Cognitive Expertise through Repetition Enhanced Simulation (CERES): Training to Understand Topographic Maps

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ABSTRACT

Understanding topographic maps is a difficult perceptual and cognitive process that is fundamental to Land Navigation training. Here we describe progress with an accelerated training protocol using high-repetition simulation-based training to develop map reading skill prior to field exercises. This novel training approach, CERES, is based on procedurally generated microsimulations that provide high-repetition practice associating a topographic map with a first-person terrain viewpoint. Each simulation-based training event is completed in 30-60 seconds, allowing for large numbers of training microsimulations to be completed per hour of study. With many repetitions, a process of implicit learning is engaged, leading to the development of fluid, automatic, and expert cognitive performance. The CERES training approach is accomplished using procedural generation of terrain environments, associated topographic maps, and first-person perspective videos of movement through the terrain. Participants indicate understanding of the map by reporting the orientation of video movement on the associated topographic map. Feedback about the accuracy of this orientation judgment is provided and task difficulty is adjusted adaptively to guide learning. With practice, participants gradually improve their ability to connect the three-dimensional terrain video features of the simulated environment with the structure implied by the contour lines from the two-dimensional topographic map representations. Understanding the relationship of map to environment is necessary for navigation and to make planning decisions appropriate to the environment. The CERES training approach is designed to supplement traditional classroom instruction and support initial steps toward expertise through simulation-based practice prior to experience in the field.

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INTRODUCTION

Understanding the three-dimensional terrain environment communicated by a two-dimensional topographic map is a difficult cognitive and perceptual task typically learned through long experience. Even though geographic location can be determined with technology (GPS), decision-making contingent on the environment still requires deeper map understanding and, in some environments, GPS may not be reliably available. Here we describe a novel training approach for developing topographic map understanding skills through training. Future training development for the US military demands efficient and effective learning environments and the ability to prepare personnel in core skills prior to field operations.

The CERES project is an ongoing research program (Schmidt, Feinstein, Grabowecky, & Reber, 2019) that reflects the development of a new, high-repetition training approach to skill building that aims to accelerate learning and increase expertise prior to practical skill use in the field. This approach is designed as a supplement to traditional lecture-based teaching and comprehensive field exercises. While traditional methods can be effective, they are not designed to maximize the 'sets and reps' that are critical for acquiring real expertise. Practice can be acquired with Simulation-Based Training (SBT) but these approaches are usually based on training scenarios requiring laborious planning and design by expert scenario authors and do not use the large numbers of repetitions requisite to build expertise. Using procedural content generation within an SBT protocol, our new approach aims to provide many hundreds of training examples in carefully constructed contexts aimed to maximize experience with the core underlying cognitive and perceptual skills. After training, we hypothesize that participants will be able to use these skills in a rapid, fluent and intuitive manner, leaving more cognitive resources available for complex decision making and general situational awareness.

Topographic Map Reading

Reading and understanding topographic maps is challenging for many reasons. Because a 3D terrain is rendered as a 2D surface, topographic maps compress information and may represent it in a way that is not intuitive for everyone (Clark et al., 2008). The scale of the 2D representation is also vastly different than that of the 3D terrain that it represents so that aligning features presented at the terrain scale with those at the map scale may be difficult, and the orientation of the map does not intrinsically align with the orientation of the individual in the environment (Clark et al., 2008). Topographic maps and other 2D representations are well-suited for perceiving the relative locations of terrain features, but they are not well-suited for understanding what terrain features will look like (St. John, Cowen, Smallman, & Oonk, 2001). In contrast, 3D representations provide information about the shape of terrain features. However, a single 3D view, such as a picture may present ambiguous and thus confusing relative location cues (St. John et al., 2001). Replacing static 3D images with 3D videos improves relative distance cues by largely eliminating the ambiguities inherent in a single view and more closely approximating real-world navigation.

