Learning and Long-Term Retention of Task-Specific Training in a Non-injured Population Using the Computer Assisted Rehabilitation Environment (CAREN)

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Abstract. Task-specific training in virtual environments (VEs) can provide practice for skills that are transferred to real-world settings. The present study examined skill acquisition and retention of a non-injured population performing a sensorimotor navigation task in the Computer Assisted Rehabilitation Environment (CAREN). Seventeen subjects participated twice weekly for 6 weeks, with follow-up visits at 3-month intervals for one year. Subjects performed a navigation task, where they drove a virtual boat through a scene using weight shifting and body movement. Subjects improved over time on all outcome measures. A significant effect was observed for visit number on total score, time to complete the task, number of buoys navigated successfully, and number of penalties incurred. No differences were observed between the last training visit and any follow-up visit. Task-specific training in immersive VEs may be effective for warfighter operational skills training and rehabilitation of wounded warriors, by utilizing tasks that lead to long-term retention.

Keywords: CAREN · Virtual environment · Task-specific training · Retention · Operational tasks

1 Introduction

Task-specific training has been used successfully in a variety of injured and healthy populations [1–4] and can serve as a method of providing practice before applying the skills in real-world settings. Various studies have analyzed the effect of different methods of training a motor skill and demonstrated that mentally practicing a motor skill provides some improvement in performance [5], but does not serve as a replacement for physical practice [6]. Virtual environments (VEs) have been used to augment practice of motor tasks by simultaneously challenging physical and mental performance, particularly in the field of rehabilitation [7, 8]. VEs can provide feedback to the subject such as body positioning and can even incorporate physiological measurements like heart rate and muscle activity. Some research has shown that augmented

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feedback in a VE has a direct effect on performance of a real task, indicating that the components of the VE can directly relate to rehabilitation or training performance [9]. Distributing practice of a skill across multiple days is an important factor in optimal motor skill learning and retention [10]. Constant training is more effective for skill acquisition, while variable training is more effective for skill retention [11]. Previous work studying task-specific training of the wounded warrior has shown improvements in skill learning and retention in VEs [4]. Additionally, in military and law enforcement populations, more realistic training scenarios have a greater physiological effect on subjects compared with less realistic training on the same skill. These scenarios have also produced greater motivation to succeed in subsequent trainings [12, 13]. The relevance of the training task and multisensory cues are important [14] to its transference to actual task performance.

The Computer Assisted Rehabilitation Environment (CAREN; Motek-Forcelink BV, Amsterdam, The Netherlands) is a VE that has the capability to provide relatively realistic training scenarios. The CAREN consists of a force plate-instrumented treadmill that sits atop a six-degrees-of-freedom motion platform. Visual displays are projected on a large screen and can be synchronized with the platform and/or subject movement. Although previous work has studied task-specific training of motor skills in a variety of environments among healthy and injured populations [15], including patients with stroke, traumatic brain injury (TBI), and lower-limb amputation, little is known about skill learning and retention using the unique CAREN platform. The purpose of this study was to understand the adaptation of healthy, non-injured adults performing a navigation task in an immersive VE and to determine the long-term retention of this task-specific training over time.

2 Methods

2.1 Subject Population

Seven male and 10 female subjects participated in this study. The mean±standard deviation age for the subjects was 29.24 ± 4.41 years and body mass index was 22.97 ± 3.04 kg/m^2. Subjects were healthy and had no known orthopedic injury or other injury affecting their balance, learning, or vision. Volunteers gave written informed consent. This study was approved by the Naval Health Research Center (NHRC) institutional review board.

2.2 Task-Specific Training Program

The task on the CAREN involved a virtual boat navigation course in which subjects stood on the motion platform facing forward and navigated through a slalom course of 50 buoys. Subjects were instructed to use body movement to control the direction and speed of the virtual boat by shifting their body forward, backward, and side-to-side. Reflective markers placed on the subjects' shoulders and captured using an optical motion capture system (Motion Analysis Corporation, Santa Rosa, CA) allowed them to interact with the VE and navigate the virtual boat through the course (Fig. 1).

Fig. 1. A subject navigates a boat through a virtual scene in the CAREN

Platform motion mimicked the movement of the boat through the course and over the waves. Subjects participated in the training twice a week for 6 weeks, for a total of 12 visits. The initial training session occurred at visit 1 and the final training session occurred at visit 12. Follow-up tests were also conducted up to 1 year later at 3, 6, 9, and 12 months following the 12^{th} training visit, for a total of 16 testing sessions.

2.3 Measurements

A total score was calculated using an algorithm that accounted for the number of buoys that were navigated successfully, the number of objects (buoys [−1 point] and islands [−5 points]) hit, the time to complete the task, and specific course parameters (held constant for the sessions in this study: i.e. maximum wave height = 3 m and maximum boat speed = 15 m/s). Study outcomes included total score, number of buoys successfully navigated, penalties for objects hit, and time to complete the course.

2.4 Statistical Analyses

A multiple regression analysis was conducted to evaluate how well each performance variable predicted the overall score. The predictors were completion time, penalties, and buoys successfully navigated, while the criterion variable was the overall task score.

A one-way repeated-measures analysis of variance (ANOVA) was conducted to determine if there were differences in outcome measures over the 12 training visits. When Mauchly's test indicated assumption of sphericity was violated, Greenhouse-Geisser corrected tests were reported. Post hoc tests using Bonferroni correction were conducted to determine if there were significant differences between visits. Only sequential visit-to-visit scores (i.e., visit 1 compared with visit 2, visit 2 compared with visit 3, and so on) and comparisons between visit 1 and all subsequent visits were reported.

