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Age and weekly physical activity are correlated with ballistic VR decision making and reaction time shooting performance at rest

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Ballistic virtual reality (VR) can measure shooting performance reliably in trained and untrained subjects. The purpose of this investigation was to determine whether baseline traits such as age, habitual physical activity, and prior experience are correlated with VR decision-making and reaction time performance. Thirty participants completed a series of VR tests—*Color Shapes* and *Steel Plates*—while shooting a laser-guided and CO_2-recoil fitted rifle at digitally-projected targets. The first test measured decision-making as a function of shooting a series of correct shapes (squares/triangles/circles) and colors (green/red/blue), twice, in under 2 s. The second test measured left-to-right target transition shooting skills on six, equidistant metal plates placed 7 m away from the shooting line. Age was correlated with (1) lower decision-making scores during the *Color Shapes* array identification test and (2) slower target transition time, smaller throughput (time/accuracy) and *Hit Factor* [(correct hits-misses)/time] on the *Steel Plates* test. Weekly physical activity had an inverse effect. A multiple regression model revealed that age and weekly activity combined predicted the *Hit Factor*, the most relevant shooting proficiency metric. Tactical populations scored significantly better than non-tactical in the decision-making task. Age and physical activity may plausibly predict ballistic performance, whereas tactical experience positively modulates better decision-making.

Keywords Virtual reality, Ballistic simulator, Decision-making, Reaction time, Exercise physiology

Virtual reality (VR) technology has gained considerable attention from military and law-enforcement units due to its potential to enhance learning and motor skills. The most relevant VR test batteries used in these professions involve go/no-go shooting tasks, sustained fire at variable distances, target transition, shot-on-target accuracy, de-escalation crises, and reaction time to first decision[1–6]. Immersive VR scenarios are thus broadly used by tactical agencies to teach trainees how to handle lethal and non-lethal decisions in a low-risk/high-reward environment, with the overarching goal of increasing safety and proficiency while on duty[7]. Although there are numerous VR applications, ballistic VRs can decrease implementation barriers while enhancing traditional training in preparation for real-world challenges, making it an ideal tool for tactical assessments.

We previously demonstrated that a realistic ballistic simulator intended for police and military training could be rapidly converted into a research assessment tool to capture marksmanship (accuracy/precision), decision-making, and reaction time metrics with good internal consistency and reliability independent of experience level[8]. Based on our preliminary evidence, and evidence from other similar investigations[3,4,9,10], laser-guided ballistics are adequate and realistic surrogates to real-weapons systems for measuring tactical performance. Ballistic technologies other than the V-100 described herein have been used to screen performance during simulated stress[11], marksmanship during sleep deprivation[12–15], and performance after acute exercise[16]. In contrast, the relationship between subject demographics and ballistic performance has not been fully characterized.

Previous evidence suggests that physiological characteristics may influence shooting performance[16–19]. Whereas age has shown negative and proportional effects on psychomotor task performance[20–22], particularly during VR simulations[23], contrasting evidence from the shooting literature suggests that age does not have a

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significant impact on static ballistic performance[24,25]. Conversely, physical activity/conditioning[15,16,26,27] and tactical experience[28] demonstrate the reverse effects.

VR tests that involve target discrimination or between-static target transitions rely on a sustained-attention performance mobilization model and spare-utilized capacity model, whereby the former can precisely identify states of focus and mind-wandering and the latter speed and response variability (i.e., speed-accuracy trade-off)[29]. Understanding how individual factors may influence these psychological ballistic VR domains can be crucial for (1) enhancing the performance of law enforcement and military personnel, and (2) assessing whether individuals are sufficiently fit to maintain active duty or transition to retirement. To our knowledge, there is no VR shooting-related study that has carefully quantified decision-making and reaction time performance as a function of age and physical activity, thus, it is important to determine whether these individual traits can be used to predict ballistic-relevant tasks prior to field deployment.