Topographic map reading also requires complex spatial processing to enable decision making appropriate to the environment (Taylor, Brunye, Taylor, 2008). Successfully implementing these cognitive skills depends on comparison between a contour map and the first-person perspective of the navigator, who must envision how the contour lines on the map correspond with the viewed environment. Participants rely on component processes, such as mental rotation in this process to transform the allocentric mental model of the topography implied by the contour lines into alignment with an egocentric, first-person frame-of-reference (Wickens, 1999). Novices are prone to make errors in this upward mental rotation of the first-person view (or forward rotation of the map) (Hickox and Wickens 1999; Aretz and

Wickens 1992). Thus, it is an important part of land navigation training programs to help novices develop these topographic map reading skills.

Simulation-Based Implicit Learning Tools

A primary goal of the CERES training approach is to find a way to build expertise prior to the lengthy process of developing field expertise. By providing larger numbers of practice repetitions in a training environment, expert-level skill acquisition should be greatly accelerated. The benefits of SBT tools are greater cost and time efficiency for trainings in which task experience is beneficial for learning. Task learning through numerous repetitions has been shown as a critical factor in facilitating expertise development (Anderson, 1991; Fisk, Ackerman, & Schneider, 1987; Schneider, 1985). This process of expertise development is facilitated through the implicit memory system, in which repeated experience leads to a reshaping of neuronal structures, as defined in the general principle of plasticity (Reber, 2013). For implicit learning to occur and, subsequently, for expertise to develop, repeated interactive practice must be experienced.

Prior SBT approaches have generally not attempted to use a high-repetition approach with hundreds of training scenarios. One reason for this limitation has been a lack of content due to inability to create the necessarily large number of scenarios for training stimuli. Technological advancements in procedural content generation have allowed the current approach to overcome that limitation to create arbitrarily large numbers of scenarios to be implemented through the CERES approach to SBT. This enables the design of the CERES protocol with large numbers of trials completed rapidly in each hour of training in order to facilitate implicit learning. Our prior research has shown that decision making can be improved by providing trainees with a large number of rapid practice trials with feedback to improve learning strategies and stimuli-environment pattern extraction (Squire et al., 2014). In a study of domain specific expertise, for example, those with higher expertise in basketball showed greater accuracy in judgments based on implicit extraction of situational context in rating the difficulty of basketball acts (Dane, Rockmann, & Pratt, 2012). This demonstrates that more experience can translate to higher performance in scenario-based judgments.

TRAINING PROTOCOL METHODS

Procedural content generation

A critical technological element of being able to do repetitive practice on map reading with a large number of 'sets and reps' is the need to have a large number of maps and terrains to experience in order to understand the maps. In collaboration with Charles River Analytics (PI: James Niehaus, Ph.D.) we developed stimulus generation software based on the Unity software engine. This software consists of a set of algorithms for generating constrained, random terrain surfaces and tools for rendering both maps and first-person perspective videos reflecting a simulated interaction with the terrain.

The terrain generation process starts with setting the parameters for each terrain. The total area for each terrain was set at 5 kilometers (km) x 5 km. The vegetation biome for each terrain was set as either a grassland or snow-covered desert type. Vegetation parameters such as tree type, tree density and grass density were then selected. The tree types were conifer, broadleaf, and palm, with terrains containing one or multiple types. Terrain features, such as hilliness and the number of valleys and ridges were created from a terrain generation algorithm that randomized height and smoothing parameters. Terrains were then individually edited to specify vegetation and feature distribution.

Topographic maps were generated from the randomly generated terrains providing a standard two-dimensional representation of the variation in heights across the terrain. As shown in Figure 1, each terrain was associated with a 5 km x 5 km topographic map that was similar to standard map scales (1:25,000) when rendered on the training computer screen. We also prepared topographic maps at a 1:5,000 scale reflecting a 1 km x 1 km section of the map that participants connected to a first-person perspective. The topographic map generation process was significantly improved from previous reports (Schmidt et al., 2019). The current process produced maps much closer to standard military use specifications (10-meter contour lines with thicker contour lines every 50 meters of elevation). Numeric altitude indications were also added procedurally, improving the ability to understand the elevations on the map.

