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ORIGINAL ARTICLE

Bringing the field into the lab: a novel virtual reality outdoor march simulator for evaluating cognitive and physical performance

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Abstract

Soldiers, athletes, and rescue personnel must often maintain cognitive focus while performing intense, prolonged, and physically demanding activities. The simultaneous activation of cognitive and physical functions can disrupt their performance reciprocally. In the current study, we developed and demonstrated the feasibility of a virtual reality (VR)-based experimental protocol that enables rigorous exploration of the effects of prolonged physical and cognitive efforts. A battery of established neurocognitive tests was used to compare novel cognitive tasks to simulated loaded marches. We simulated a 10-km loaded march in our virtual reality environment, with or without integrated cognitive tasks (VR-COG). During three experimental visits, participants were evaluated pre- and post-activity, including the Color Trail Test (CTT), the Synthetic Work Environment (SYNWIN) battery for assessing multitasking, and physical tests (i.e., time to exhaustion). Results show that Strong or moderate correlations ($r \geq 0.58$, $p \leq 0.05$) were found between VR-COG scores and scores on the cognitive tests. Both the SYNWIN and CTT showed no condition effects but significant time effects, indicating better performance in the post-activity assessment than in the pre-activity assessment. This novel protocol can contribute to our understanding of physical-cognitive interactions, since virtual environments are ideal for studying high performance professional activity in realistic but controlled settings.

Keywords Physical effort · Cognitive load · Virtual reality · Military · Load carriage

Abbreviations

CAREN	Computer assisted rehabilitation environment
CATR	Center of advanced technologies in rehabilitation
CTT	Color trail test
HR	Heart rate
Phys	Activity condition with physical load only
Phys + Cog	Activity condition with simultaneous physical and cognitive load
SYNWIN	The Synthetic Work Environment computerized test battery
SD	Standard deviation
TMT	Trail making test
TTE	Time to exhaustion test
VR	Virtual reality
VR-COG	Cognitive tasks in virtual reality settings
VRE	VR environment

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1 Background

Athletes, soldiers, and rescue personnel must often perform intense and prolonged physically demanding activities while maintaining cognitive focus and situational awareness. Under these conditions, they are required to make rapid decisions while processing information from multiple sources using different sensory modalities (Brisswalter et al. 2002; Harrison and Horne 2000). These efforts can cause significant stress, leading to physical and cognitive fatigue and, in turn, to poor performance. For example, individuals exposed to stressful conditions can experience “perceptual narrowing”, during which inattention to perceptual cues leads them to ignore alternatives or make decisions based on incomplete information (Kavanagh 2005).

It is commonly hypothesized that cognitive and physical functions both draw central nervous system resources, such that their simultaneous activation can cause reciprocal disruptions in the performance of both (Labelle et al. 2013; Dietrich and Audiffren 2011; Dietrich 2009; McMorris et al. 2018; Schmit and Brisswalter 2020). Previous studies reported changes in neurocognitive function with heightened physiological demands. Shared resource models, such as the reticular activating hypofrontality model (Audiffren 2016; Dietrich et al. 2018) suggest that physical activity exhaustion and stress differentially impact explicit and implicit information processing systems. Specifically, tasks requiring frontally-mediated executive processes are argued to be negatively affected under extended physiological efforts whereas tasks supported by lower order sensorimotor pathways will be unaffected (or perhaps emphasized) under these conditions. These interactions between physical and cognitive functions are particularly pertinent in the context of military activity, due to critical ramifications for the success of operational missions and for soldier performance and health.

In most cases, pre-post studies examine the effects of exercise on physical (Nindl et al. 2007; Sams 2014; Ziemann et al. 2011; Sobhani, et al. 2014) or cognitive (Brisswalter et al. 2002; Yanovich et al. 2015) performance separately. Some protocols involve acute and relatively short bout of exercise (Ziemann et al. 2011; Paas and Adam 1991; Davranche and Audiffren 2004; Dietrich and Sparling 2004; Mahoney et al. 2007; Audiffren et al. 2009; Kamijo and Abe 2019) while others examine the effects of prolonged exercise, where fatigue comes into play (Nindl et al. 2007; Sams 2014; Sobhani, et al. 2014; Yanovich et al. 2015; Eddy et al. 2015). For example, Eddy et al. evaluated the effects of load carriage and physical fatigue on cognitive performance. Participants walked for two hours with or without a load (40 kg, 46% of body weight in average) while being cognitively assessed using two cognitive tasks (auditory go/no-go and visual target detection), over 30 min (6* 5 min blocks) during the march. With load, performance in both cognitive tasks declined over time (Eddy et al. 2015), showing that physical load can be detrimental to cognitive performance during physical effort.

Recently, a test battery was developed for measuring cognitive functions in soldiers carrying various loads during long marches (Armstrong et al. 2017). It was demonstrated that during loaded marching, cognitive demands reduce the accuracy of soldiers' responses. In contrary, it has been shown that moderate-intensity physical exercise improved post activity executive functions such as accuracy and reaction time (Davranche and Audiffren 2004; Kamijo and Abe 2019; Chang et al. 2012; Ludyga et al. 2016; Tempest et al. 2017; Sanders et al. 2019).

Apart from these findings, there are several voids in the existing literature on the effects of physically and cognitively demanding activities on functioning in both domains, and on the interactions between them, specifically during prolonged effort. Most studies have evaluated physical effects without systematically introducing cognitive demands (with the exception of Yanovich et al. 2015). When included, cognitive functions have generally been assessed using neurocognitive paper-and-pencil tests or straight forward computer adaptations of these tests, rather than mission-oriented challenges tapping a range of relevant competencies, such as executive functions. The ecological validity of these examinations is clearly compromised, prompting further investigation of the effects of both physically demanding and mission-oriented activities, such as loaded marches, load carriage effects on cognitive and physical performance in more realistic environments, during exposure to various stressors.

The investigation of prolonged cognitive effects while simultaneously engaging in physical effort has yielded mixed results. These outcomes may be attributed to the absence of a proper cognitive effort during the physical activity, primarily due to methodological constraints. In the present study, we employed VR apparatus to introduce context-related, ecological cognitive tasks alongside the physical effort.

A technology-based solution well-suited to this line of research is virtual reality (VR), which used over the past decade to study human function (for review Parsons 2015) and for clinical purposes (Cano Porras et al. 2019; Porras et al. 2018). Large-scale VR laboratories, can potentially resolve the aforementioned shortcomings, as they enable controlled, systematic, and repeated introduction of cognitive tasks during different degrees of physical exertion (walking on a treadmill incorporated in the VR system). VR technology can also include adaptation of classic pencil-and-paper tests inspecting specific cognitive competencies (e.g., Plotnik et al. 2021). Essentially, immersion in a realistically designed VR environment (VRE) makes it possible to study behavior under ecologically valid conditions, with laboratory grade control.