What is the relationship between individual physiological characteristics and VR shooting performance metrics such as decision-making and reaction time? We hypothesized that average decision-making and reaction time performance will decay as a function of age and augmented as a function of habitual physical activity. In addition, we further speculated that tactical experience would further modulate the relationship. To address this question, we enrolled men and women from various training backgrounds to undergo a series of ballistic assessments that objectively measured their decision-making and reaction time to determine (1) how age, physical activity, and tactical experience influence their mean ballistic performance, and (2) whether baseline demographics can be used to predict their tactical performance.

Materials and methods

Participants

The original study rationale is described in greater detail elsewhere[8]. We enrolled 30 healthy men and women (24M/6F) from the campus community to participate in an exploratory ballistic VR reliability study. Using the VirTra V-100, we determined that marksmanship, decision-making, and reaction time metrics can be captured with good test–retest reliability after one familiarization session and sustained thereafter[8].

Participant height and weight were measured to the nearest ± 0.1 of a kilogram and centimeter, respectively, on an electronic stadiometer (SECA 703 Digital, Hamburg, Germany) while participants wore light clothing and no shoes. Participants completed a validated and reliable habitual exercise survey (International Physical Activity Questionnaire Short Form; IPAQ-SF) to describe the type, intensity, and duration of their physical activity per week[30]. The automatic IPAQ-SF grading scale produced a weekly metabolic equivalent (MET; 1 MET = 3.5 ml O_2/kg/min) score that summarized walking, moderate, and intense physical effort as "MET Minutes/Week"[31]. Participant experience ranged from civilians, law-enforcement, reserve officer training cadets, and veterans; if they held a job in law enforcement, military, or had participated in sanctioned shooting competition events (i.e., United States Practical Shooting Association; USPSA) before enrolling in the study, they were categorized as "tactical". None had experience with this type of VR technology prior to enrolling in the study. A summary of the baseline measures is provided below (Table 1).

Variables	Mean	SD
Sex (male/female)	24M/6F	
Age (years)	26.4	7.0
Height (cm)	175.9	9.3
Weight (kg)	85.6	18.1
BMI (kg/m^2)	27.4	4.0
Physical activity (minutes/week)	194.0	123.9
Physical effort (METs/week)	4711.0	2832.0
	***n*-size**	
Gun experience#		
1 = Never shot a gun before	0	
2 = Shot laser, non-recoil guns	0	
3 = Shot paintball, airsoft, recoil guns	5	
4 = Shot real guns	25	
Tactical experience*		
Civilian	19	
Military	6	
Police/SWAT	3	
Competitive background*	2	

Table 1. Participant measures (n = 30). *BMI* body mass index, *METs* metabolic equivalents. *Civilians were considered "non-tactical." Military, police/SWAT or participation in USPSA sanctioned pistol/rifle competitions (i.e., competitive background) comprised the "tactical" populations. #The gun experience scale was adapted from data published elsewhere[32].

The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and as stipulated by the university policy regarding human subject research. All experimental protocols and documents were approved by the Ohio State University Biomedical Institutional Review Board (IRB2023H0410). Informed consent was obtained from all participants.

Test visit procedures

Participants self-selected their preferred time of the day to attend all visits at our ballistic VR testing center. There was one familiarization session (V0) held prior to all experimental visits to expose participants to the simulator and to curtail their learning effects. During this visit, trained staff demonstrated to participants how to hold and shoot an infrared M4 laser-guided rifle (irM4, SB Tactical, NV, USA)—fitted for compressed CO_2-gas recoil—at digitally-projected targets. Importantly, the participants were encouraged to find the most comfortable foot and arm stance to hold a rifle in a standing unsupported position (i.e., no gun sling) over sustained shooting periods. This training session applied to all participants, independent of their training background.

The evaluation portion of the study comprised a familiarization and 3 experimental visits (V1–V3). Participants reported to the testing facility at the same time of the day with a ~ 1–2 day washout in-between visits.