Using the Unity engine, 20 first-person perspective videos of movement through the terrain were rendered for each of the 25 1 km^2 maps per terrain (500 total per terrain, 10,000 across all procedurally generally content). Each video clip was 12 seconds in length, demonstrating an eye-level point of view of the virtual world. The beginning 5 seconds of

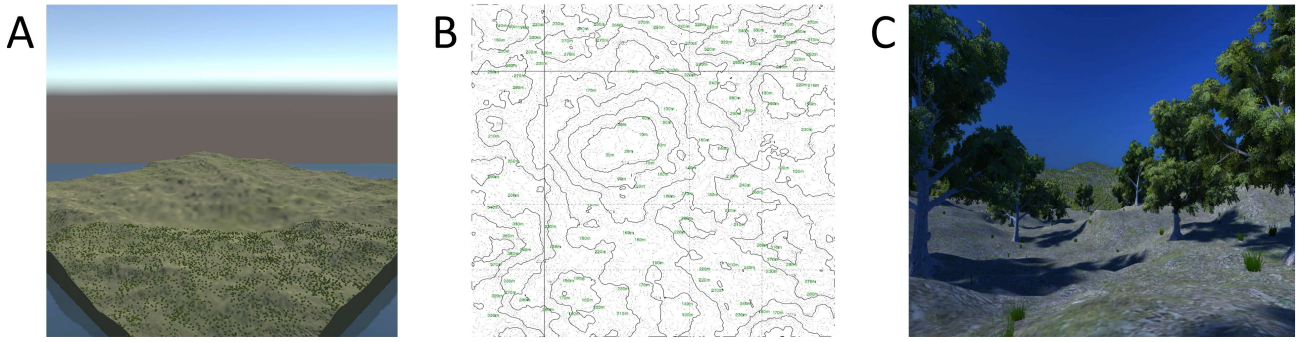

Figure 1: Procedurally generated terrain and associated topographic maps. (A) View of full randomly generated 25 km² terrain within Unity-based editor (B) Map of the 5 km x 5 km terrain (rendered on screen at 1:25,000 scale). (C) Still image from a first-person perspective video of stimulated movement through the procedurally generated terrain.

the video displayed a forward trajectory, moving at a speed of 10 meters per second. The next 5 seconds of the video stopped forward movement, and then spun rightward, at a speed of 70 degrees per second to provide a 350-degree view of the surroundings. The final 2 seconds of the video was static (see Figure 1). All videos included clear skies and a consistent time of day (3 p.m.). Participants were informed of this time-of-day consistency and were encouraged to use the in-video cast shadows to support orienting.

Participants

A total of 11 fluent English speakers between 18-35 years old were recruited from a university and the surrounding community in the midwestern USA. Prior topographic map experience was not a participation requirement, and individual familiarity with topographic maps was not reported. Participants completed up to ten 1-hour training sessions within 2 weeks of starting the experiment. Participants were compensated 15 dollars for each hour of participation, to a maximum of 150 dollars. Each participant gave informed consent prior to enrolling in the study. The first 4 participants completed all but the first session remotely using lab-provided laptop computers. The subsequent 7 participants completed all sessions in the lab.

Materials

Following the procedural content generation process described above, we created 20 terrains for use in the training protocol. Each terrain thus had pre-generated stimuli for up to 500 associated potential training trials. Storage of the content for each terrain was approximately 500-750 MB on disk and the total database of training stimuli was approximately 12 GB.

The presentation of stimuli, response collection and feedback were implemented within PsychoPy (version 3.2.3; Peirce et al. 2019), an open-source computer software package designed for stimulus presentation and data collection based on the Python programming language.

