Cognitive Expertise through Repetition Enhanced Simulation (CERES): Topographic Map Reading

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ABSTRACT

Understanding a topographic map is a non-trivial cognitive and perceptual process that is a critical part of Land Navigation training for many military personnel. The three-dimensional representation implied by the contour lines on a map must be mentally constructed and transformed in order to tie the map representation to the visual perception of the world. Understanding the relationship of map to environment is necessary for navigation and to make planning decisions appropriate to the environment. Developing this skill is a learning process typically accomplished through a traditional combination of instruction and field exercise, with expertise developing from further extensive field experience. The CERES project aims to accelerate the development of map reading expertise using a novel practice protocol using simulation-based training to provide many hundreds of practice events rapidly and inexpensively. With a large number of repetitions, a process of implicit learning is engaged, leading to development of fluid, automatic, and expert cognitive performance. The training approach is accomplished by using procedural generation of terrain environments from which topographic maps are also generated. Over training, topographic maps are repeatedly paired with first person perspective views within the simulated environment, each shown briefly (30s total). Participants express understanding of the map by successfully indicating their facing orientation from the first-person perspective. During training, feedback about the accuracy of their orientation judgment is provided and the task difficulty is adjusted adaptively. With practice, participants gradually improve their ability to connect the visual features of their location with the structure implied by the contour lines on the maps and to correctly read their position and facing on the map. An improved ability to understand the topographic maps is shown in better performance on a no-feedback post-training assessment (compared to pre-training) reflecting preliminary success at training rapid, intuitive map understanding using a high-repetition simulation-based training protocol.

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INTRODUCTION

Future training concepts for the US military demand efficient and effective learning environments for education, training, and readiness assessments. Topographic map reading during land navigation training continues to be critical for many military personnel. Typical protocols rely on lecture-based teaching and comprehensive field exercises, which require laborious planning and coordination to develop extensive training scenarios. Novel approaches can complement traditional classroom instruction and field exercises by leveraging computerized algorithms to rapidly author topographic map reading training content. A new high-repetition, simulation-based training approach aimed to provide 100 terrain-based training events per hour, with the goal of accelerating land navigation training by enabling non-experts to make more effective decisions.

Topographic Map Reading

Topographic map reading requires complex spatial processing to enable decision making appropriate to the environment (Taylor, Brunye, Taylor, 2008). Successful implementation of this cognitive skill 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. Component processes, such as mental rotation, are relied upon 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 advantageous for land navigation training programs to help novices develop these topographic map reading skills.

The generalizable skill of topographic map reading can be applied to specific terrains to engage processes that build up terrain-specific knowledge over time. This advanced geographical knowledge bifurcates into two forms: mental maps and the relative location of landmarks (Thorndyke and Hayes-Roth, 1982). Extensive map study directly leads to the development of mental maps, which is the ability to reconstruct an accurate mental rendering of an area. In parallel, knowledge of the relative location of landmarks, key to knowing how to get from one location to another, is instead best developed through *experience* within the environment (Williams, Hutchinson, Wickens, 1996). Importantly, these two types of advanced geographical knowledge develop concurrently and together optimize navigational fluency and understanding (Montello, 2005).

Simulation-Based Implicit Learning Tools

Simulation-based tools provide a cost and time effective platform to provide high-repetitions of the "experiential" components of training. With large numbers of experiential-based terrain decisions, a process of implicit learning is engaged, which is critical to the development of fluid, automatic, and expert cognitive performance (Anderson, 1991; Fisk, Ackerman, & Schneider, 1987; Schneider, 1985). The core idea is that implicit memory reflects a general principle of plasticity within the brain that leads to adaptive reshaping of performance to match experience. Implicit learning in this context is experiential, interactive, and requires large numbers of repetitions to mature, typically accruing through practice during field exercises.