The primary objective of the present study was to develop and proof the feasibility of a VR-based experimental protocol that enables to rigorously explore the effects of prolonged (i.e., 2 h) physical and cognitive efforts. Attempting to simulate a military mission, we systematically introduced context-related cognitive tasks tapping the following competencies: memory, computation, navigation (i.e., spatial orientation), and object detection. Performance on these tasks was compared to performance on commonly used and validated cognitive assessments. Our secondary objective was to quantify the after effects of cognitive combined with physical loads, i.e., the residual effects of dual-tasking, following a simulated loaded road march using a virtual environment. The present study can be viewed as an extension of previous study in which physiological and cognitive effects were studied following a 10-km march (Yanovich et al. 2015). Using the controlled VRE, we were able to separate the relative contribution of cognitive load during pre-mission physical activity to physical and cognitive readiness immediately following a demanding task.

We hypothesized that scored of VR-based cognitive tasks presented during the march would correlate with scored on previously validated cognitive tests, and that both physical and cognitive capabilities would be affected to a greater extent after joint exposure to physical and cognitive efforts than after exposure to physical effort alone.

2 Methods

The study was conducted at the Heller Institute of Medical Research (The Institute for Military Physiology, IDF Medical Corps) and the Center of Advanced Technologies in Rehabilitation (CATR), both located at the Sheba Medical Center in Israel.

2.1 Rationale

The study was primarily designed to assess the feasibility of a VR environment-based protocol that simultaneously exposes participants to physical and cognitive demands. While the protocol includes several novel elements, the focus was on comparing new cognitive tasks presented in the context of simulated loaded military missions to conventional, validated cognitive tests (primary objective). We also conducted a pilot study to assess the aftereffects of cognitive load during a strenuous simulated 2-h march (*pre-mission effort*) on physical and cognitive performance after the exposure i.e., the residual effects of dual-tasking (secondary objective). We used a trial design, with participants undergoing three activity sessions in random order, each comprising one of the following conditions: simultaneous physical and cognitive load (Phys + Cog condition), physical load only (Phys condition), and rest (as a control). For our primary objective, the outcome measure was correlation between the new VR-based cognitive tasks (during the Phys + Cog condition; see *Protocol* below) and a cognitive testing battery presented prior to and following the Phys + Cog condition. For the secondary objective, we conducted a within-subject pre-post comparison to determine the effects of the activity conditions on physical and cognitive performance.

2.2 Participants

Twelve healthy civilians were recruited in accordance with the following inclusion criteria: 1) male; 2) 21–30 years old; 3) served in a combat position in the military, during which they experienced loaded marches; 4) self-declared ability to endure 10-km forced walking while carrying a substantial load in a backpack; 5) above average aerobic ability (maximal oxygen uptake, VO_2max, above 42.4 ml/kg/min; Astrand 1960). Exclusion criteria included any orthopedic or other health issues. These criteria were established with the objective of ensuring that participants could successfully complete the physically demanding segment of the protocol—specifically, the ability to march a 10 km walk with a substantial load in a backpack. Consequently, we opted to recruit young men who had recently served in a combat position in the military, as such positions often involve similar marches. Mean (± SD) values of the demographic variables for included participants were as follows: age 23.9 ± 2.0 years; weight 72.0 ± 7.5 kg; height 170 ± 5 cm; BMI 24.9 ± 1.8 kg/m^2; VO_2max 58.3 ± 7.9 ml/kg/min.

Participants were informed about the study's purpose and possible risks. Their final inclusion in the study was subject to medical clearance by the study's physician and signing of an informed consent form. The study was approved by the Human Use Committee of the Sheba Medical Center (SMC-2664–15) and by the Medical Corps (IDF- 1526–15).

2.3 Apparatus

We used the Computer Assisted Rehabilitation Environment (CAREN; Motek Medical©, Amsterdam, the Netherlands) high-end system. The system consists of a moveable platform (3 m diameter) with six degrees of freedom of movement (translations and rotations). A dual-belt instrumented treadmill is embedded within the platform. This installation is placed in a dome-shaped space. A virtual visual scene is projected on the interior surface of the dome using eight projectors, creating a 360° visual display that provides a sensation of full immersion and visual depth perception. A surround sound system provides auditory stimuli congruent with the scenery. The visual flow is synchronized with the speed of the treadmill (Fig. 1).

2.4 Protocol

First, each participant was invited to a preparatory visit, during which his height and weight were recorded, backpack size and weight were adjusted (see *Supplementary File 1*, *Sect. 1*), and a VO_2max test was performed (see *Supplementary File 1, Sect. 2* for test description). Height (cm) was measured using a stadiometer (ADE, Germany; result ± 1 cm), and body mass (kg) was measured using an electronic flat scale (SECA, 803 model, Germany; result ± 100 g). VO_{2max} (ml/kg/min) was measured using a continuous uphill stepwise treadmill-modified Bruce protocol (Bruce 1972). During the VO_{2max} test, we recorded heart rate (HR; bpm) using the Polar RS800CX heart rate monitor (Polar®, Finland). In addition, participants were familiarized with one of the baseline cognitive evaluations (SYNWIN battery, see below); they repeated the test five times with 5-min breaks between consecutive tests. Then, as noted above, participants attended three separate activity visits, undergoing one of the following protocols in each (in random order): Phys + Cog, Phys only, and rest. The physical component was a 10 km treadmill march (see details below). During the rest visit, participants sat in a room for 2 h, during which they were exposed only to non-demanding activities such as reading a book. The time interval between visits ranged from 7 to 14 days, based on participant availability.

Each visit included the following components: a. baseline (pre-activity) assessment (see details below); b. exposure to two hours of activity/rest; and c. post-activity assessment (see details below). The pre-activity assessment included cognitive evaluation only, and the post-activity assessment included cognitive and physical evaluations. The protocol outline is presented in Fig. 2.

2.4.1 March settings

Participants were asked to arrive to each visit in shoes and clothing suitable for physical activity. By combining treadmill operation profiles (speed and inclinations) with congruent visual flow speed, we simulated a 10 km march at a speed of 5 km/h and 1.15° slope (2% grade) in hilly Mediterranean terrain with nearby and distant villages [Fig. 1; see also *Supplementary File 1, Sect. 3 & Supplementary File 2 (video)*]. To simulate diverse terrain, every 20 min the treadmill slope increased to 3.4° (6% grade) for 5 min and then returned to the original slope. The duration of the march was exactly 2 h. This is similar to the march settings used in previous research (Yanovich et al. 2015).