Protocol Implementation

Overview: Participants completed 10 sessions (one hour each) of computer-based training in which they completed as many trials as possible attempting to connect the movement direction in the first-person perspective video with the topographic map of the associated terrain. Training was concentrated within a section of the terrain to allow participants to gradually develop a better sense of that specific topography and of how the map and perspective videos were related. Training was adaptive in that consecutive accurate answers advanced the training to a new section of the current terrain and then eventually to a new terrain. On the first day of training, participants were instructed in-person by a research team member on reading and understanding topographic maps via a series of self-paced instructional slides. This introduction was necessary as the participants (from the university community) were not necessarily familiar with topographic maps prior to enrolling in the study. We then provided participants with instruction on the specific details of the experimental protocol, including the larger scale terrain, the section maps and the perspective videos. We also instructed our participants on the procedure for making their training responses and options (see below). After the first day of training, 7 participants completed the rest of the training sessions in person in our research lab, while 4 participants took home laptops containing the protocol to complete at home.

Structure of a training trial (Figure 2): Each time a participant began practice on a new terrain, the training software/program first showed the overall 5 km^2 topographic map of the entire terrain. Thereafter, each trial started with a 1 km^2 view that included a blue circle indicating the approximate location of the participant's viewpoint on that map. Participants could study the map for up to 20 seconds or choose to proceed more quickly. The software then played the video twice. The participant could terminate the video to proceed to the response phase upon understanding the direction of travel. Next, the program again presented the 1 km map to the participant, which as before showed a blue circle indicating the location of the first-person video. Here the program asked the participant to indicate the direction the viewpoint was facing (and initially traveling) in the video. A two-step process indicated the direction, first by asking participants to choose the closest cardinal direction (N, S, E, W) and then adjust an arrow to more precisely reflect their understanding of the direction of travel. The two-step process could be completed either by keyboard or with a computer mouse. Participants were given up to 30 seconds to complete their response. After completing the response, the program provided feedback, showing the correct answer and accuracy of the response (error measured in degrees). In addition, the program provided on-screen encouragement to facilitate accurate responses (<15 degrees, "Perfect!", <30 degrees, "Good job!", <45 degrees, "Close!") and help maintain engagement with the task. During occasional self-paced breaks, participants were shown the tally of each of these accurate response types.

Additional training options: We provided participants with several other self-directed options during training to facilitate task learning. If they found the task difficult, they could request a change for a single trial to a 'dual display' mode in which the map was shown simultaneously with the video. In this mode, a moving indicator was provided on the map showing both the location and direction of movement. It was expected that participants would use this option early in training when first learning the map reading skill. When viewing the 1 km^2 map, participants also had the option to switch to the larger 5 km^2 map view in order to identify key features (attack points) on the larger map that might not be visible on the individual sectional maps.

