From a submarine to a virtual environment and vice versa

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ABSTRACT

Limited access to operational equipment is a constraint on military training and a principal reason why alternative solutions for training, such as virtual environments (VEs), are needed. Limited access to operational equipment for training is a widely recognized problem that also limits, less obviously, conduct of the behavioral research required to determine training transfer from a VE to the real one. In this study, we assessed the training effectiveness of a VE by an indirect method that did not require access to the operational equipment and by a classic method, which made use of privileged access to a submarine. We wanted to explore an experimental method to help inform the interpretation of future behavioral studies on the training effectiveness of VEs when access to operational equipment is not possible. For these reasons, we conducted two experiments. The first employed a reverse transfer-of-training paradigm that used the VE for learning and evaluation and the second employed a forward transfer-of-training paradigm that used the submarine for learning and evaluation. Each experiment required navy personnel to complete an emergency drill, which involved isolation of a bulkhead within a submarine. Initial transfer-of-training and improvements with practice to criterion (i.e., error-free performance) were used to compare the performances of a trained group with a novice group in each experiment. Although the task is complex, involving procedural, mechanical, and spatial components, the outcomes reported here are for spatial learning only. We focus on this aspect of the task because many costly solutions have been sought to interface humans with VEs for tasks that involve locomotion within extended spaces. Both experiments yield evidence of positive training transfer and indicate that locomotion devices are unnecessary for effective training transfer. They also indicate that the results of a reverse transfer-of-training evaluation do not mirror forward transfer.

ABOUT THE AUTHORS

Lochlan E. Magee is a graduate of the University of Toronto with a PhD in experimental psychology. Since 1980 he has worked as an applied scientist with Defence Research and Development Canada and, in various capacities, has been responsible for the conduct and management of R&D activities associated with the design, use and evaluation of low-cost training simulators for the Canadian Forces. Dr. Magee is also an adjunct professor in the Math and Computer Sciences Department of the Royal Military College of Canada.

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INTRODUCTION

Dwindling access to military equipment is widely recognized as a reason for developing a virtual environment (VE) for training. However, the efficacy of VEs for military training is not well established. A reason is because behavioral research aimed to determine training transfer is similarly hindered by the unavailability of operational equipment. The preferred method of determining training transfer is to make use of the operational equipment as the transfer environment. In this study, we used privileged access to a submarine as an opportunity to assess the training effectiveness of a VE by this method, as well as by an indirect method, which did not require access to the operational equipment. While our main purpose was to determine the training effectiveness of the Victoria Class Virtual Submarine (VCVS), a VE developed by the Royal Canadian Navy eLearning Centre of Expertise (NeLCoE), in Quebec City, we also sought an experimental method that would help inform the interpretation of future behavioral studies of training effectiveness when access to operational equipment might not be possible.

The VCVS is one of several game-based, desktop VEs of the Canadian Virtual Naval Fleet (CVNF) that has been proposed as a solution for training navy personnel who need to gain procedural and spatial knowledge of large naval vessels. We conducted two experiments and compared the results to assess the training effectiveness of the VCVS. The first experiment employed a reverse transfer-of-training (RTOT) paradigm that used the VE for learning and evaluation, and the second employed a forward transfer-of-training (FTOT) paradigm that used the submarine for learning and evaluation. Each experiment required navy personnel to complete an emergency drill that involved sealing a bulkhead within the submarine.

Initial transfer-of-training and improvements with practice to criterion (i.e., error-free performance) were used to compare the performances of a trained group with a novice group in each experiment. Although the task is a complex one, involving procedural, mechanical, and spatial components, the outcomes reported here are for spatial learning only. Additional outcomes are reported by Magee, Thompson, Cain & Kersten (2012). We focus here on the spatial aspect of the task because many costly solutions are offered to interface humans with VEs for tasks that involve self-directed exploration of extended spaces on foot. Various devices (e.g., CyberWalk, Technische Universität München) have been invented to provide a walking interface for controlling self-directed movements within a VE. The interactive experience is thought to be helpful for acquiring spatial knowledge of a large unfamiliar structure such as a submarine, ship, or oil rig. A practical question is: “Is it necessary to interface a learner to this type of VE with a locomotion device in order to achieve successful training transfer?” Our results suggest that it is not.