Participants were secured to the system in a manner that did not limit their mobility or cause discomfort [see Fig. 1 and *Supplementary File 1, Sect. 3 & Supplementary File 2 (video)*]. They walked while carrying a backpack weighing

Fig. 1 The Computer Assisted Rehabilitation Environment (CAREN) is a fully immersive virtual reality system with a 6 degrees of freedom moveable platform, synchronized with virtual visual scenery projected over a 360° dome-shaped screen. A treadmill is embedded in the platform and its speed is synchronized with the visual flow. A surround sound system provides auditory stimuli congruent with the scenery. A motion capture system (Vicon) and set of force plates in the treadmill provide performance data. In the current study, participants walked while carrying a backpack weighing 30% of their body weight, and were safely secured to the system during the entire march. A bag of drinking water was available (hung on the upper right side of the metal frame)

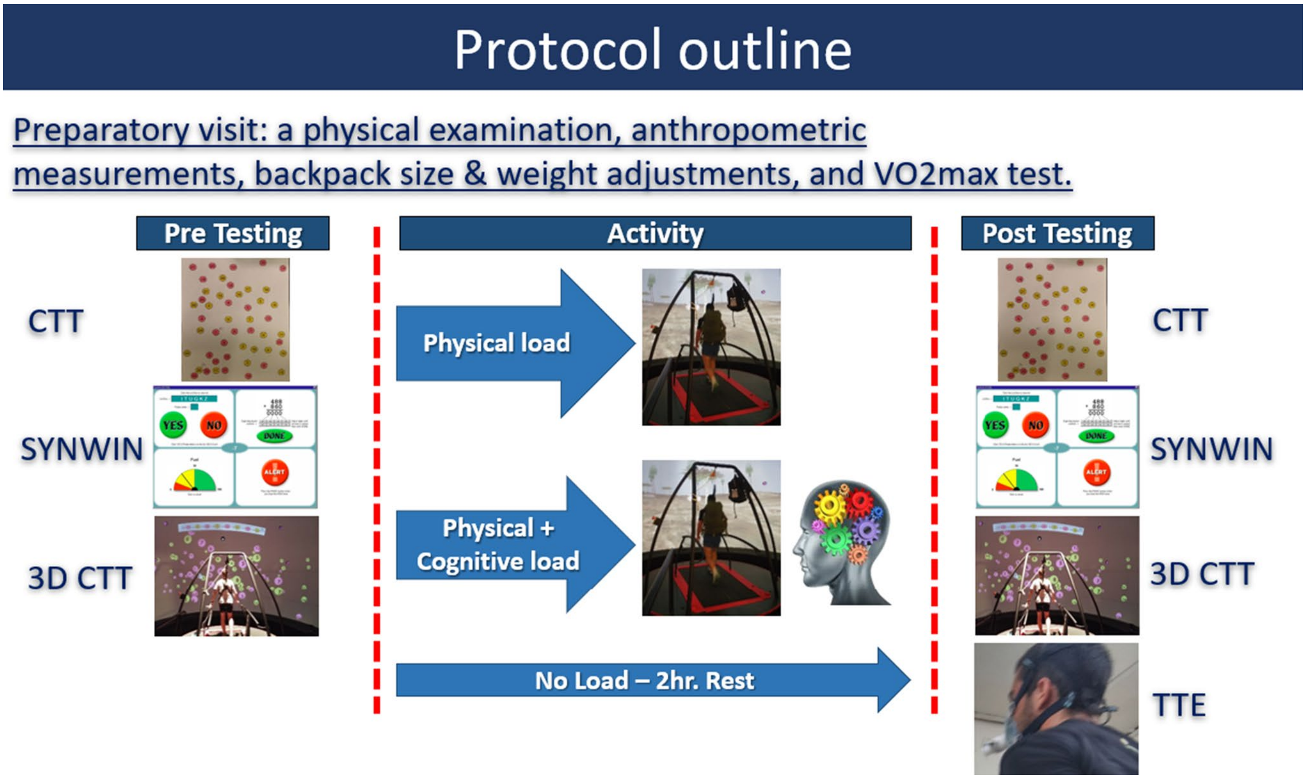

Fig. 2 The protocol outline involved participants attending a preparatory visit initially, during which measurements and adjustments for the physical protocol were conducted. Subsequently, participants attended three visits, with the order randomized. Each visit began with a cognitive battery, followed by a 2-h session of one of three physical efforts: solely physical load, simultaneous physical and cognitive load, or rest. The visit concluded with a repeat of the cognitive battery and a Time to Exhaustion (TTE) test. To validate the new VR cognitive tasks, comparisons were made between the cognitive battery performed before and after the effort during the same visit

30% of their body weight, as typically carried by high performance professionals (e.g., combatants). In the Phys + Cog condition, participants also carried a two-way radio transceiver (‘walkie-talkie’). Participants also had access to a drinking bag containing cold water, which was placed near the treadmill and not carried.

We found it imperative to acclimate the participants to this VR environment. Upon entering the VR simulator, a qualified instructor closely guided subjects with detailed instructions, emphasizing safety with a secure harness and a precaution against falling. After initial guidance, participants were encouraged to walk freely, acclimating to the VR environment with the instructor nearby. During free walking, the instructor observed for anomalies, intervening with clear explanations if needed (e.g. favoring one side of the treadmill). This approach ensured a smooth and secure experience.

2.4.2 Context-related cognitive tasks during the march

In the Phys + Cog condition, participants performed cognitive tasks that simulated military tasks while marching, including navigating, detecting and reporting “enemy forces” and static and dynamic objects of interest, and memorizing the status of allied forces to which they were exposed via ongoing radio transmission.

2.4.3 Navigation

Prior to marching, participants memorized for two minutes the navigation route based on a map simulating aerial photos of the environment (Fig. 3A). Though the map was available for use during the march, they were encouraged to rely on memory as much as possible and were notified that they would be scored accordingly. The virtual route consisted of several straight walking intervals of different lengths, separated by 90° left and right turning points. The turning points were marked with noticeable landmarks, e.g., wells, road boards and old barrels, etc. These landmarks were also indicated on the map (Fig. 3B).

Navigation was conducted by choosing a direction to turn (left or right) once a landmark was identified (total of five navigation decision points). The signal to turn was given by pointing a stick with a reflective marker attached to it, which was captured by a motion capture system (Vicon, Oxford, UK; sampling rate 120 Hz). [see the VR-based navigation process in *Supplementary File 1, Sects. 4–5 & Supplementary File 3 (video)]*.

This task primarily involved the following three cognitive functions (Moffat 2009):

1. Visual and spatial memory;
2. Attention and visuospatial skill;
3. Spatial orientation.

2.4.4 Detection and reporting of visual elements ('visual')

Prior to the march, participants were informed that while they were walking, different objects would appear in the environment ("in the sky and on the sides of the road"), such as fighter jets, armored fighting vehicles (tanks), steel figure targets (simulating hostile combatants), and villages [see Fig. 4 and *Supplementary File 1, Sects. 4,6 & Supplementary File 3 (video)*]. Participants were instructed to identify these objects and memorize specific information about them, such as quantity, directions and position. To avoid misidentification, participants were shown pictures of the target objects prior to the march. To evaluate participant performance of these detection tasks (in a pre-defined order), the experimenter used pre-recorded questions to ask

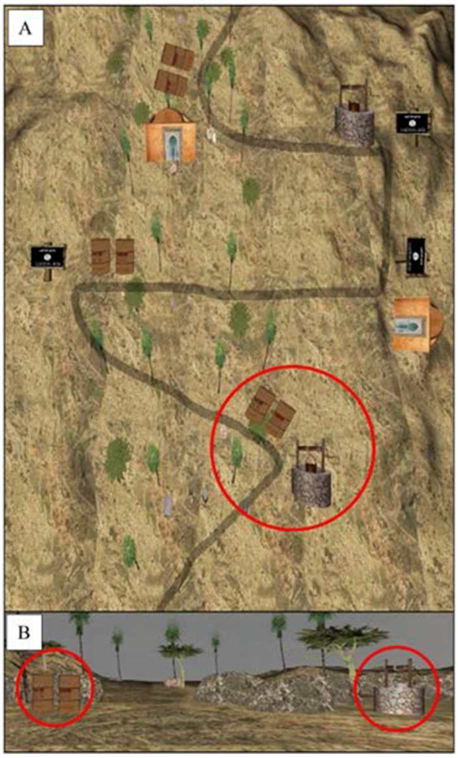

Fig. 3 **A** Schematic map of the march route. **B** Example of a well and barrels (marked with red circles) marking the first turn

Fig. 4 Examples of the visual elements for detection during the march. **A** A typical Mediterranean village. **B** Steel figure targets. **C** Fighter jets passing while compass rose is presented to allow estimating of azimuth. **D** Armored fighting vehicle ('tank')

participants to report information, via the two-way radio, regarding specific, previously seen objects.