Ballistic VR measures

The decision-making task—*Color Shapes*—tested rapid and correct target discrimination. The test comprised of a cardboard cutout displaying a 3 × 3 array of circles, triangles, and squares color coded in red, blue, or green. With the target facing away from the participant, the automated computer algorithm displayed a prompt (e.g., blue square) for ~ 2 s to allow the participant to anticipate the correct shape and color. Following the prompt, the target turned and faced the participants for 2 s. At this stage, participants were conditioned from the familiarization visit to shoot 2 consecutive bullets in rapid sequence at the correct shape and color. Adequately shooting the correct target, twice in under 2 s, earned 1 point; failure to engage the target twice, reacting too slowly (> 2 s), or shooting the incorrect target earned 0 points. There were a total of 10 stages per run with a ceiling of 10 points.

The total reaction time task—*Steel Plates*—comprised of six equidistant metal paddles, placed on a horizontal steel rack 7 m away from the shooting line. The purpose of this task was shoot the steel plates in rapid sequence from left-to-right as rapidly as possible. The starting cue and time splits were initiated and captured automatically, respectively, by the on-board ProTimer software. Total time, hits, misses, and *Hit Factor* (see formula below) were manually recorded from the VR action report displayed on screen.

$$Hit\ Factor = \frac{Correct\ hits\ (points) - Misses(points)}{Completion\ time\ (s{:}ms)}$$

Participants completed 5 runs of *Color Shapes* and *Steel Plates* per visit, for a total of 15 runs throughout the study (5 runs/visit × 3 visits). The results were averaged across the experimental visits and reported as a grand mean. Visual depictions of the user interface and tasks are presented below (Fig. 1).

Statistics

All data was analyzed using a commercially-available statistics package (GraphPad Prism, ver. 9.1.0, CA, USA). Significance was set a priori at an alpha two-tail level of 0.05. Data was screened for normality using the Shapiro–Wilk test and visually inspected with residual plots. Correlations between shooting parameters and the baseline variables of interest were examined with Pearson's correlation coefficient. The strength of the correlation was determined according to prior standards, where *r*-values between 0.1 and 0.3 denoted a small effect; 0.3–0.5 an intermediate effect; > 0.5 a strong effect[33]. To accept a valid regression model, we constrained our model to an absolute skewness value of < 3, absolute kurtosis to < 8 and variance of influence factor to < 3[34]. Tactical versus non-tactical performance on the decision-making task was evaluated with an independent t-test. The effect size of the t-test was calculated using Eta squared (η^2), where values of 0.01, 0.06 and 0.14 represented a small, medium, and large effect size, respectively[33].

Results

Correlations

Age and physical activity were significantly correlated with decision-making and reaction time metrics. The mean and median for age physical METs effort was 26 and 24 years, and 4711 and 4426 METs per week, respectively. Mean reaction time (mean ± SD) to first decision-making during the complex *Color Shapes* decision-making task was 1060 ± 130 ms. Age was directly correlated with slower first reaction time to decision-making ($r = 0.47$; $p = 0.009$) during the *Color Shape* presentation (Fig. 2). In other words, the time that trainees needed to identify the correct shape and color, and then correctly shoot the first bullet, slowed down proportionally with age.

During the *Steel Plates* target transition test, both age and METs were significantly correlated with (1) total completion time (2.51 ± 0.55 s), (2) throughput (0.41 ± 0.07), and (3) hit factor (2.43 ± 0.39 points) (Fig. 3). Age was correlated with slower target transition time ($r = 0.48$; $p = 0.019$), lower throughput ($r = -0.41$; $p = 0.044$), and lower hit factor ($r = -0.37$; $p = 0.044$). Conversely, weekly METs were significantly correlated with faster target transition time ($r = -0.48$; $p = 0.014$), greater throughput ($r = 0.41$; $p = 0.022$) and greater hit factor ($r = 0.40$; $p = 0.026$)—effects opposite relative to age.