EXPERIMENT 1: REVERSE TRANSFER OF TRAINING (RTOT)

Method

Task

One of the many emergency drills that must be known by all qualified submariners aboard a Victoria Class submarine is isolation of Bulkhead 35 (BH 35). Submariners must know the locations, names, functions and operation of the valves and tools that are needed to isolate this bulkhead. The task was chosen by subject matter experts (SMEs) because it must be known by all qualified personnel aboard the submarine and because it was judged to be a good example of the type of task that submariners need to be able to perform reliably.

The task is performed differently for different situations. For this study, the shutdown procedure used in the event of a fire was selected. This involves six valves, located on two decks, which can be checked or operated from either side of the bulkhead. The order in which they are checked or shut is not important for successful completion of the task. However, the task is not performed the same way on opposite sides of the bulkhead. The structural surroundings are different, and the location of the valve controls, their direction of operation, their appearance, and the locations and types of tools that might be needed to check or shut the valves differ. Trainees are normally taught the task aboard the submarine (as a small group or individually) and are individually assessed two days later. To satisfy the training criterion, the trainee must be able to perform the task once without error.

Participants

Twenty healthy volunteers medically fit for duty and free of any signs and symptoms of acute illness were recruited as participants. Only males volunteered. The participants included ten Ordinary Seamen (OS) of the Royal Canadian Navy (RCN) who were unfamiliar with the layout of a submarine and ten task-qualified submariners serving aboard Her Majesty's Canadian Ship (HMCS) Corner Brook, a Victoria Class submarine. The naïve participants formed the Experimental (E) group. They ranged in age between 18 and 35 years. The experienced participants formed the Qualified (Q) group; they ranged in age between 26 and 50 years and possessed an average of 13.2 years of experience within the Navy (an average of 9.75 years submarine service).

All participants were informed fully of the details, discomforts, risks and potential benefits associated with the experimental protocol. They provided informed consent and all were compensated for their participation, in accord with the protocol that was approved by the Human Research Ethics Committee of Defence Research and Development Canada.

Virtual Environment (VE)

The VE was presented on a laptop computer running Windows XP with a 15-inch liquid crystal display (LCD). The graphics provided realistic images of the inside and outside of HMCS Corner Brook. Sample imagery of the VE is shown in Figure 1.

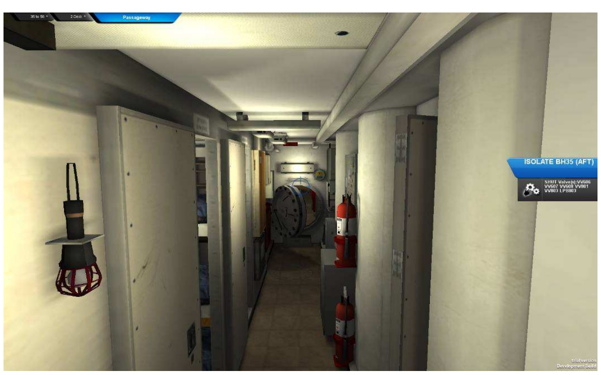

Figure 1. Sample imagery of the VE

Navigation within the VE was controlled with the letters w, a, s and d to move forward, left, back or right, respectively or by use of the directional arrow keys on the keyboard for these movements. The shift key, the control (Ctrl) key, and the space bar were used to run, crouch or jump, while actions to cross a bulkhead, climb a ladder, or use a flashlight were controlled with keys e, r, and f, respectively. The user's point of view (POV) within the VE was controlled with a computer mouse. Forward movement of the mouse tilted the view downward, backward movements tilted the view upward, and movements to the right or left moved the view to the right or left. The gains on these controls were adjusted for easy use.

Experimental Design

A between groups repeated measures experimental design was used (2 groups, 18 trials maximum). All members of both groups participated individually. The members of the E group were informed that their task was to learn the locations, names, functions and operation of the valves needed to perform the task from both the forward and aft sides of the bulkhead. While comfortably seated, within an empty classroom, they were verbally guided through the VE. An experimenter helped each participant locate each valve of the submarine that needed to be operated in order to perform the task. The order in which the procedure was demonstrated (i.e., commencing forward or aft, or on 1 Deck or 2 Deck) was randomized to avoid order effects. During this familiarization session, the participant also learned how to control his movements with the mouse and keyboard and was told the name, method of operation (including any tool use), and function of each valve that needed to be checked or operated.

After familiarization with the interface to the VE and the task, each member of the E group was given a 15-minute rest. All members of the group were told that they would subsequently need to perform the task perfectly to reach criterion, but that they could ask for help at any time and that they would be provided corrective feedback if they made a mistake. They were told to continue to practice the task until they could do it from beginning to end without error or need for help. The practice tasks were delivered in blocks of six trials with a 15-minute rest period in between. A maximum of three blocks (i.e., 18 trials) was allowed.