This task primarily involved the following three cognitive functions:

1. Visual scanning;
2. Spatial orientation;
3. Short term memory (Xu and Chun 2006).

2.4.5 Memorizing status of other allied forces ('Calc&Mem')

Participants were informed that there were three 30-soldier allied units walking in parallel to them, identified as the green, blue, and red units. They were also informed that they would occasionally be given updates (using the two-way radio) on the status of these forces. Each report included information about one of the units, for example, "three soldiers from the red unit have been wounded and evacuated" or, "five new soldiers have joined the blue unit." Periodically, participants were asked to provide status reports regarding the current number of soldiers in each unit, requiring them to perform calculations upon receiving the information and to memorize the updated numbers continuously throughout the march [see *Supplementary File 1, Sects. 4,7 & Supplementary File 3 (video)*].

This task primarily involved the following three cognitive components (Tombaugh 2006):

1. Working memory;
2. Short-term memory;
3. Mathematical calculations.

2.4.6 Pre-activity and post-activity cognitive assessments

The following validated neurocognitive tasks were administered before and after the three physical activity sessions:

1. The color version of the Trail Making Test (TMT; (D'Elia, et al. 1989; Reitan 1958; Reitan and Wolfson 1995), also known as the Color Trails Test (CTT), which assesses selective attention, visual and perceptual tracking abilities, and working memory (D'Elia, et al. 1989; Reitan 1958; Reitan and Wolfson 1995), see *Supplementary File 1, Sect. 8*.
2. The Synthetic Work Environment (SYNWIN) computerized test battery, which assesses short-term memory, working memory, cognitive concentration, visual perception, multitasking, reaction time, and data processing (Elsmore 1994). The full battery comprises four subtasks, presented simultaneously in a 5-min session: a simple memory task, an arithmetic computation task, a visual monitoring task, and an auditory monitoring task. However, in the current study, we did not use the auditory monitoring task due to technical issues, as participants were not able to clearly hear tones produced by the software. The SYNWIN battery has been used in past trials to investigate the effects of various tasks and environmental factors on cognitive performance (Elsmore 1994; Braude et al. 2011; Matsangas et al. 2014; Barron and Rose 2017; Beer et al. 2017), see *Supplementary File 1, Sect. 9*.

   To minimize learning effects while performing this battery, participants repeated the battery several times during the baseline visit. After confirming that no further score improvement was observed, the participant moved ahead with the protocol. No more than 5 repetitions were required to reach this stage.
3. A VR version of the CTT test (Plotnik, et al. 2017), the results of which are reported elsewhere (Plotnik et al. 2021).

2.4.7 Post-activity physical evaluation

For assessing the subjective physical effort difficulty, participants filled a visual analog scale (VAS)—the Borg rating of perceived exertion (RPE) scale immediately after the physical effort. Values range from 6- no exertion at all to 20- maximal exertion (Gunnar 1982).

We used the time to exhaustion (TTE) test only in the post-activity physical assessment, after 30 min of rest (during which the post-activity cognitive evaluation was conducted). The TTE protocol was conducted similarly to the work of Yanovich et al. (2015) (using a motor-driven treadmill, as follows: after a 2-min warm-up (5 km/h, 2% slope), the pace and inclination was increased to match the participant's anaerobic threshold intensity (calculated from the VO_2max test, see *Supplementary File 1, Sect. 2*) and maintained for 15 min. If the participant managed to sustain this 15-min stage continuously, the pace was kept constant while the inclination was elevated by 2% every 4 min until the participant reached subjective exhaustion. While performing the TTE test, a silicone mask was placed on the participant's face to measure respiratory values and to adjust the intensity to match his pre-defined anaerobic threshold, until he completed the first 15-min stage. The primary outcome of the TTE test was the maximum running time achieved.

2.5 Outcome measures and data analysis

2.5.1 Outcome measures for the primary objective

We evaluated the correlations between participant scores on the validated cognitive tests and their scores on the new ecological cognitive assessment administered during the simulated march in the VR environment (VR-COG). We checked correlations with both the pre-activity and post-activity scores on the validated cognitive tests.

CTT outcome measures include Part A execution time (CTT_A), which measures visual and perceptual tracking and sustained attention, and Part B execution time (CTT_B), which measures working memory, divided attention, sequencing skills, inhibitory control, and cognitive flexibility (D'Elia, et al. 1989; Sanchez-Cubillo et al. 2009; Arbuthnott and Frank 2000). To evaluate the effect of activity, the difference between post-activity score and pre-activity score was calculated for each part of the task (ΔCTT_A, ΔCTT_B).

The SYNWIN produces a composite score based on performance in the three sub-tasks (a simple memory task, '*Memory*,' an arithmetic computation task, '*Math*,' and a visual monitoring task, '*Visual*'). To evaluate the effect of activity, the differences post-activity and pre-activity SYNWIN total and sub-task scores were calculated (SYNWIN ΔScore, ΔMemory, ΔMath, and ΔVisual monitoring).

The VR-COG outcome measures included total score for each cognitive task (navigating, detection and reporting of static and dynamic objects, and memorizing). A composite score was calculated based on all tasks using a weighted average (e.g., 5 navigation questions, 16 detection questions and 8 memory questions).

2.5.2 Outcomes measures for the secondary objective

The pre-activity and post-activity cognitive and physical performance scores for all three sessions are compared and reported as preliminary data, as customary in pilot validation studies.

2.6 Statistical analysis

Means ± standard deviations (SD) are presented. To address the study primary objective of proof the feasibility of the new VR-COG assessments, we used Pearson correlations between the VR-COG scores and the pre-activity and post-activity cognitive assessment scores.

To address the study secondary objective, we used a Time (pre-activity and post-activity) by Condition (three visit types) repeated measures ANOVA. Post hoc pairwise comparisons were performed using Bonferroni correction (n = 3).

To evaluate participant exertion level in the different experimental conditions and whether fatigue was reached, a repeated measures ANOVA was used to compare time to subjective exhaustion during the TTE running test. Post hoc pairwise comparisons were performed using Bonferroni correction (n = 3).

Pearson correlation analysis was used to assess the correlation between HR at rest and post-rest TTE score.

Effect size within the repeated measures analyses are reported as Eta-squared. Post-hoc power analysis was conducted on the correlation and the repeated measures analyses using G-power (Faul, et al. 2009).

Statistical significance level was set at $\alpha = 0.05$; analyses were conducted on SPSS software (SPSS Ver. 24, IBM).