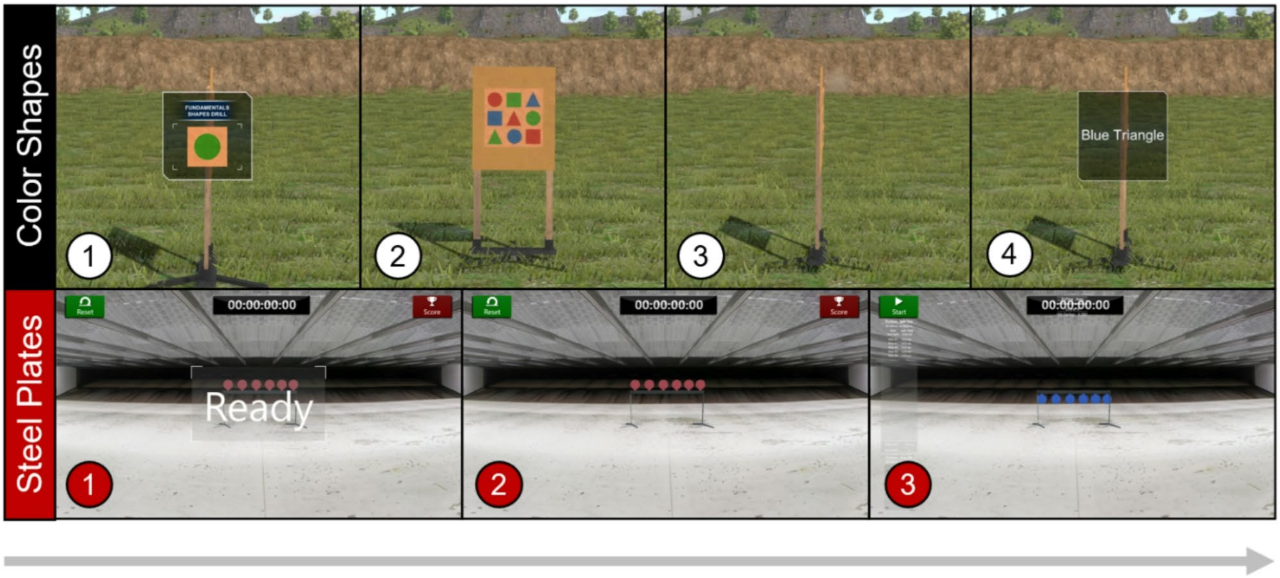

Fig. 1. User Interface. The color shapes challenge (top row) tested decision-making. Step 1–4 represent the chronological order of events where (1) the main cue was presented, (2) the target turned 90° to the participant where the correct cue had to be engaged twice to score points, (3) the target turned away from the participant after 2 s, and (4) the next cue appeared. The *Steel Plate* (bottom row) battery was designed to measure reaction time as a function of target transition. From step 1–3, participants (1) shot the "Start" button then rapidly held a steady aim at the first red plate in compressed-ready position, (2) awaited "shooter ready, standby, *beep*" cue that removed the "Ready" text overlay on the automatic *beep*, and (3) proceeded to shoot all the plates from left-to-right until all plates displayed blue. After the sixth plate was shot, the timer stopped automatically then participants shot the "Score" button to display their results.