The members of Q group were also familiarized with the interface to the VE, with the laptop and mouse in front of them on a table, but they received this exposure to the VE while seated in the submarine's wardroom, or one of the mess rooms. Afterward, each submariner in the Q group was asked to perform the task to criterion within the VE. The delivery of the trials was the same as for the E group.

Participants in both groups were told that it was important to take the shortest route between valves so that the total path length would be a minimum distance. This instruction was provided to train wayfinding by encouraging the development of survey knowledge, rather than landmark or route knowledge of the spatial environment (see Lapeyre et al., 2011, for definitions of these three types of spatial knowledge and their effects on wayfinding performance). The participants were also told that the total amount of time needed to complete the task was not important; this instruction was provided primarily for the safety of the members of the E group, who would later be asked to perform the task aboard the submarine in Experiment 2.

All participants began each trial at one of six starting positions chosen randomly. The starting locations were typical work or rest spots not near a valve. The errors made by each participant were recorded as they practiced. Spatial errors included wrong turns and failure to take the shortest route to the next valve. To achieve the task criterion, the participants needed to complete the task perfectly once, without either a procedural or spatial error.

Results

Trials to error-free navigation

We use the first instance of error free navigation as the dependent measure. Procedural errors alone, or together with spatial errors, always determined the number of trials to task criterion, hence most participants received practice at the task beyond the point at which they were able to navigate without error. Thus the results reported in this experiment indicate the number of trials that were needed to achieve error-free navigation and not the number of practice trials that the participants received.

Figure 2 provides a bar graph that cumulates the number of participants in each group able to locate all the valves without error on successive attempts. As shown, eight submariners in the Q group made no spatial error on their first attempt at isolating the bulkhead within the VE. In comparison, no member of the E group was able to perform the task without spatial error on his first attempt. The median number of spatial errors for the E group on trial 1 was 1.5 errors. The difference in the number of errors made by each group on the first trial is significant (Mann-Whitney U = 95.0, p < .001, one-tailed). This result indicates successful transfer of spatial knowledge, from the submarine to the VE. It also indicates that the keyboard inputs do not cause much control difficulty since the experienced submariners were immediately able to navigate successfully within the VE.

Figure 2 also shows that all members of the Q group were able to find their way to the valves without error on their second attempt. In contrast, only three (30%) members of the E group could find their way without error on their second attempt and up to ten trials were needed by other members of this group to achieve task criterion. The median number of spatial errors committed by the E group prior to achieving task criterion was 5.5 errors. A Mann-Whitney U test contrasting the total number of errors committed by the E group with the Q group prior to achieving criterion yields U = 97.0, p < .0001. This outcome further indicates that the qualified submariners were able to apply their spatial knowledge of the submarine within the VE and that they had very little difficulty establishing spatial awareness within the VE.

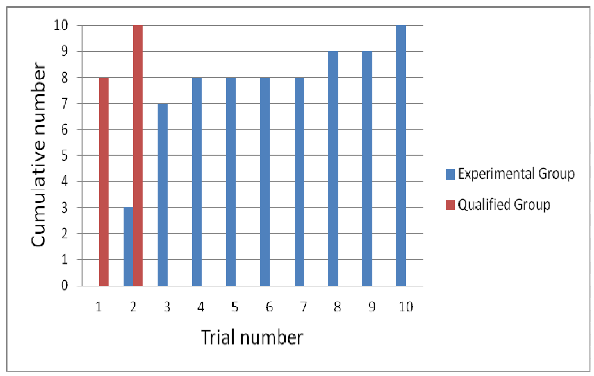

Figure 2. Error-free navigational within the VE

Discussion

The empirical results associated with reverse transfer provide behavioral evidence of the positive training benefits of the VE. Qualified submariners were able to demonstrate the knowledge that they possessed about the spatial environment of the submarine and that it could be used immediately within the VE. The superior performance of the Q group within the VE also indicates that experienced submariners are able to make use of the sensory cues provided by the simulation and that they can adapt readily to its human-computer interface. On this basis, there seems to be no apparent need to improve the fidelity of the visual cues (e.g., larger field-of-view) provided by the VE, or a reason to add other sensory cues to the VE (e.g., sounds), in order to support task performance or learning. There is also no apparent need to add a more elaborate control interface, such as a walking device, to improve wayfinding within the VE.