3 Results

3.1 Primary objective: feasibility of the new VR-COG tests

3.1.1 Human interction and adaptation to the VR enviromant

Regarding immersion, interaction, and adaptation in the VR simulator, while we did not administer specific questionnaires for evaluation, we were impressed that the participants felt comfortable with the facility and the task. In particular, participants demonstrated a keen understanding of the virtual environment, freely navigating within it, consulting the provided map for orientation if needed, and actively scanning their surroundings as instructed when presented with the cognitive challenges while they marched. Their ability to adapt and engage with the virtual world was evident in their confident and unrestricted exploration.

3.1.2 Correlations: VR-COG and CTT

Strong or medium correlations were found between three out of the four VR-COG scores (total score and sub-tasks) and at least one of the CTT component scores (Table 1).

Table 1 Correlation coefficients (Pearson) between pre-activity and post-activity Color Trail Test (CTT) scores and VR-COG scores

Task type	Pre CTT_A	Post CTT_A	Δ CTT_A	Pre CTT_B	Post CTT_B	Δ CTT_B
Total score	**−0.75****	**−0.70***	0.48	−0.56	−0.52	0.18
Navigation	**−0.84****	**−0.61***	**0.69***	**−0.59***	−0.32	0.45
Visual	**−0.61***	**−0.72****	0.28	−0.52	−0.57	0.08
Calc&Mem	−0.55	−0.54	0.34	−0.39	−0.48	0.00

*$p \le 0.05$ (2-tailed). **$p \le 0.001$ (2-tailed). *Calc&Mem* calculation and memory; *CTT* Color Trails Test

Statistically significant results are presented in bold font

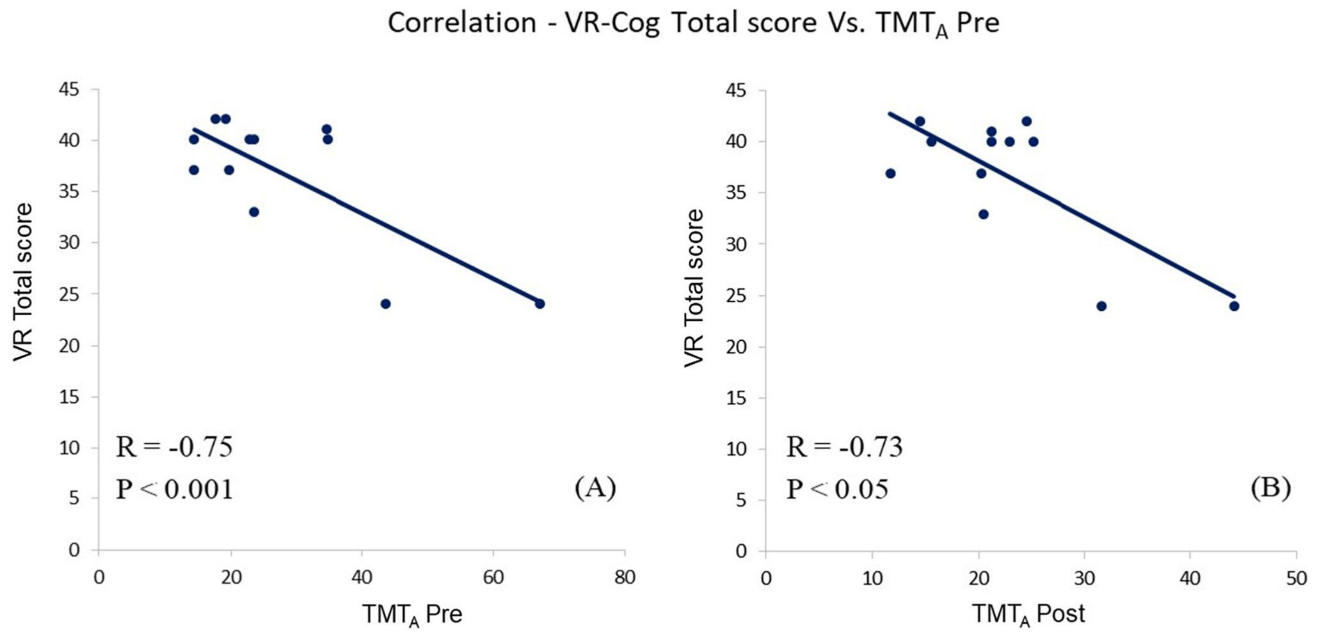

Fig. 5 Correlation analysis (Pearson) between the TMT$_A$ PRE (**A**) and POST (**B**) score and the VR-COG Total score. See also Table 1 for more details. Regression line equations: $y_A = -0.3185x + 45.593$; $y_B = -0.5489x + 49.119$

The negative correlations are in accordance with the fact that larger CTT$_A$ and CTT$_B$ are indicative of poorer performance, which higher scores on the VR-COG represent better performance.

VR-COG total score showed strong negative correlations with both the pre-activity and post-activity CTT$_A$ scores (see scatter plots in Fig. 5). VR-COG navigation score showed a strong negative correlation with the pre-activity and post-activity CTT$_A$ scores and with the pre-activity CTT$_B$ score, as well as a strong positive correlation with ΔCTT$_A$ (indicating an activity effect). Visual VR-COG score showed a strong negative correlation with the pre-activity and post-activity CTT$_A$ scores. VR-COG Calc&Mem scores were not correlated with the CTT components.

3.1.3 Correlations: VR-COG and SYNWIN

Strong or moderate positive correlations were found between all the VR-COG scores (total score and sub-tasks) and at least one of the SYNWIN component scores (Table 2). VR-COG total score showed a strong positive correlation with the pre-activity SYNWIN total score, with the post-activity SYNWIN memory sub-task score, and with the pre-activity SYNWIN math sub-task score. VR-COG navigation score showed a strong positive correlation with the pre-activity SYNWIN total score and the pre-activity SYNWIN math sub-test score. VR-COG visual scores showed a moderate positive correlation with ΔVisual monitoring SYNWIN sub-task score. VR-COG Calc&Mem score showed a strong positive correlation with the pre-activity and post-activity SYNWIN total scores, the post-activity SYNWIN memory sub-task score, and the pre-activity and post-activity SYNWIN math sub-task score. For example, Fig. 6 shows the correlation between the VR-COG Calc&Mem score and SYNWIN math sub-task score.