This type of learning is not normally capitalized on in simulation-based training, but recent advancements in rapid procedural content generation of thousands of topographic maps and first-person renderings enable simulation-based tools to provide a robust training set from which to train the implicit learning system. Advances in understanding the organization in human memory indicate that implicit learning can be leveraged earlier in training by rapidly providing lots of practice events (with feedback). Once developed, this implicit knowledge improves performance by effortlessly extracting patterns from the environment to support decision making (Reber, 2013). For example, high domain expertise in basketball leads to much more accurate intuitive judgements, as would be expected if intuition was supported by implicit extraction of the statistics of the environment during acquisition of domain knowledge (Dane, Rockmann, & Pratt, 2012).

TRAINING PROTOCOL

Software was developed to evaluate the feasibility and effectiveness of engaging implicit learning in a high-repetition, simulation-based topographic map reading training protocol. State-of-the-art advancements in procedural generation of simulated terrain stimuli were used to rapidly build a training set of topographic maps and simulated worlds. A high volume of terrain-based practice was then driven by rapidly presenting topographic maps and simulated terrain challenges, using feedback to shape performance.

IRB Consent

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

Participants

A total of 60 fluent English speakers between 18-35 years old were recruited from Northwestern University and the surrounding community. Participants were compensated $15 per hour for their participation. Informed consent was provided by each participant prior to enrolling in the study.

Terrain Stimuli Procedural Generation

Individually authoring scenarios is impractical for the hundreds of simulations required in high-repetition training. Software was thus developed by Charles River Analytics using content generating algorithms to render high volumes of unique simulation environments to use across training exercises (Figure 1). The software is implemented within Unity (a programming system for virtual reality environments) and uses freely available assets to create the virtual environments used to produce short training scenarios rendered as video clips and topographic maps. There are three main aspects to this process: world generation, video rendering, and map rendering.

For the world generation process, parameters were set indicating the overall topographic complexity of the terrain to create together with vegetation density. The first step identified the core elements of the scenario and which parameters would be randomly varied and across what range. All the environments were created using a standard set of assets and a map that was always 1km x 1km in size. We then identified four parameters on which we could impose a range of values to create different random environments: topography (hilliness), vegetation (trees and bushes), time of day (noon to dusk) and weather (clear to light rain). These were each defined over a [0.0, 1.0] range and associated with specific visual conditions. The software allows for variation in time of day and weather conditions, but these are not currently in use. The topographic maps used in training are rendered from this randomly created terrain.

For the creation of stimuli videos, a simple language syntax was created to describe the location, viewing orientation and movement trajectory for the created environment. The embedded Unity physics engine appropriately placed the viewpoint relative to the current location ground level. The available commands through the movement definition include stepping forward, turning left/right and looking left/right. An initial location was provided with a series of movement commands and an overall length of the video to be rendered. The movement steps were computed and a movie file rendered of the first-person perspective of the trajectory.

A separate module was developed that calculated a topographic map with 10m contour lines for areas where the land height varied. With this it was possible to render hundreds of stimuli by creating a random terrain environment, deriving a simulated topographic map from the environment, then creating 15-30 video clips of walking movement in random locations and directions around the map.
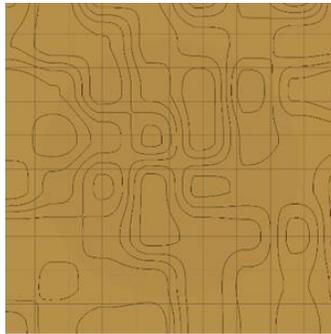
Figure 1: Illustrations of a topographic map and first-person renderings used in an example trial.

Protocol Implementation

The training protocol was implemented in Python within the PsychoPy3 framework, an open-source library of Python functions for implementing experimental psychology research designs.

Explicit Pretraining

Each training protocol began with 5 minutes of didactic instructions explaining the task interface and guiding the learner's attention to key features in interpreting topographic maps with respect to the simulated environments (Figure 2). Hills, Valleys, Saddles, and Ridges were explicitly showcased on the topographic map and in the stimulated environment. Didactic training like this is often provided to a learner early in training to highlight key features of map and environment correspondence (e.g., concentric contour lines indicate elevation change). This knowledge "scaffolding" can guide early skill development in support of correct learning, as it is made clear to the learner what needs to be done and how to do it (Pea, 2004).