In comparison to the performance of the Q group, naïve participants in the E group collectively required practice to achieve proficiency within the VE. This outcome is a positive indicator for training transfer since improvement with practice by an inexperienced group indicates that learning is occurring within the VE. Without a clear indication of learning with the VCVS, there would be no reason to expect training transfer to the submarine.

The results shown in Figure 2 also indicate that individuals differ widely in their ability to acquire spatial knowledge from the VE; several participants needed only a few trials to learn their way about the virtual submarine, but other participants required many more trials. This range of ability is found for virtual and real environments (Wolbers and Hegarty, 2010) and it suggests that up to 10 practice trials with the VE could be needed to learn the locations of the valves and the shortest paths between the valves aboard the real submarine.

On the basis of the clear differences in the performance of the Q and E participants on the first trial, and the improvement with practice shown by the E participants, we predict that the spatial knowledge gained by the E group within the VE will transfer positively to the submarine and that the E group will reliably outperform a control (C) group whose members are introduced to the task aboard the submarine. We also predict that the E group will achieve criterion aboard the submarine within a few trials and that up to ten trials might be needed by the C group to demonstrate proficiency following familiarization training. In the next experiment, we test these predictions by examining the extent to which forward transfer of training results mirror reverse transfer of training results. We anticipated that many factors could affect this relationship. For instance, the effect of the difference in the knowledge level of the trained participants in each experiment, and the effect of the difference in the availability of sensory cues or locomotion control within the training environment of each experiment, could independently or interactively affect transfer or learning.

EXPERIMENT 2: FORWARD TRANSFER OF TRAINING (FTOT)

Method

Task

As in Experiment 1, the task was the 6-valve shut down of BH 35. However, in this experiment, the task was completed aboard HMCS Corner Brook. The submarine was docked, and lighted normally (i.e., dimly). Only the duty watch keepers and an occasional maintenance worker were on board. All passageways and access panels were free of unusual obstructions. All participants had to locate, identify, state the function, and specify the appropriate action for each valve and any tool that might be required to complete the task. For safety reasons, the participants were prohibited from actually operating the valves and were informed that the amount of time needed to complete the task was not important. Again, the starting location for each trial was randomly chosen and the order in which the valves were checked or shut did not matter for task completion, so long as the most direct route to each valve was taken.

Participants

Twenty healthy participants medically fit for duty and free of any signs and symptoms of acute illness volunteered to participate. Ten of these were the E group from Experiment 1. The others composed the C group including eight OS and two Leading Seamen (LS) of the RCN who were all unfamiliar with the layout of the submarine. The members of the C group were all males and ranged in age from 20 to 49 years.

All participants were informed fully of the details, discomforts, risks and potential benefits associated with the experimental protocol. They provided informed consent and all were compensated for their participation, in accord with the protocol that was approved by the Human Research Ethics Committee of Defence Research and Development Canada.

Experimental Design

As in Experiment 1, a between groups repeated measures experimental design was used (2 groups, 18 trials maximum). The members of the E group were escorted individually aboard HMCS Corner Brook two days following their training with the VCVS. They were taken directly to the control room to register with the Duty Watch Supervisor and to receive a safety brief (i.e., instructions on evacuation procedures and the operation of the Emergency Breathing System and Emergency Escape Breathing Device). Participants in the E group were then taken directly to one of the six randomly chosen start locations, as in Experiment 1, and asked to perform the task.

Members of the C group were also escorted individually aboard HMCS Corner Brook for registration and a safety briefing. Immediately afterward, they were guided to the six valves necessary to isolate BH 35 on both the forward and aft sides of the bulkhead. They were told the names and functions of the valves, the tools required and the direction of their operation. As in Experiment 1, the order in which the procedure was demonstrated (i.e., commencing forward or aft, or on 1 Deck or 2 Deck) was randomized to avoid order effects. Immediately after the familiarization session, the participants of C group were escorted off the boat by the most direct route possible.

Two days afterward they returned to HMCS Corner Brook. They were again taken to one of six randomly chosen start locations and asked to demonstrate the 6-valve shut down of BH 35 by taking the most direct possible route, stating the names and functions of the valves, and indicating the direction of operation and any tools required.

Each participant continued to attempt to isolate BH 35 until he was able to complete the task once from either side of the bulkhead without error or assistance. The experimenter followed the participant around the submarine to answer questions, to correct mistakes, and to record all errors and requests for help. Participants in both groups were allowed up to 18 attempts, with breaks, as in Experiment 1.