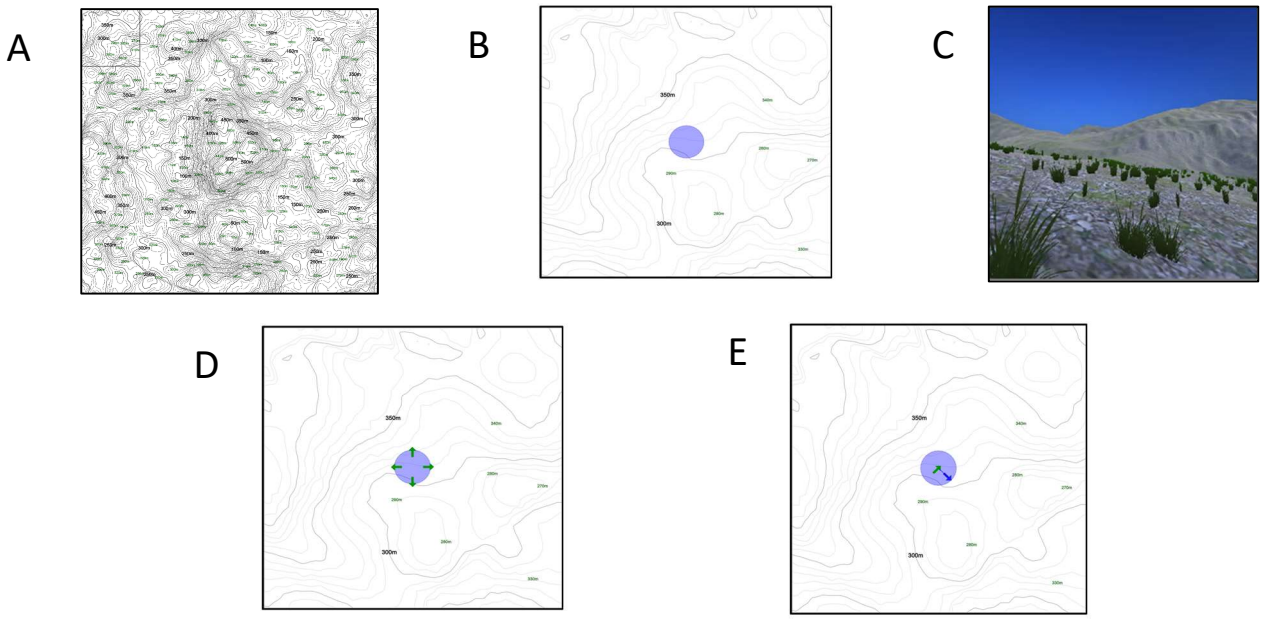

Figure 2: Procedure for a single map training trial. (A) 5 km^2 map of the whole terrain. (B) 1 km^2 map of a terrain section with location indicated as the center of blue circle. (C) Video of movement within the terrain. (D) Response phase where participant indicates their understanding of the direction of travel. (E) Feedback provided about accuracy with the correct answer shown as a blue arrow.

During the response phase, we also provided two options to making the orientation response. If a participant was unable to determine the direction of movement, they could opt out of responding. The goal of this option was to reduce guessing. We measured the use of this option to explore whether it would be a way to embed adaptive features into

training such as selecting easier trials, although this feature was not yet implemented. We also provided participants with the option to report a malfunctioning trial video. Because the entire content database was algorithmically generated, individual trials were not fully curated and could potentially lack enough visual information to orient. This option was intended to explore the possibility of having trainees help curate and improve the training stimulus set.

Adaptive training elements: After completing a trial, participants immediately began another trial that was randomly selected from the same map section. If a participant was able to score less than 30 degrees of error for 3 consecutive trials (or attempted 20 trials on that section), a new map section was selected for further training. Once all 25 map sections within the larger 5 km^2 terrain were successfully completed, participants moved to training with a new terrain.

Assessment trials: In an attempt to characterize the progression of general map reading skill, participants were periodically interrupted in training with a set of 10 assessment trials. These were drawn randomly from a novel terrain in the map database and were presented without feedback. We included these trials as a general measure of map understanding separate from knowledge developed about the specific terrains the participant had been experiencing.

Overall training protocol structure: Participants completed 10 hours of training across 10 sessions. During the first session, they received the general map reading instruction, three dual display practice trials, five regular task practice trials and an initial set of assessment trials. Thereafter participants completed approximately 50 minutes of map training and one assessment test each session over the next 9 sessions. During training, we offered participants self-terminated breaks after every 5 minutes of training. During these breaks, they were given feedback about their overall performance and had the option to review the instructional slides. We used orientation accuracy and response speed on practice maps (training trials) and unpracticed maps (assessment trials) as an indicator of the retention and transfer of implicitly and explicitly learned skills.

RESULTS

Inclusion/exclusion criteria

Out of the 11 participants recruited, 3 were excluded from the final analysis. One participant withdrew from the study after the first session. Two participants were excluded due to noncompliance with the training protocol that emerged over the protocol sessions. One participant developed a strategy of rapid, random responding without an attempt to identify the direction of movement in the video and thus completing a large number of inaccurate trials (3,256 total trials compared to an average of 806 for the rest of the group). Another participant responded exclusively using cardinal compass points without an attempt to more precisely indicate movement direction. The remaining 8 participants' data over the 10 training sessions were analyzed.