Figure 2: Sample pretraining slide, explicitly highlighting a key relationship between contour lines and the simulated first-person environment.

Demonstration and Practice

Following the instruction slides, the experimenter guided the learner through demonstration and practice trials. Three demonstration trials were presented during which participants passively viewed movement through topographic maps and the associated terrain environments side-by-side. Motion was represented on the topographic map as a blue circle marking the location in the terrain environment at a given moment and moving along a white line indicating the total distance covered in the video, simultaneously demonstrating the corresponding movement through the simulated environment and topographic map. Following the demonstration trials, participants completed two practice trials, actively engaging with the training interface described below.

Active Learning with Feedback

Early didactic support and guided demonstrations in training work to prevent the counterproductive consequences of making too many bad decisions early in the learning process, avoiding the unpleasant feeling of "thrashing." However, this alone is insufficient for map reading skill development. Rather than passively learning terrain-based decision making, actively making decisions and receiving feedback increases retention of training content (Slamecka and Graf, 1978). Importantly, it is critical for trainees to be allowed to make some errors, learning the process of error recognition and correction itself (Keith and Frese, 2008; Schmidt and Bjork, 1992).

Response and Feedback

The response and feedback interface are presented in Figure 3. The shaded circle within the map represents a circumscribed region within which the movement through the terrain environment occurs. The center of the circle represents the origin of motion. During the response phase of the task, the participant used the mouse scroll wheel to set the orientation of a blue arrow in the direction they believed indicated the direction of forward movement through the terrain environment. The participant then clicked the mouse to submit their
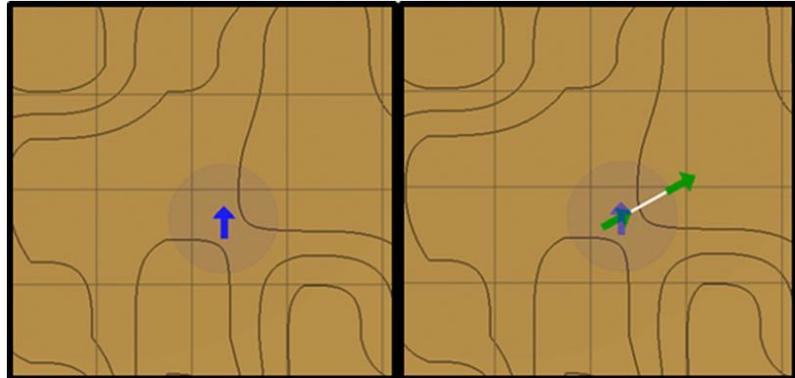

Figure 3: Zoomed-in screenshot of response and feedback interface.

answer once the arrow was set in the desired orientation. Once the participant made a response, a green arrow appeared on the map for several seconds, showing the correct orientation of the simulated movement. Participants were also shown a numeric value that indicated how many degrees separated the blue arrow (their response) and the green arrow (the correct answer). Error was defined as the difference in degrees between the response arrow and the correct orientation of the perspective in the video. All responses with error larger than 90 degrees were considered "incorrect" and were rounded to 90 degrees. This cut-off was chosen to not overly penalize participants for trials where they were guessing or not enough information was provided in the stimuli to make an accurate decision. Variance in performance data is presented as Standard Error of the Mean (SEM), which is the standard deviation of the sampling distribution, providing an estimate of how far the sample mean is likely to be from the population mean.

EXPERIMENT 1

The first round of testing enlisted 10 research subjects. Due to a scheduling conflict, 1 subject withdrew during the training. The initial protocol required each participant to complete 150 terrain decisions over a 45-minute training session. There were 3 blocks of 50 training trials, with each block containing 5 maps with 10 trials each.

began with an untimed map study phase. Participants then initiated a 4 second video of movement through the simulated terrain. Immediately after the video, the map was re-presented and participants were allowed 30 seconds to orient the arrow on the map in the direction they were facing. Immediately following the response, the participant received visual and numeric feedback about the accuracy of their decision.