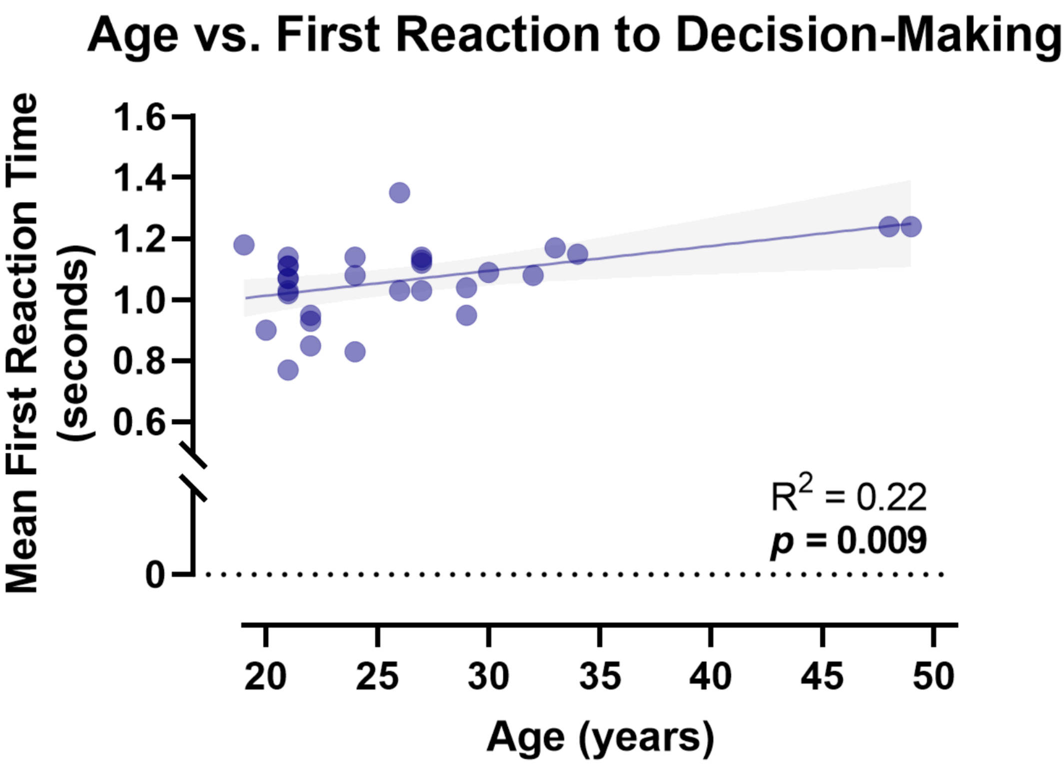

Fig. 2. Decision making as a function of age. Approximately 22% of the variance in the time required to identify and shoot the correct shape and color was explained by age. Larger mean reaction time indicates worse performance. The shaded area around the line-of-best fit denotes the 95% confidence interval.