Training completed

Participants completed an average of 38 trials (SEM=4) in the first session and then completed an average of 85 (SEM=2) trials for the remaining sessions, for an average total of 806 (SEM=142) training trials across all sessions. The smaller number of trials on the first session reflected both a general increase in the rate of task performance and the additional time spent in the first session on general navigation instruction. Within each session, participants generally completed one set of assessment trials.

Orientation accuracy

We evaluated accuracy of the participants' judgment of the direction of movement separately for the training and assessment trials within each session (Figure 3A). We scored overall accuracy during a session as the median error for that participant in that session (to minimize the impact of large directional error responses that likely reflected guessing). In addition, we collapsed session scores across pairs of sessions to provide a smoother, better overall description of the learning process across the 10 hours of training. We measured reliable improvement as a paired t-test comparing the first pair of sessions to the final pair of sessions, $t(7)=3.79$, $p<.05$. Additionally, an evaluation of the overall learning curve by a one-way repeated measures (linear trend) revealed a significant improvement in accuracy, $F(1, 7)=6.33$, $p<.05$. A change in accuracy on the assessment trials from the first session pair to the final pair was not statistically reliable, $t(7)=1.80$, $p<.15$. However, the overall learning curve of the assessment trials by a one-way repeated measures showed a significant improvement, $F(1, 7)=8.11$, $p<.05$. Orientation judgments were not significantly different between assessment (M=43.1, SEM=6.7) and training trials (M=40.7, SEM=4.9), $F(1, 7)=0.49$,

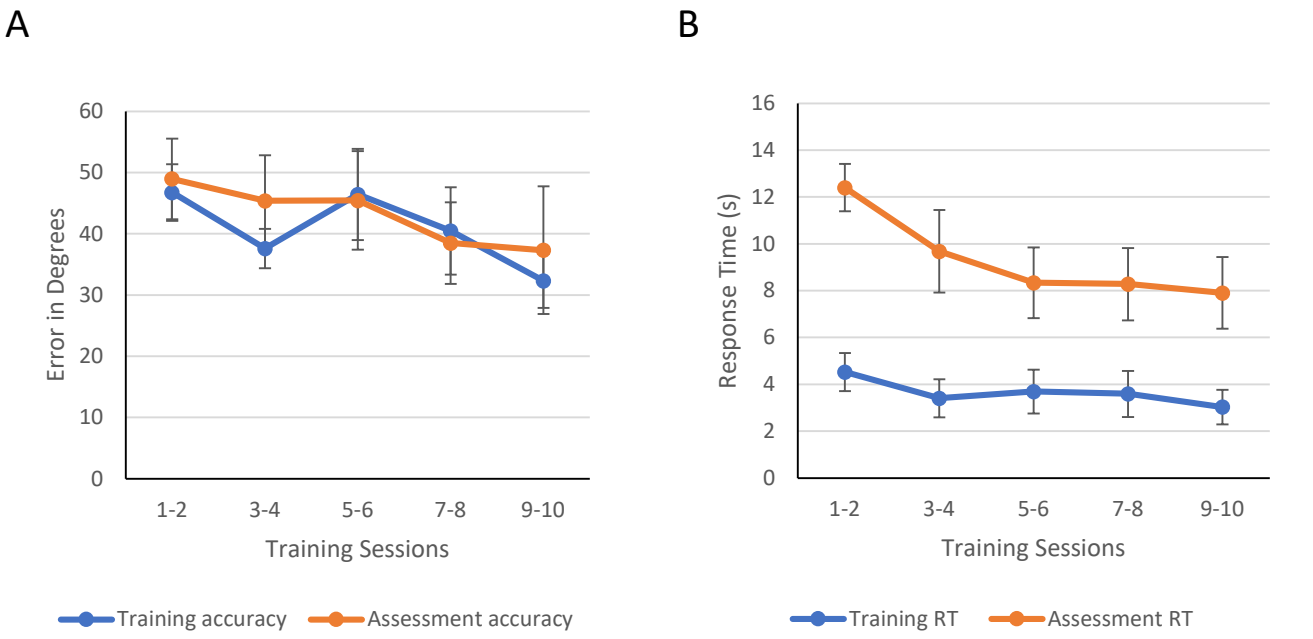

Figure 3: Improvement in performance across training sessions. (A) Participants' orientation accuracy judgments became increasingly accurate with practice during training and improved at a similar rate during the interspersed assessment trials. (B) Time to make the orientation response increased slightly during practice, particularly for the assessment trials, which were also slower overall.

p=.51. The performance gains on both types of trials was modest and most participants were still fairly inaccurate at the end of training (~30 degrees of error, too inaccurate for successful navigation).