Results

All participants improved during the 150 training repetitions, with an average orientation accuracy increase of 13 degrees (SEM=2.2) between the first and last blocks of training (Figure 4). A within-subjects ANOVA across the 3 blocks of training indicated that error in orientation was significantly reduced with increased practice, $F(2,898) = 19.7$, $p < .001$. Within-subjects contrasts revealed a significant linear effect across blocks of training, $F(1,449) = 36.9$, $p < .001$.

The training effect differed substantially between learners, with improvements across training blocks ranging from 3.4 to 24.5 degrees of improvement in orientation accuracy. Notably, there was substantial interindividual variability in the rate of performance gains in the last block of training.

Figure 4: Average degrees of orientation error and individual learning curves across the 3 blocks of training.

Learning within each new terrain was also found by collapsing across all maps and looking at orientation error as the amount of experience within a new terrain increased. Learning across the trials within each map was suggested by reliably better performance on the last trial of a map (M=55.3, SEM=2.9) compared to the first trial of a map (M=60.8, SEM=2.8). This suggested that participants were not only improving across the experiment, but also nested within each map was learning to use context-specific knowledge as experience developed beyond their current location.

EXPERIMENT 2

The high individual variability in learning rate during the first round of testing motivated the addition of an adaptive parameter to personalize training. Changing the amount of practice based on the current skill level of the trainee accommodates individual differences in cognitive ability, such as those found in mental rotation (Gugerty and Brooks, 2004; Hegarty and Waller, 2005).

Enrolled in Experiment 2 were 10 research participants. A new set of maps and terrains were procedurally generated for the training set. All procedures were the same as Experiment 1 except that participants were able to advance to the next map in the training set early if they reached an accuracy criterion of 30 degrees of error or less for 2 consecutive trials. With this adaptive parameter, individualized amounts of practice are enabled should the learner's performance indicate that he or she finds a particular map more or less difficult. If participants don't reach criterion, they continue practicing the map until completing all 30 trials of the environment.
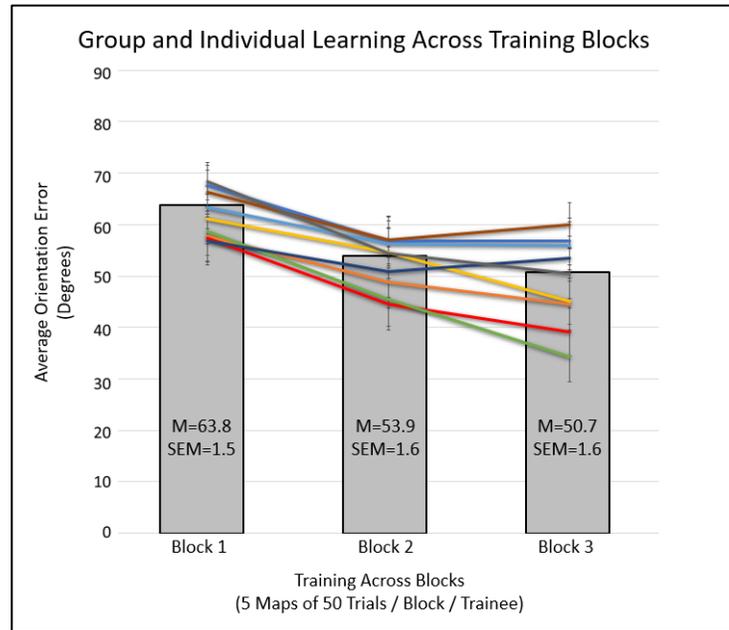
Results

Participants completed an average of 177.5 training trials (SEM=13.4) across 11.3 different maps (SEM=1.2), with an average response time of 6.13 seconds (SEM=0.1). The nature of the adaptive protocol allowed for large differences in the number of maps completed, with some participants only completing 8 maps while one high performer completed 19 maps (Figure 5). The number of practice repetitions also varied substantially between trainees, with a low of 98 training trials and a maximum of 214 trials completed across the 45-minute training session.