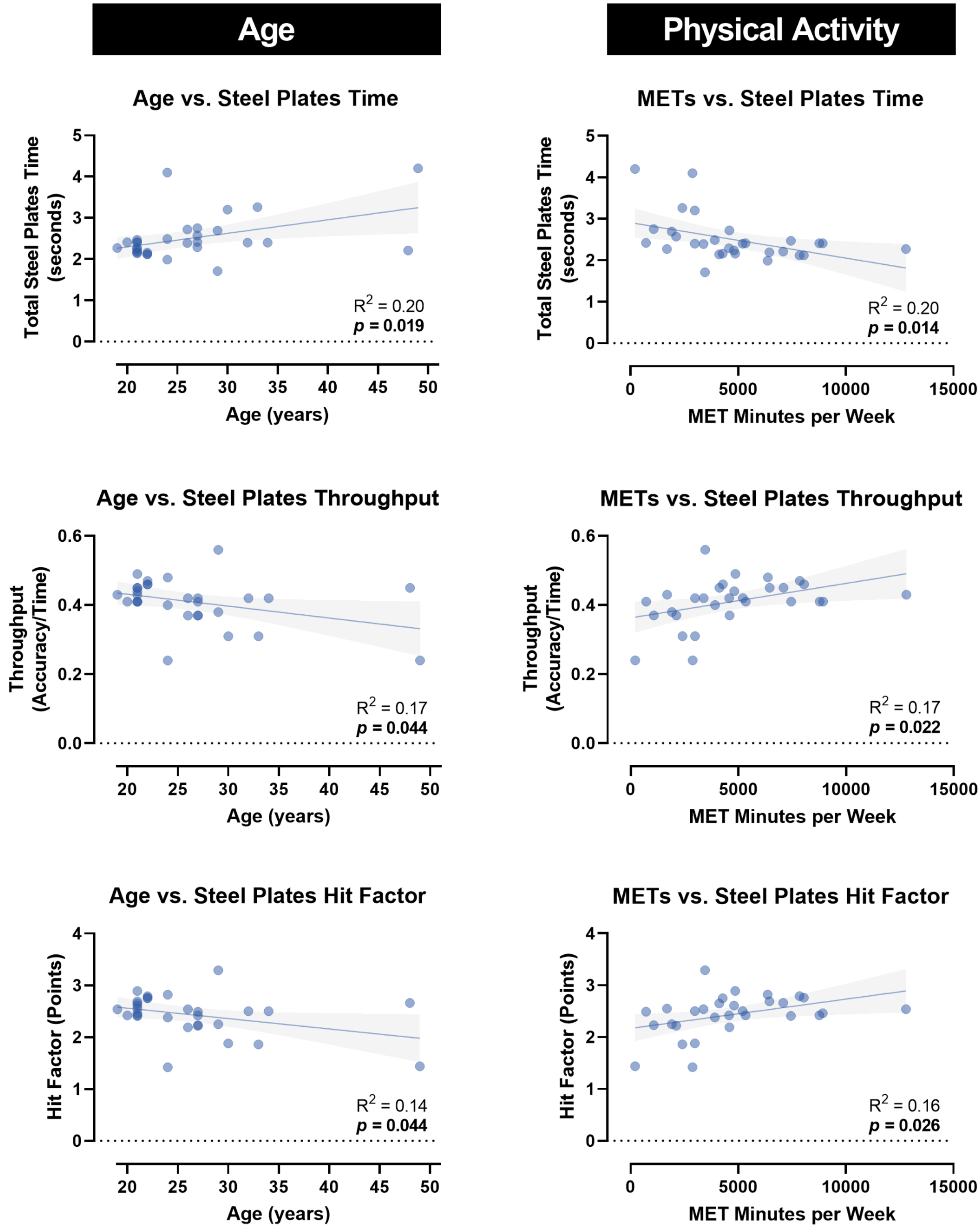

Fig. 3. Target transition performance as a function of age and physical activity. There was a significant and opposite effect of age and physical activity on *Steel Plate* performance. Whereas age had a negative influence on all time-dependent *Steel Plates* parameters, physical activity guided by MET minutes per week had a positive effect. Faster completion, and larger throughput and hit factor, denote better performance. The shaded area around the line-of-best fit denotes the 95% confidence interval. *METs* metabolic equivalents.

Parameter estimates	Variable	Estimate	Standard error	95% CI (asymptotic)	|t|	*p* value
β0	Intercept	2.586	0.3392	1.890 to 3.282	7.623	< 0.001
β1	MET minutes per week	4.258e−005	2.589e−005	− 1.055e−005 to 9.571e−005	1.645	0.112
β2	Age	− 0.01339	0.01005	− 0.03402 to 0.007243	1.331	0.194

Table 2. Multiple regression results.

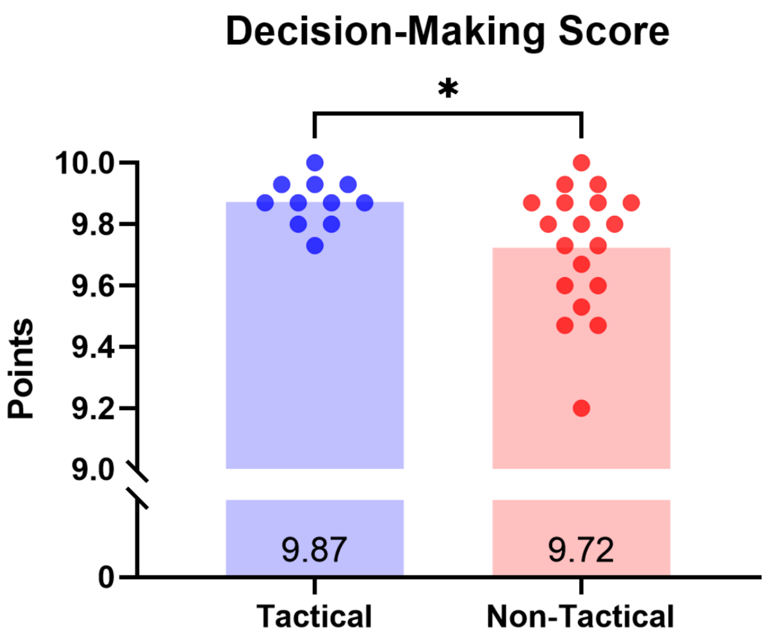

Fig. 4. Decision making as a function of experience. Decision-making data between tactical ($n = 11$) and non-tactical ($n = 19$) populations were compared with an independent t-test. On average, tactically-experienced participants scored 2% better on the *Color Shapes* decision-making task compared to non-tactically experienced participants (*$p = 0.027$). The number at the bottom of the bar chart denotes the group mean.