Results

Figure 3 provides a bar graph that shows the cumulative number of participants in each group that with practice succeeded in finding their way to all valves without mistake and by the shortest path.

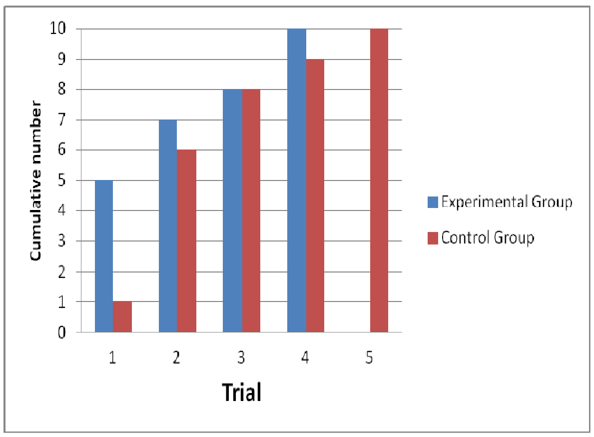

Figure 3. Error-free navigation within the submarine

Five members of the E group (50%) made no spatial error on their first attempt to perform the task aboard the submarine, whereas only one member (10%) of the C group did as well. The median number of spatial errors made by the E group on their first attempt at the task was 0.5 errors whereas the corresponding median for the C group was 2.0 errors. This difference between the performances of the two groups is statistically significant (U = 77.5, p < .02, one tailed). The result has important practical significance since it indicates that spatial knowledge gained with VE practice two days earlier can be transferred directly to the submarine. It means that familiarization training and a modest amount of practice with the VCVS (about 45 minutes) is reliably better than familiarization training aboard the real submarine. However, the benefit of VE training is less evident with subsequent practice aboard the submarine by those who could not demonstrate proficiency immediately.

Figure 3 shows that four attempts at the task aboard the submarine were necessary for the E group to achieve criterion, even though all members of the group had met criterion two days earlier within the VE. In comparison, five attempts, only one more than the E group, were needed for all members of the C group to achieve criterion. This difference between groups is not statistically significant (U = 66.5, p > .05, one tailed), nor is the median number of spatial errors committed by the E group prior to achieving task criterion, 0.5 errors, significantly less than the median number of spatial errors committed by the C group prior to criterion, 3.0 errors (U = 69.5, p =.07, one tailed). Consequently, it appears that the advantage of prior training with the VE was extended to one half of the E group, but not to the other half, since a difference in performance between the two groups is not apparent with practice aboard the submarine.

The main difference between the patterns of results shown in Figure 3 and Figure 2, is that the VE trained group (group E) required more trials to reach criterion aboard the submarine in Experiment 2 than the submarine qualified group (group Q) needed to reach criterion within the VE in Experiment 1; this difference is marginally reliable (U = 68, p < .1, one tailed).

Similarly, fewer trials were needed by the untrained group (group C) to achieve criterion aboard the submarine in Experiment 2, than the untrained group (group E) needed to achieve criterion within the VE in Experiment 1; but this difference is not reliable (U = 67, p > .1, one tailed).

Discussion

The present study employed two experimental approaches, each including immediate transfer and practice phases, to acquire additional behavioral evidence of the validity of the VE without additional need for access to the submarine. The conduct and comparison of the results of reverse and forward transfers of training also afforded an opportunity to compare the outcomes of each method. The goal of this comparison was pragmatic since the classic, forward transfer of training method not only requires access to operational equipment, but can also be very expensive, difficult to implement and sometimes dangerous to conduct (see McCauley, 2006). An RTOT experiment avoids these concerns and provides a method that can potentially reduce uncertainty about the effectiveness of the VE before the conduct of a FTOT experiment. In both experiments reported here, we examined initial transfer and improvement with practice. It is not uncommon for experienced personnel to require a few trials in a simulated environment to adapt to its peculiarities and it is clear from the performance data provided by the Q group in the RTOT experiment that prior experience with the submarine is evident immediately and shortly after initial exposure to the VE. The very clear findings that the experienced submariners in the Q group required many fewer trials in the VE, and made many fewer errors on their way to criterion, than the novices in the E group led us to expect significant positive training transfer to the submarine on the first attempt and on subsequent attempts to achieve error-free performance with practice.