Figure 5: Average degrees of error between maps

In post-training interviews many of the participants reported feeling like they were improving at the task. In addition, two participants reported a lot of prior experience with and interest in maps and these participants (4 and 10) completed the most trials and maps across the protocol. The observation that prior experience with map reading led to better performance in our simulation-based training protocol suggests that our procedurally generated stimuli was of sufficient fidelity to tap into externally developed map reading skill.

We observed that there was substantial variability in the difficulty of the procedurally generated terrains for this task. Map 5 is an example of a challenging terrain, taking participants an average of 21.7 trials (SEM=2.7) to complete, with 10 people attempting it but only 6 reaching performance criterion within the 30-trial limit. In contrast, though confounded by practice effects and self-selection of better learners late in the training set, Map 11 is an example of an easier terrain that took an average of 7 trials (SEM=2.3) to complete, with all 4 participants who attempted the map reaching criteria with an average of 34 degrees of error (SEM=4.9). These observations suggested that the training efficacy might be further enhanced by additional curation of the training stimuli to select the most effective stimuli for practicing map reading.

EXPERIMENT 3

The high variability in participant training rates and heterogeneity in terrain difficulty relied upon in adaptive protocols made the extraction of learning curves an ineffective approach to quantifying the improvement over an hour of training practice. In order to better objectively measure learning improvements in these dynamic training protocols, pretest and posttest assessments of orientation performance were added to quantify changes in skill following training.

A total of 12 participants were recruited for this experiment. We reduced the maximum number of repetitions within a map to 15 trials, to avoid spending excess time on unusually difficult or confusing terrains. All other protocol parameters were the same as described in the preceding experiments, with the addition of a pretest and a posttest assessment of orientation performance.

Participants completed a 10-trial assessment before and after the 45-minute training. There were two assessment forms, Form A and B, and the pretest/posttest order was randomized between participants, along with the order of the trials within each test Form. Each trial was a novel map and video pair presented using the same parameters as training, with the exception that no feedback (i.e., no green arrow) was provided. Both Forms were designed to be identical so as to objectively assess performance gains due to training.

Results

Participants completed an average of 78 training trials (SEM=8) across 8 maps (SEM=1), with an average response time of 8.6 seconds (SEM=.17). A paired-samples t-test showed that participants made significantly fewer errors in orientation during the posttest assessment compared to the pretest assessment, $t(11) = 2.76$, $p < .019$. On average, accuracy improved by 9.8 degrees (SEM=3.6) on the post-training assessment, with 10 of 12 participants improving pretest to posttest (Figure 6). The two trainees who did not demonstrate performance improvements progressed slowly through the training, completing as few as 3 maps with 45 total trials throughout training.
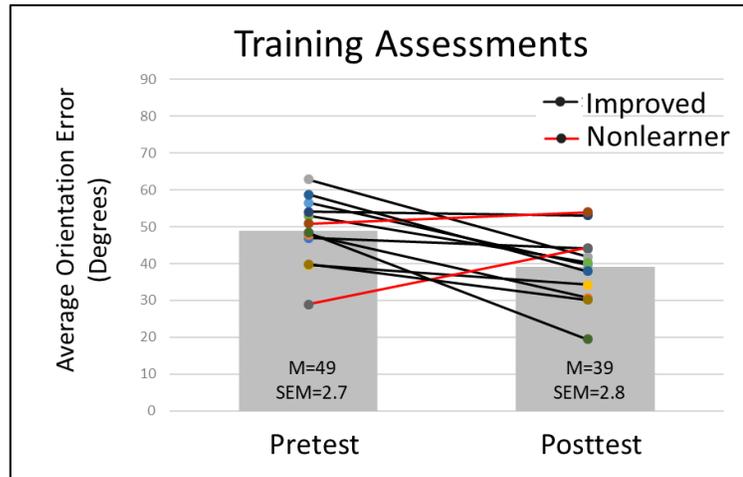

Figure 6: Improvement on the assessments given before and after completing the training protocol.