Regression

The relationship between age, physical activity and shooting performance was further inspected with a least-squares multivariate linear regression. Age and weekly METs were included as the main effects, and *Steel Plates* hit factor as the outcome (Table 2). We revealed that both age and weekly METs produced a significant regression model [$F(2, 27) = 3.718$; $p < 0.001$] that could predict the hit factor. Independently, age [$F(1, 27) = 2.705$; $p = 0.112$] and weekly MET minutes [$F(1, 27) = 1.173$; $p = 0.194$] did not predict the total hit factor score. The R^2 and adjusted R^2 values of the overall model were 0.22 and 0.16, respectively. The regression equation is summarized by the following formula:

$$\text{Hit Factor score} = 2.59 + \left(4.26 * 10^{-5}\right) * \text{MET minutes} - 0.013 * \text{Age}$$

Tactical versus non-tactical decision-making

Approximately one-third of the cohort met the “tactical” classification criteria at baseline, whereas the other two-thirds were considered “non-tactical”. There was no age or METs physical activity differences between the two independent cohorts. The only significant difference was the *Color Shapes* total decision-making score (out of 10). Using an independent t-test, we determined that the tactical cohort scored on average ~ 2% better in the decision-making task compared to the non-tactical ($t(28) = 2.54$, $p = 0.027$, $\eta^2 = 0.164$) (Fig. 4).

Discussion

The purpose of this exploratory investigation was to determine whether baseline characteristics—age, physical activity, experience—are correlated with ballistic VR shooting performance in VR-naïve trainees ($n = 30$). Age and weekly physical activity effort were significantly correlated with reaction time to first decision-making and static target transition speed. Both declined over lifespan whereas physical activity mitigated age-dependent performance losses. A multivariate regression model including both age and physical activity predicted *Hit Factor*, the most relevant shooting proficiency metric. Trainees who held tactical jobs prior to participating scored significantly higher in the decision-making task versus non-tactical populations, plausibly owing to an ecologically valid rifle and target system.

The first reaction time to decision-making increased ~20% from the first to the last decade in this cohort. The *Color Shapes* test stipulated identifying a correct shape and color in <2 s and shooting the correct target presentation with a hammered pair (2 consecutive bullets) to score points. Studies that have included other stressor variables than time pressure, such as negative conditioning with an electric shock, soap-cartridge rounds, or electric knife charge[7,16,19] revealed a 12–20% faster reaction time in trainees—a contrasting result from this investigation. Adding external stressors can moderate arousal[35,36], an effect primarily explained by additional pressure required to shoot[37]. Inclusion of stressors other than time pressure was outside of the original scope of this investigation since the original goal was to control for confounders that could (1) impair decision-making, (2) enhance reaction time, or (3) both[10,19,37,38], and to isolate the individual factors predictive of shooting performance at rest. Our findings indicate that aging increases the time required to make the first decision when constrained by time and without other external pressure—an insight that can guide tactical agencies in implementing countermeasures or revise retirement criteria.

Physical activity, specifically weekly MET minutes of effort, demonstrated the inverse effect of age. Whereas age was related with a worsening effect across primary shooting parameters in the *Steel Plates* target transition task, self-declared weekly physical effort was associated with faster target transition reaction times. Whereas others have reported no effects of acute physical activity on shooting performance, physiological surrogates of physical fitness such as hand-grip[27,39,40] or cardiovascular regulation[4]—outcomes reflective of chronic training adaptations—can in fact predict and positively influence shooting performance across a wide range of experienced officers[16]. Our findings must be carefully framed within the context that our (1) VR assessments were performed while at rest, (2) in a low-stress environment, and (3) while participants recalled their weekly habitual physical activity with reasonable accuracy.