3.2 Secondary objective: activity condition effects

3.2.1 Cognitive evaluation

Figure 7 presents the CTT$_A$ and CTT$_B$ measures for all experimental conditions. CTT$_A$ score showed no significant condition effect, but did show a significant time effect ($F_{(1,11)} = 7.65$, $p = 0.02$, $\eta 2 = 0.41$), as the mean post-activity execution time, over conditions, was 5.2 ± 1.9 s shorter than the pre-activity execution time (better performance). Post-hoc analysis showed that CTT$_A$ score improved by 6.1 ± 6.8 s ($p = 0.003$) in the rest condition but showed no significant improvement in the Phys and Phys + Cog conditions. CTT$_B$ score showed a significant time effect ($F_{(1,11)} = 12.43$, $p = 0.005$, $\eta 2 = 0.53$), as the mean post-activity execution time, over conditions, was 4.9 ± 1.4 s shorter than the pre-activity execution time (better performance). Post-hoc analysis showed that CTT $_B$ score improved by 7.7 ± 5.0 s ($p = 0.002$) in the rest condition but showed no significant improvement in the Phys and Phys + Cog conditions. There was a significant Condition effect ($F_{(2,22)} = 4.8$, $p = 0.026$, $\eta 2 = 0.30$), but post-hoc

Table 2 Correlation coefficients (Pearson) between pre-activity and post-activity Synthetic Work Environment (SYNWIN) battery and VR-COG scores

Task type	Pre SYNWIN Score	Post SYNWIN Score	SYNWIN ΔScore	Pre Memory	Post Memory	ΔMemory	Pre Math	Post Math	ΔMath	Pre Visual monitoring	Post Visual monitoring	ΔVisual monitoring
Total Score	**0.77****	0.56	0.16	0.22	**0.66***	0.17	**0.78****	0.55	0.13	−0.25	0.23	0.46
Navigation	**0.67***	0.50	0.16	0.13	0.44	0.13	**0.68***	0.49	0.14	0.00	0.28	0.20
Visual	0.49	0.20	−0.19	0.28	0.40	−0.05	0.48	0.18	−0.21	−0.40	0.15	**0.58***
Calc&Mem	**0.81****	**0.71***	0.37	0.18	**0.81****	0.31	**0.83****	**0.69***	0.33	−0.24	0.18	0.41

*$p \leq 0.05$ (2-tailed)

**$p \leq 0.001$ (2-tailed)

Calc&Mem calculation and memory

Statistically significant results are presented in bold font

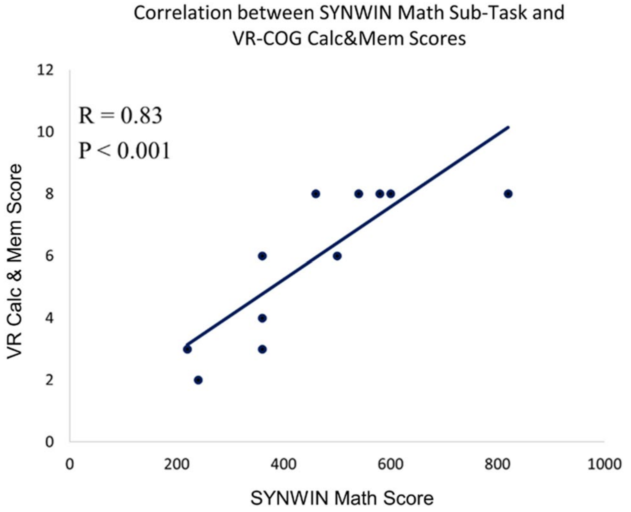

Fig. 6 Correlation analysis (Pearson) between the Synthetic Work Environment (SYNWIN) math score and the VR-COG Calc&Mem score. Due to the relatively discrete nature of the values, we also conducted Spearman correlation analysis and found significant correlations (Spearman roh = 0.87, $p < 0.001$). Regression line equation: y = 4.741x + 109.03

analysis showed no differences between conditions. Note that while not significant ($p = 0.08$), it seems that the added cognitive effort in the Phys + Cog condition tended to lessen the improvement in CTT_B associated with physical effort alone (51.03 ± 3.4 s). Similarly, evaluation of mean change over time for the three conditions in both CTT execution times (i.e., Δ CTT_A and ΔCTT_B) revealed no significant differences.

Figure 8 presents the SYNWIN composite scores for all three conditions, before and after activity. Only a significant Time effect was found (F(1,11) = 6.64, $p = 0.026$, $\eta 2 = 0.37$). In all conditions, composite score tended to be higher post-activity than it was pre-activity (rest: 833 ± 255 vs. 878 ± 244 pts., Phys: 828 ± 200 vs. 885 ± 189 pts., and Phys + Cog: 870 ± 177 vs. 889 ± 286 pts., respectively). However, post-hoc analysis showed no significant time differences in each condition separately.

3.2.2 Physical evaluation

As expected, both physical conditions elicited higher HR values than the rest condition (rest: 57 ± 2 bpm, Phys: 107 ± 8 bpm, Phys + Cog: 108 ± 8 bpm, $p < 0.0005$). No significant difference was found between HR values during both physical efforts. To evaluate exertion level in the different experimental conditions and whether fatigue was reached, times to exhaustion (TTE) running test scores were compared. Due to a technical problem in one of the experiments, the TTE analysis was based only on 11 participants. Post-activity TTE results were

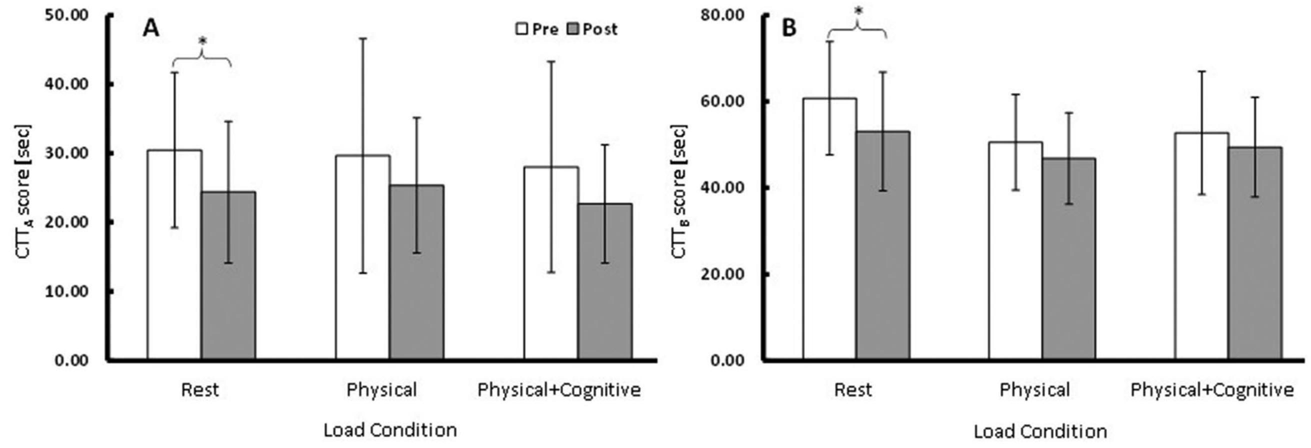

Fig. 7 Pre-activity and post-activity CTT_A (**A**) and CTT_B (**B**) scores for all experimental conditions; $*p < 0.05$