Response time

We analyzed response time data in the same manner as the orientation accuracy scores (Figure 3B). Paired t-tests comparing first and last sessions indicated that improvement on the assessment trials was reliable, $t(7)=2.87$, $p<.05$ and marginally reliable for training trials, $t(7)=1.96$, $p<.10$. Assessment trials (M=9.3s, SEM=1.3) were notably slower than training (M=3.7s. SEM=0.8), $F(1, 7)=11.07$, $p<.05$. However, since the first assessment trials were the very first trials completed by participants, some of the speed improvement may have been simply due to learning the response interface. The slower response time on assessment trials across the rest of the training sessions reflects the fact that these trials required participants to judge orientation on terrains that they had not practiced, which led to more time taken to make the orientation response although the accuracy of the response was similar to the training trials.

Additional response option usage

Participants were provided with response options to indicate an unsure choice rather than make a guess, and to denote a 'bad video' that they believed could not be used to determine orientation. These options were used very sparingly (M=3.8 for 'guess', M=0.63 for 'bad video' out of an average 806 trials) indicating that participants tended to feel that they could make an estimate of the direction of travel for the overwhelming majority of the videos. Two options were provided during training for remedial review of the process of connecting the topographic map to the terrain in the movement videos. During each break (every 5 minutes), participants could have reviewed the original instruction slides about map reading. However, this option was only used 9 times in total (out of 110 opportunities), mostly in the first two sessions. On an individual video, participants could also request a 'dual display' mode that showed the video and map simultaneously with the movement location and direction indicated. This option was mainly used by two participants (only 15 and 19 times) indicating a lack of interest in this additional training support.

In general, throughout the high-repetition training protocol, participants preferred to keep completing training trials as the main mechanism of learning. This appears to reflect good engagement with the task (for the 8/10 participants who complied with task instructions) and may be a characteristic of a reasonably successful learning-by-practice approach.

DISCUSSION

After 10 hours of training, orientation accuracy and decision-making response times improved, showing that training based on procedurally generated content produced robust learning. Although the ending orientation accuracy was likely not enough to support successful navigation in the field, the training task is more constrained and difficult than field navigation. The rapid-fire training protocol used here precluded participants' control of their viewpoint and limited their first-person view of the terrain to a single short movement trajectory. This constraint creates a more difficult challenge for determining orientation but participants still improved their performance, showing better topographic map understanding. Participants trained on a very small fraction of the existing database. If the number of training repetitions or if the length of the training protocol had been increased, participants could have continued training towards additional expertise development. The navigation improvements observed here were gained at considerably lower expense than deploying personnel to live terrain sites for training. The lightweight training protocol approach by which participants interact only with still images and pre-rendered video can be made available to trainees not only within a structured classroom environment but also in a discontinuous (ad hoc) manner for opportunistic training. However, the CERES approach has not yet been validated with comparison to live orienteering (or other terrain reasoning) tasks to measure how in-task performance relates to navigation and decision-making in the field.

The levels of participant task compliance and engagement with the current version of the protocol are likely areas that could see further improvement (based on the need to exclude non-compliant participants). While military personnel are likely to be more motivated to develop map reading skill than our naïve community participants, we hypothesize that better task engagement will lead to better learning. Several participants volunteered that they appreciated the ongoing count of highly accurate responses shown on screen at each break and that this motivated them to try to achieve as many of these as possible. The ability to incorporate quantitative feedback to trainees about progress and accuracy across the many trials of training is a feature that will be further incorporated into future versions of CERES.