Hit Factor is a highly relevant and well-regarded performance metric between tactical units (i.e., higher score = better performance), comparable to VO_{2max} in aerobic athletes. We revealed that *Hit Factor* can be predicted by both age and self-reported physical activity effort, although not independently. Given that augmenting this performance outcome is a top priority in tactical training, it is essential to determine which additional variables may influence *Hit Factor* and, more importantly, establish what constitutes a good versus bad score in the *Steel Plates* target transition task. Even though tactical units frequently use static plate drills in training, there is no normative database to compare our results to other evidence. Publicly available information from shooting competitions suggests that obtaining a *Steel Plates* rack *Hit Factor* > 2.0 is considered good[41], a value that 87% of our sample achieved with ease.

Participants who held jobs in law-enforcement or the military prior to enrolling into the study scored better in the decision-making tasks compared to civilians. A similar study that compared novices with expert trainees in a virtual friend-or-foe scenario corroborate our findings by demonstrating that experts are ~15% more likely than novices to shoot the correct target, accurately (~20% better marksmanship), despite having comparable reaction times to first decision[6]. Our *Color Shapes* battery was originally designed by the VR manufacturer from a collaboration with Air Force research group to screen pilots for sustained and distributive attention to random stimuli. This task was moreover important to screen for "perceptual ambiguity," a stress-induced phenomena that can alter the visual field and perception of color, which affects approximately one-half of officers on duty[38]. Evidence from tactical decision-making literature suggests that for every 1 year spent in a tactically-relevant job, decision-making under pressure (time or assailant charge) improves by ~1%[19]. Although our study design was performed at rest and only under time pressure, it is important to note that our 2% difference in decision-making between tactical versus non-tactical populations was measured using non-human targets. Moreover, it is important to highlight that the *Color Shapes* test controlled for both correct-decisions and time when calculating total decision-making score, bolstering the notion that tactical members can be both correct and fast despite having a reaction time comparable to untrained civilians.

Several strengths and limitations need to be acknowledged for informing future study designs. The strengths of this study include using a previously tested VR simulator that captures reliable ballistic measurements using computer randomized decision-making events (as opposed to a proctor manually activating the VR) and realistic recoil and feel infrared rifles[8]. Limitations include a relatively small sample size and VR test prompt timing. First, this sample size was originally intended to produce preliminary results for designing larger studies (n = 80–100), effects that can be further refined and strengthened by stipulating a priori age and male/female enrollment goals to reduce baseline sample heterogeneity. Secondly, the *Color Shapes* and *Steel Plates* batteries were programmed by the software to maintain consistent between-event timing, with no time component variability between shooting prompts. This consistent anticipation from the initial prompt to the shooting action is a threat to action readiness specificity, meaning that participants may have become conditioned to anticipating the next prompt versus adapting to more variable prompt-to-prompt presentations[42]. Modulating between-target presentation timing is expected to provide more insight into whether perceptual processing or experienced handling can explain the underlying results observed herein, or if the differences as a function of age, physical activity and tactical experience can be used to predict real-world performance.

Conclusions

Age and physical activity were significantly correlated with VR decision-making, reaction-time performance and *Hit Factor* in a diverse, VR-naïve cohort. Decision-making performance was further augmented by tactical experience, suggesting that police and military populations can rapidly adapt to time-constrained decision-making environments without additional pressure to shoot. These findings warrant the development of robust equations that (1) can predict the precise age when a soldier or law-enforcement officer will experience a decline in shooting performance, (2) apply the correct exercise type, intensity, and duration necessary to countermeasure age-dependent performance decline, and (3) identify other surrogates predictive of subsequent shooting performance. Future ballistic VR research should continue utilizing reliable ballistic VR shooting platform across larger and more diverse cohorts to strengthen the findings herein and translate them to real-life applications.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests
The authors declare no competing interests.

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