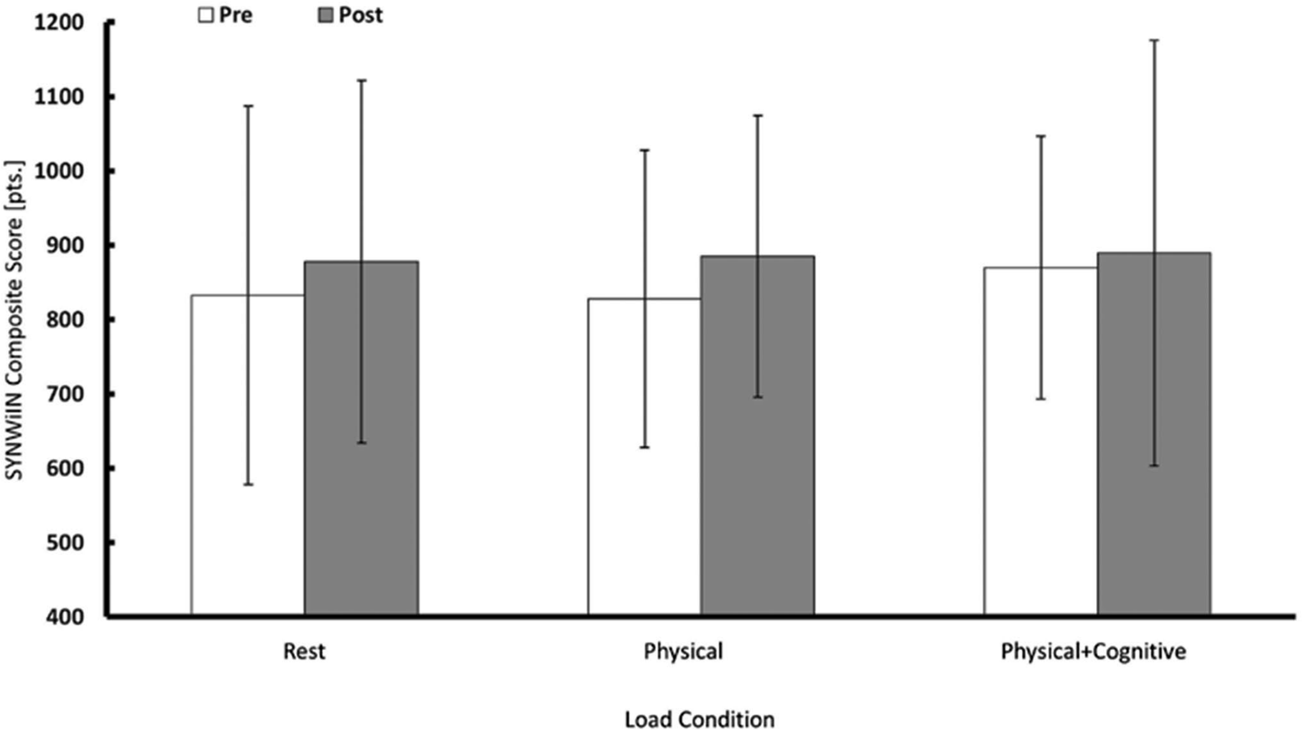

Fig. 8 Pre-activity and post-activity SYNWIN composite scores for all experimental conditions

very similar in the two physical effort conditions, and as expected, Post-rest TTE tended to be higher than them (rest: 22.06 ± 3.34 min, Phys: 20.36 ± 5.13 min, Phys + Cog: 20.56 ± 4.95 min). A significant Condition effect was found ($F(2,20) = 3.76$, $p = 0.04$), however, post hoc analysis showed no significant differences between each two conditions. These results indicate that while both physical efforts caused a greater physiological response, as indicated by the HR values, cognitive effort did not cause greater post-exercise exhaustion or reaching fatigue. Pearson correlation analysis showed a strong-negative correlation between HR during the two hours of physical activity and post-activity TTE score in the Phys and the Phys + Cog conditions ($r = -0.72$, $p = 0.019$; $r = -0.74$, $p = 0.015$, respectively), but not in the rest condition. These findings indicate that participants who experienced higher heart rates (i.e., greater intensity) while walking, tended to reach physical exhaustion earlier (reduced TTE).

3.2.3 Fatigue

Schmit and Brisswalter showed that reaching fatigue during activity is an important determinant of exercise-related changes in cognitive function (Schmit and Brisswalter 2020). Here, we tried to maintain the participants under physical effort without reaching fatigue by using known protocol, army training load matched and continues HR measurements.

On average, the participants performed the physical load while reaching 58% of their maximal HR as was measured on the VO_2max test preformed on the preparatory visit (rest: 56.94 ± 8.73 bpm, Phys: 111.31 ± 13.70 bpm, Phys + Cog: 110.66 ± 13.54 bpm), HR measurements were in the margin of light intensity scale (Medicine, A.C.o.S. 2013).

Accordingly, VAS RPE results showed that subjectively, participants reported on both Phys and Phys + Cog efforts to be light efforts (VAS = 11.4 ± 2.3, and 12.0 ± 3.0, respectively).

Wang at el. showed that cognitive fatigue during sustained performance of a prolonged cognitive task, can be detected by using intraindividual variability over time, in addition to error rate from different time periods (Wang et al. 2014). For evaluating the cognitive abilities during the two hours march, we compared the total score results from the first quarter (Q1, i.e., first 30 min of the march) to the last quarter (Q2, i.e., last 30 min of the march), normalized by the number of questions. For statistical comparison we used a nonparametric Mann–Whitney test. No statistically significance differences were found, in the total score and in the intraindividual variability as reflected by the SD ($Q1 = 1.583 \pm 0.34$, $Q2 = 1.385 \pm 0.2$ points, $p = 0.095$, $U = 42.5$, $Z = 1.67$). From these findings, we can assume that, nor physical or cognitive fatigue were reached.

3.2.4 Post hoc *power analyses*

Post-hoc power analyses conducted on the repeated measures investigations resulted in high study power for all analyses ($1\text{-}\beta = +0.99$). Post-hoc power for the correlation analysis between main scores of the SYNWYN, VR-COG, and CTT yielded medium power scores ($1 - \beta = 0.57–0.92$).

4 Discussion

This study demonstrates the feasibility of a novel experimental protocol based on large-scale VR system, involving both physical and cognitive loads. Our VR environment and accessories simulated a military march incorporating cognitive tasks designed to mimic actual military tasks. The cognitive engagement was achieved using context-related cognitive tasks that could then be compared with ‘gold standard’ cognitive tasks. We began to assess the effects of combined physical and cognitive effort on post-activity physical and cognitive performance. VR enables participants to experience situations under ecologically-valid but controlled conditions (Porras et al. 2018; Rizzo et al. 2011). Thus, behavioral responses studied under VR settings are representative to the anticipated behavior in the daily natural settings.

4.1 Summary of findings

Strong or moderate negative correlations were found between the VR-COG total, navigation, and visual task scores and CTT_A scores (T1; Fig. 5 & Table 1), and strong or moderate positive correlations were found between all the VR-COG scores and at least one of the SYNWIN component scores (e.g., Fig. 6 & Table 2). These findings support the feasibility of alternative context-related VR-based testing schemes that measure cognitive constructs similar to traditional, validated tests.

The secondary objective of the study was to compare the two activity conditions, and to determine the added effect of cognitive load. Physical activity was found to elicit some physiological exhaustion without reaching fatigue in comparison to the rest condition, as expressed by the TTE test results. However, adding a cognitive load did not cause an additional change in TTE score. In addition, the comparison between pre-activity and post-activity cognitive assessments (Figs. 7, 8) showed no condition effects but did show significant time effects, indicating better performance in the post-activity than the pre-activity assessments. The one exception was the condition effect found for CTT_B, suggesting better performance after activity than after rest.

4.2 Fesability of the ecological VR environment

Our VR application was designed to assess performance on various cognitive demands expected from high performance professionals (e.g., soldiers, rescue personnel, and athletes) including sustained attention, visual perception, and integration of information from multiple sources. The application is unique in allowing evaluation of these cognitive abilities during physical activity.