In the FTOT experiment, the benefit of training with the VE was evident on initial transfer to the submarine. The results show that practice with the VE provided novices with spatial knowledge that they could use immediately aboard the submarine and that prior task training with the VE is better than familiarization training aboard the submarine itself. However, the initial advantage provided by VE training was soon lost for two reasons. First, some participants in the E group required as many as four trials to demonstrate task proficiency aboard the submarine, even though they had demonstrated task proficiency within the VE two days earlier. We suspected that the learning criterion we used, in order to match the criterion used by the Navy for submarine qualification, might be a factor because it does not guarantee knowledge of the task from both sides of the bulkhead. Since the task is performed differently on opposite sides of the bulkhead, it is possible that some participants in the E group satisfied the learning criterion in the VE, but had not learned to perform the task completely from the other side of the bulkhead. By chance some members of the E group could have been tested aboard the submarine on a side of the bulkhead that they did not know well. However, an examination of the sequences for forward and aft presentations within the VE and aboard the submarine failed to reveal an effect consistent with this explanation. In fact, two of the five participants in the E group, who navigated without error on their first attempt aboard the submarine, succeeded even though they had not succeeded previously on that side of the bulkhead within the VE. Consequently, it seems more plausible to conclude that achieving task criterion is no assurance against memory loss over two days.

Another reason why the benefits of the VE are not evident with practice aboard the submarine is because the task seems to be learned more readily within the submarine. The median number of trials needed by the E group to learn the task within the VE was 3.5 trials whereas the median number of trials needed by the C group to learn the task aboard the submarine was 2.0 trials. Since there are no known differences between the two groups that would differentiate their learning rates, a simple interpretation is that the submarine provides more sensory cues for learning than the VE thereby allowing the task to be learned with less practice. Although the number of trials taken to demonstrate error-free spatial performance within each environment was not statistically significant, this explanation is consistent with studies of training transfer that generally find transfer effectiveness ratios (TERs) from simulated to real environments that are much less than 1.0 (Fletcher & Orlansky, 1989). In other words, it is common to find that one trial in the real world is worth several in the simulated environment.

Hence, the results of the RTOT experiment provided behavioral evidence for initial, positive FTOT. The results of the RTOT experiment also suggested that very few trials would be needed by the E group to demonstrate proficiency aboard the submarine and that significantly more trials could be needed by the C group. The results of the FTOT experiment mirrored the initial transfer of training results of the RTOT study but not the results of the practice phase. The likely explanation for the differences in outcomes is that the amount of experience with the task possessed by the members of the trained group within each experiment is the important factor. The qualified submariners in the RTOT experiment had many years of experience whereas the experimental participants learned it only once to criterion prior to the FTOT experiment. Consequently, additional training within the VE would likely improve its benefits and increase the similarity of results. Although we did not purposefully vary the amount of practice that the VE trained group received, four of the five participants who found their way about the submarine without error on their first attempt had also practiced the most within the VE because they committed procedural errors that prolonged their practice session and exposure to the VE.

Another possible reason why the results of the FTOT experiment do not fully mirror the RTOT results is because the submarine promotes learning more readily than the VE. The plausibility of these causes and the evidence from the two experiments reported here indicate that training transfer from the VE to the submarine could best be achieved by overtraining with the VE (i.e., by training beyond criterion with the VCVS) and that an estimate of the number of trials that could be saved aboard the submarine should not exceed about 25% of the number needed for a novice group to match the performance of an experienced group within a RTOT study. Since the availability of the VE is much greater than a submarine for training, and since the costs of the VE including its development are much, much less than the daily costs of a submarine at dock, the VE is a very cost-effective approach even if over learning and a low transfer effectiveness ratio are considered.

In sum, the behavioral results obtained in the two experiments that form this study provide converging evidence that the VCVS affords positive training benefits for isolating BH 35, a task that was chosen by SMEs to represent the spatial and procedural drills that qualified submariners need to know in order to respond to an emergency aboard a Victoria Class submarine. It seems reasonable to conclude that the VCVS could be used to train other drills that involve spatial knowledge of the submarine and that VE training can provide spatial knowledge of large structures without a locomotion interface.

ACKNOWLEDGEMENTS

The authors would like to thank the officers and crew of HMCS Corner Brook and the staff of CFB Esquimalt for making this project possible, and the officers, crew, and trainees of HMCS Chicoutimi who took time to provide us with additional feedback on the VCVS. We also wish to thank and acknowledge Major François Gilbert for providing the opportunity to assess the VCVS and for providing the administrative coordination necessary to implement the study. We thank his development team and the instructional designers of the VCVS, including Mr Guy Boulet and Mr Kamil Andrzejewski, who also provided software and technical support for the experimental implementation.

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