Form A was given as the pretest for 8 participants while Form B was given as the pretest for 4 participants. Of the 10 participants who improved in performance pre-test to post-test, 7 received a Form A pretest and 3 received Form B pretest. For the two subjects who did not improve in performance, one received Form A first and the other Form B first. Thus, it appears the signal extracted from the no-feedback assessments is likely not a function of differential assessment difficulties and test order. The assessments were also not found to be significantly different from each other, $t(11) = 1.25$, $p=.21$.

Subject-Matter Expert Feedback

To receive additional feedback on the overall training approach, we engaged with the local Naval Reserve Officer Training Corps organization (NROTC at Northwestern University and the Chicago area). All feedback suggests that the general approach should be valuable. We demonstrated the software to the Land Navigation instructor and, based on his suggestions, we modified the first-person videos to incorporate 45 degrees of visual angle left-right scanning of the terrain before forward movement. Two NROTC students completed this training protocol and both participants improved at the task, completing an average of 75 practice trials across 6 maps.

Because of the value of feedback from both subject-matter experts doing training and trainees engaged in Land Navigation training, we are currently pursuing opportunities for a field test with military personnel to supplement the ongoing pilot testing with community participants. Eventually a key milestone for the project will be to quantitatively establish the value of the training for improving field map reading performance (e.g., in orienteering).

EXPERIMENT 4

In an effort to encourage more repetitions and practice, we imposed an 8 second limit each on the study and decision phases of the trials. This duration was chosen based on the average response time of the earlier experiments. A total of 8 participants were recruited for this experiment, with all other procedures the same as described in earlier experiments.

Results

Participants completed an average of 130 training trials (SEM=16) across 12 maps (SEM=1.5), with an average response time of 4.5 seconds (SEM=0.6). Half of the participants improved in orientation accuracy in the second half of training compared to the first, while 3 participants demonstrated improvements on the training assessment.

On average, there were no reliable differences between performance on the pretest (M=48.9, SEM=3.4) and posttest (M=55, SEM=3.4). Though this protocol accomplished a high number of training repetitions, on average participants' error increased between the two assessments (M=-6.16 degrees, SEM=5.54). One outlier subject managed to complete 230 training trials within the 45-minute session, yet this subject had the worst improvement score on the assessments.

EXPERIMENT 5

An alternate display approach was also tested in an effort to decrease the overall error in the task while keeping the number of training repetitions high. Simultaneous presentation of both the map and video can reduce the cognitive load of the terrain decision, which could facilitate learning. A total of 20 participants were recruited for this experiment. For this training protocol, the topographic map and terrain video were displayed side-by-side, collapsing all the separate trial phases described in prior protocols into one simultaneous stimuli display. Participants had 24 seconds to simultaneously study the map, watch the looping video, and orient the map arrow into alignment with the first-person facing direction.

Results

Trainees completed an average of 159.9 training trials (SEM=14) across 16 maps (SEM=1), with an average total trial time of 9.4 seconds (SEM=0.1). There were no reliable group-level differences in performance between the pretest (M=48 Degrees; SEM=2.5) and posttest (M=48 Degrees; SEM=2.8). The 11 participants who did improve on posttest performance had on average 50 fewer training trials (M=138.8; SEM=16.6) compared to participants who did not improve. In the simultaneous display protocol, as the decision-making time is speeded, more maps and repetitions come at the sacrifice of accuracy in orientation performance.

GENERAL DISCUSSION

Using procedurally generated terrain content in simulation-based topographic map reading training, successful delivery of 100 simulation-based decisions was achieved within 45 minutes. Data from 5 experiments demonstrates the feasibility of this approach to successfully improving training of novice users on the basics of orienting a topographic map.

High-Repetitions

The goal of developing a high-repetition map reading training protocol was successful. All trainees successfully completed a high volume of terrain-based decision-making practice. Participants completed no fewer than 50-100 terrain decisions across a 1-hour training session. Efforts were made to maximize the number of repetitions within the 1-hour training session. Through the iterative process of software and protocol testing, the optimal timing parameters were honed for learning in this high-repetition simulation-based trainer. The qualities of the training trials (e.g., time pressures, cognitive workload) were important factors in tempering the number of terrain decisions required of trainees. Using the sequential presentation of terrain stimuli, optimal timing parameters for learning allow for 1-2 terrain decisions per minute (~80 total over 45 minutes of training). Preliminary success in delivering high volumes of practice with this micro-simulation approach is a significant departure from traditional training that focuses on comprehensive exercises.