We found a strong correlation between VR-COG total score and CTT_A (Table 1). Shorter CTT_A execution time indicates better visuo-perceptual performance. The fact that the navigation and visual sub-tasks, but not the Calc&Mem sub-task, contributed to this correlation supports our assertion that these sub-tasks primarily evaluate visuo-perceptual abilities (D'Elia et al. 1989; Sanchez-Cubillo et al. 2009).

Interestingly, the navigation sub-task was also correlated with pre-activity CTT_B, reflecting that both these tasks require decision-making based on visual input. The CTT $_B$ test involves, for example, divided attention, cognitive alternation, and inhibition control. These abilities are also tapped during the navigation task, in which participants must scan their environment and make decisions based on a particular landmark. In contrast, the Calc&Mem sub-task involves cognitive functions, such as mathematical calculations, that are not involved in CTT performance.

These interpretations are corroborated by the correlations between the VR-COG measures and the SYNWIN test (Table 2). While the VR-COG total score, navigation, and Calc&Mem sub-tasks were correlated with SYNWIN total score and other sub-tasks, VR-COG visual score was correlated only to the visual monitoring task, which relies on a specific, similar cognitive ability.

It is noteworthy that the SYNWIN battery was designed to evaluate multitasking, as different sub-tasks are presented simultaneously. This effect was achieved more ecologically and naturally using our new VR application.

While exerting themselves physically in the VR environment, participants were required to process and memorize information from multiple sources until they were required to report about it. In the meanwhile, they performed other cognitive tasks (i.e., navigation and calculation). Thus, working memory was required in all the VR-COG tasks. Indeed, strong relationships between working memory and multitasking have been documented in the past (Hambrick et al. 2010; Redick et al. 2016), and specifically working memory was found related to the performance on the SYNWIN battery (Hambrick et al. 2010).

4.3 The effect of strenuous marching and simultaneous cognitive load on cognitive performance

Cognitive performance as assessed by the CTT and SYNWIN tests was not affected significantly by both exercise protocols (Figs. 7, 8). Post-hoc analysis showed that the visits order did not have any effect on the participants' results. Based on this and on the fact that we took the measure of acclimatizing the participant to the SYNWIN battery (see *Methods*), we rule out that the post–pre comparison was affected by learning. The fact that the subjective fatigue levels in the post-activity were relatively low may partially explain the lack of deterioration in performance post-activity cognitive performance.

In attempting to explain the lack of condition effects, we address aerobic fitness, exercise duration, and timing of cognitive evaluation. Participants recruited for this study presented high aerobic fitness (high VO_2max), which made the physical load intensity to be light to moderate for them (~50% of VO_2max, 58% of maximal HR). It has previously been shown that exercise of light to moderate intensity has no appreciable effects on cognition. Athletes are generally not expected to present cognitive changes during exercise of any intensity, while less fit participants have shown better cognitive performance after moderate, but not light, exercise (Labelle et al. 2013; Kamijo and Abe 2019; Hüttermann and Memmert 2014; Pontifex et al. 2009).

Another factor potentially affecting the relationship between exercise and cognitive performance is exercise duration. When dealing with prolong physical activity, the duration of the activity, together with its intensity level and fatigue threshold for each participant personally, will affect the cognitive performance (Dietrich and Audiffren 2011; Schmit and Brisswalter 2020; Sanders et al. 2019; Davranche et al. 2015). While our protocol lasted two hours, given our participants' fitness level, it was apparently not enough to evoke significant effect on cognitive performance.

Finally, in the present study, cognitive assessment was performed only directly after the physical activity, with no condition effect. The literature indicates that the timing of evaluation after the completion of physical exercise may influence the observed cognitive performance. It has been suggested that a 0–10-min break following a single bout of exercise will not cause improvement in cognitive functions, while a break longer than 11 min might lead to significant improvement (Chang et al. 2012; Soga et al. 2015). In similar work, Kamijo and Abe (2019) showed no significant change of cognitive performance (i.e., reaction time and accuracy) immediately after 25 min of bike cycling physical activity. Significant condition effect was found only after 30 min of rest following the physical efforts (Kamijo and Abe 2019).

It should be noted, however, that for some participants, the combined cognitive and physical load tended to lower cognitive performance, while for others it appeared to cause some degree of improvement.

4.4 Practical implication

The findings that VR cognitive test results affirm the viability of context-related VR-based cognitive testing, as these tests appear to measure cognitive constructs akin to traditional, validated tests, implies that such assessments can be effectively employed in a VR setting, mirroring the characteristics of their pen-and-paper counterparts. This provides more innovative ecological approaches for assessing cognitive abilities, as has been suggested in recent years (Parsons et al. 2017).

An additional implication highlights the piloted platform's capacity as a tool for combined physical and cognitive evaluation. This positions the platform as a valid assessment tool for diverse cohorts, including both healthy and non-healthy individuals. Furthermore, it can serve as a valuable tool in rehabilitation or training, facilitating the introduction of progressively challenging tasks in both physical and cognitive domains. While the current use case was in the context of a substantial physical load, the method can be easily adapted to other use cases such as clinical cohorts.

4.5 Limitations and future directions

Our study did not assess the impact of the cognitive load on the physiology of the participants during the exposure. Future work may evaluate effects on gait and on autonomic nervous system responses. In real-world scenarios high performance professionals experience cognitive load while in stressful situations. This feasibility study needs to be followed by research where the interaction between exercise and cognitive performance is evaluated in more extreme scenarios with a greater number of stressors, to represent real field conditions more closely. Further, both VR applications and potential real-world scenarios should be adapted to different high-performance professional contexts. For example, a VR-COG battery designed for firefighters should contain elements found in their professional environment.

In addition, while suitable for our goal of a pilot feasibility study, the sample size was too small to draw solid conclusions about the effects on cognitive performance of physical exercise alone and in combination with cognitive load. In particular, to delineate different types of 'responders' to the exposures, i.e., those who show improvements vs. those who show decline in the post activity evaluations. Further, future research should encompass a control group-based study, randomly allocating participants to a group performing physical marches (control) and another engaging in physical + cognitive load marches. This approach aims to more precisely assess the effects of cognitive load during marches on both physical and mental performance.

Another limitation of the current study was the inability to fully simulate real-world sensations and environmental factors during a long march with a load, including e.g., external temperature. However, we consider this limitation as marginal with reference to the ability to introduce cognitive challenges through intense physical effort.

Finally, we recognize that this pilot study design lacks non-exercise VR-COG trial which limits our ability to investigate how cognitive performance changes during exercise.

5 Conclusions

Large-scale VR-based applications can provide well controlled ecological scenarios relevant to high-performance professionals. Within these scenarios it is possible to assess combined effects of physical and cognitive efforts. The VR-COG test array that was presented in the study can potentially assess changes in cognitive performance under physically stressful conditions. The proposed application can be used to screen high-performance professionals.

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Declarations

Competing interests No potential competing interest was reported by the authors.

Ethics approval and consent to participate All participants in the study provided their written informed consent to participate. The research protocol was approved by the Sheba Medical Center Human Studies Committee (SM-2664-15).

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