a controlled reduction. This pattern is consistent with a challenge-state response in which moderate arousal facilitates fine motor performance (Yerkes & Dodson, 1908) and with evidence that elite shooters maintain or enhance performance under competitive stress through effective regulation of attention and arousal (Oudejans, 2008; Zhao et al., 2024).

Multimodal integration and individual variability

The correlations among reaction time, temporal inconsistency, HRV, motor variability, and shooting performance support the view that performance in precision sport emerges from coordinated system interaction rather than isolated mechanisms (Bertollo et al., 2021). The substantial heterogeneity in individual adaptation profiles aligns with ecological dynamics accounts, in which variability reflects flexibility rather than noise (Davids et al., 2008), and points to the value of individualised training approaches that account for athletes' distinct cognitive, motor, and physiological response profiles.

Limitations and future directions

The main limitations of this study are the small sample size ($N = 8$), which constrains statistical power and generalisability, and the absence of a control group, which precludes firm causal inference regarding the training protocol. The timing of assessments should additionally be acknowledged as a potential confound; the mid assessment followed a federation competition, and the final assessment was conducted within 24 hours of the national championship. Observed changes therefore reflect not only training adaptation but also competition proximity, taper effect and pre- competition arousal,

which cannot be fully disentangled in the current design. The auditory stressor used represents a single, simplified pressure manipulation, and HRV was assessed using RMSSD alone. Future studies should employ larger, randomised controlled designs with active control groups and multi-dimensional pressure manipulations combining auditory, visual, and psychological stressors. Additional physiological measures including respiration rate, skin conductance, and environmental perturbations such as temperature and altitude variation would provide a more comprehensive account of embodied systems level regulation. Finally, a deeper investigation of interaction among cognitive, motor, and autonomic systems is warranted, including motor representation stability, resource allocation and sharing, dual and multitasking, judgment and decision making, task prioritisation, and possible functional synergies between systems.

5. CONCLUSIONS

Cognitive efficiency, fine motor control, and autonomic regulation showed coordinated adaptation across the training period in precision sport athletes, reflected in faster information processing, greater movement consistency, and more flexible physiological regulation. Performance remained stable, and in the case of spatial accuracy improved, under a controlled auditory pressure constraint, suggesting that embodied, multimodal training may support performance robustness under stress. These findings reinforce a system-level account of precision sport performance and suggest that training and monitoring approaches addressing cognitive, motor, and autonomic systems jointly, rather than in isolation, may better support athlete development and competition readiness.

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Conflict of Interest: The authors declare no conflict of interest.

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