Learning

Learning signals were extracted from the data collected from 60 participants over 5 different training protocols. In Experiment 1, orientation error decreased across blocks of training, with all participants performing better at the task over the 150-trials of practice. The structure of the learning suggested that, in addition to learning the generalizable skill of topographic map reading across the task, participants were also building mental representations of each new terrain as experience within that specific environment increased. There were large individual differences in learning rates, particularly in the final block of training. This motivated the addition of an adaptive parameter to personalize the protocol.

Trainees were allowed to advance through practice sets faster by demonstrating adequate knowledge of the terrain. The individuals who entered the lab with the most prior experience with topographic map reading advanced the furthest through the training set, reaching knowledge criterion faster for each terrain. This highlights the capability of the software to accommodate variability in prior experience and learning rates in real-time. Group-level learning signals were difficult to extract across adaptive training given the interindividual variability in the protocol, thus learning assessments were used before and after training in Experiment 3 to verify skill development. 10 trials of no-feedback terrain decisions were used to assess performance, with performance on the pretest being compared to performance on the posttest. Having all participants completing the same test maps and trials allowed the researchers to reduce the variability based on stimuli and focus on variability in orientation performance. Significant improvements in orientation error were evident in a posttest assessment of learning following training, with 10 of 12 participants improving in performance compared to the pretest. Efforts to increase practice repetitions further by imposing time pressures in Experiment 4 and changing the stimuli presentation in Experiment 5 did not improve learning.

Multiple cohorts of trainees provide preliminary data on the success of a high-repetition simulation trainer for engaging learning processes. Substantial individual differences in learning are accommodated by a personalized quantity of training based on the current level of skill development of the learner. An individualized learning tool like this might be able to improve performance of novice trainees while scaling to more difficult terrain reasoning for high-level performers.

Conclusion

The CERES approach to training has established the possibility of greatly increasing the sets and reps that can be obtained in simulation-based training of topographic map reading. Within a single hour-long training session, participants completed an average of 80-180 practice trials across the five data collection rounds reported here. This approach provides an opportunity to practice the skill of reading and understanding maps in a manner that was not previously possible. Initial feedback from subject-matter experts has been very supportive that this direction is likely to provide a valuable training resource for a variety of training domains (Land Navigation, Terrain Reasoning) that depend on quickly and accurately understanding the environment from a topographic map presentation.

This approach to training has the potential to provide continual assessments of map reading expertise over training by evaluating performance on no-feedback assessment trials given before and after the training session, as well as accuracy on the training trials themselves. With the protocols currently tested here, the quantitative strength of this learning signal is not yet as robust as our targeted goal. The data collection to date has highlighted challenges related to differences in difficulty of the maps and the potential importance of improving the map fidelity (e.g., by further upgrades to our procedural content generation pipeline).

In addition, we have observed robust individual differences in both learning and performance on the training protocol that appear to be related to pre-training familiarity with topographic maps. This has encouraged us to develop improvements in the adaptive character of the protocol, adjusting difficulty to the individual ability of trainees. However, the fact that pre-training familiarity with maps appears to lead to better performance is an indication that the fidelity of the simulation is sufficient to tap into the general ability to read maps. This observation is encouraging evidence that we can expect a successful transition to field testing of the protocol with military personnel engaged in Land Navigation training (and orienteering).

Having developed a protocol that meets the initial goal of greatly improving the amount of map reading practice that can be accomplished in an hour, future plans are to extend this approach further to multi-hour training sessions to more convincingly establish expertise. Ongoing development will also incorporate planned refinements to content generation and additional adaptive individualized adjustments based on individualized performance measures. These next steps will enable us to deploy a novel, valuable addition to supplement standard training and that synergizes with field experience and accelerates mastery of the skill of map reading.

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