Participants' use of the user interface elements was also instructive. In general, participants did not use the options to skip over a trial instead of guessing (or providing feedback about a particularly difficult video) and preferred to continue in the flow of training trials. Participants' low utilization rates of the re-review instructions and tips options could be an indicator of a preference to achieve expertise through increased practice rather than through increased instruction. It is also possible that participants found the instructions not helpful. The option to switch back and forth between map scales (1:25,000 and 1:5,000) was used regularly and was reported to be important to connect terrain features from the video to specific points on the map across scales. This process is very similar to the natural tendency to consider a topographic map at different distances when navigating.

Feedback from subject-matter experts has continued to be strongly positive. Land navigation experts and instructors have examined the CERES protocol during annual Technical Reviews held by Office of Naval Research program personnel and through the NROTC office at a university in the northern, mid-western USA. Instructors particularly noted the potential availability for trainees to do self-directed additional training to support existing instruction, especially for trainees who were experiencing significant difficulty in the classroom and field exercises.

The CERES training protocol, which incorporates a high-repetition practice loop with feedback (i.e., Theory of Deliberate Practice; Ericsson, 2008), enables the development of expertise through accelerated implicit learning within the domain being trained so that more expert-like knowledge representations can be built. This study shows that this type of skill training can improve navigation skills in a simulated environment using a topographic map. If these skills are shown as transferable to live orienteering tasks, a CERES-type protocol may also be useful for training skills in other areas in which field exercises are expensive and/or high risk but are vital for expertise development.

Future and ongoing development of the CERES map training protocol will focus on several additional technical improvements. With the support of our collaborators (Charles River Analytics), the procedural content generation process has been extended to include more reference features and "attack points" to connect the 2D topographic map to visible elements of the 3D terrain. These include water features and the inclusion of arbitrary objects that appear on both the map and terrain. While these features are not intended to simulate navigation through real-world environments with roads, buildings and other man-made features, it is expected that additional reference features will allow for the

creation of easier training trials that may be of use to novices. In addition, the feasibility of online content delivery is being evaluated. The lightweight structure of the CERES protocol lends itself well to online training by relying on the Unity engine only for content creation and not during administration of the protocol.

Another path for future development will be the integration of more adaptive learning features. Because trainees complete large numbers of trials in rapid succession, their current level of ability can be assessed by recent performance accuracy. From this assessment, training can be flexibly adapted to focus on easier training with feature-rich terrains that are easy to connect to topographic maps, or more challenging terrains where a deeper understanding of the contours implied in the topographic map is necessary. Through further improvements to the procedural content generation method, it will be possible to create training across a wider range of difficulty so that training can be implemented adaptively for scaffolding to better facilitate navigation skill development.

An important planned test of the efficacy of the CERES approach will be based on examining learning in military personnel and comparing knowledge derived from field tasks (e.g. orienteering during Land Navigation training) and this simulation-based training style. Greater adaptive training options during skill building (selecting terrain types and trials based on difficulty and momentary performance) may further improve learning in subsequent protocol versions. Also, individual differences in ability can be assessed during training with this style of protocol. Although 10 training hours of data per participant were included, future studies should utilize a larger subject set to decrease the influence of individual differences.

Conclusion

The CERES protocol demonstrates that training using a large database of procedurally generated terrain stimuli can improve topographic map reading skills. Across 10 hours of training, participants completed an average of 800 trials of training on judging their location and movement direction from a 3D first-person perspective video connected with a standard 2D topographic map of the terrain. Participants became faster and more accurate at the task indicating their development of the cognitive skill of topographic map understanding. While additional technical improvements are still in development, the current results show the potential value of high-repetition based SBT supported by procedural content generation.

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IRB CONSENT

All procedures and recruitment materials were reviewed, approved, and monitored by the Northwestern University Institutional Review Board. IRB approval was acquired for recruiting participants from the Northwestern University community as well as for Military Personnel (IRB #: STU00206632).

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