Paired *t* tests were conducted on available total scores between visit 12 and the four follow-up visits (3, 6, 9, and 12 months) to determine if the skills of navigating through the virtual boat task were retained. Not all subjects were able to attend all four follow-up sessions, resulting in different N values for each follow-up pairwise comparison. Data analyses were conducted using SPSS statistical software, version 19 (IBM, Armonk, NY). Significance was defined as $p \leq .05$.

3 Results

3.1 Multiple Regression Analysis

All variance inflation factors were between 1 and 2, indicating that multicollinearity was not an issue. The linear combination of the performance variables was significantly related to the overall task score, $F(3, 193) = 923.0$, $p < .005$, $R^2 = .935$, $R^2_{adjusted} = .934$, indicating that the model explains more than 93% of the variance in overall score. Evaluation of each of the variables indicates that all three variables significantly contributed to the prediction of the dependent variable (score) in the model. Overall score was significantly predicted by the number of penalties (beta = −.30, $t(193) = -14.81$, $p < .005$), task completion time (beta = −.45, $t(193) = -21.85$, $p < .005$), and buoys successfully navigated (beta = −.49, $t(193) = 22.89$, $p < .005$). From these results, the number of buoys successfully navigated made the strongest unique contribution to total score, followed by task completion time, and lastly, number of penalties.

3.2 Total Score

Total scores ranged from 1006 to 1440 points. Improvements were shown in all individuals over the 12 training visits (Fig. 2). Results showed a significant effect for visit number, $F(4.40, 70.36) = 29.975$, $p < .001$. Post hoc comparisons indicated no significant difference in total score for any sequential visits. Average total scores over the 12 training visits significantly improved, displaying an increase of 241 points between visit 1 and visit 12 ($p < .001$). Between visits 1 and 2, mean score on the task increased by 109.71 points, the largest difference in score between consecutive visits, but was not significant ($p = .138$). Other consecutive visit differences were between 0.47 and 33.18 points. All other visits (3 through 12) were significantly different from visit 1 (comparison of visits 1 and 3, $p = .011$; all other visits, $p < .001$). No significant differences in scores were reported between the final training visit and any of the follow-up visits (Table 1).

3.3 Time to Complete the Task

Time to complete the course improved over the 12 training visits. Results showed a significant effect for visit number, $F(2.75, 43.92) = 74.297$, $p < .001$. Post hoc comparisons revealed significant differences in number of seconds to complete the boat task

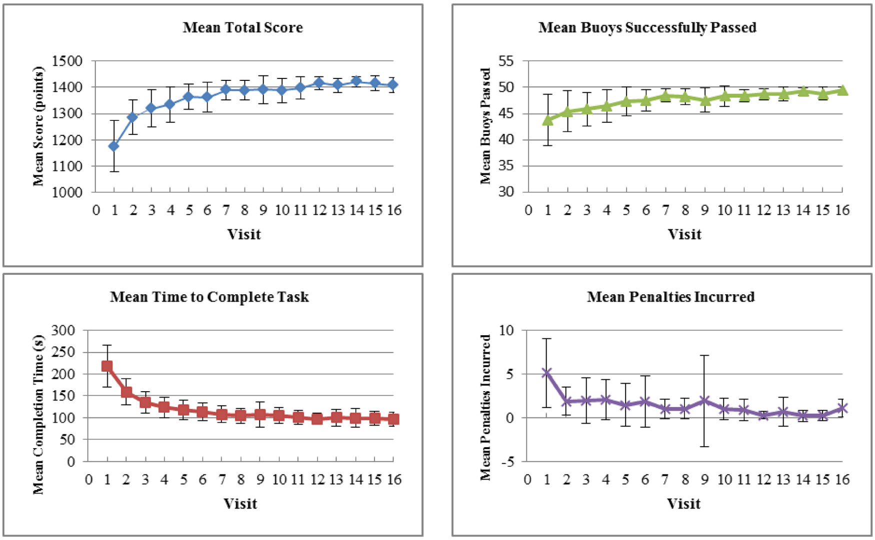

Fig. 2. Mean and standard deviations of total score, time to complete, buoys passed, and penalties incurred across the 16 visits. Follow-up visits at 3, 6, 9, and 12 months are labeled as Visit 13, 14, 15, and 16, respectively.

Table 1. Comparison of Visit 12 with follow-up visits for total score.

Pair	Variable	*N*	Total Score *M* (SD)*	*t* Score	*p* Value	95% CI
1	Visit 12	9	1416.44 (28.07)	0.67	.525	−21.66 to 39.22
	3-month follow-up		1407.67 (27.51)			
2	Visit 12	10	1414.50 (27.02)	−0.80	.445	−29.53 to 14.13
	6-month follow-up		1422.20 (19.61)			
3	Visit 12	15	1416.13 (24.84)	0.05	.958	−18.16 to 19.09
	9-month follow-up		1415.67 (27.33)			
4	Visit 12	16	1415.38 (24.38)	1.00	.332	−9.08 to 25.21
	12-month follow-up		1407.31 (28.11)			

Note: CI, confidence interval; M, mean; SD, standard deviation.

between visits 1 and 2 ($p < .001$), visits 2 and 3 ($p = .003$), and visits 3 and 4 ($p = .032$). Pairwise comparisons for additional sequential visit pairs yielded no significant results. The largest decrease in time for consecutive visits was between 1 and 2 (mean difference = 83.47 s). In one comparison (visits 8 and 9) mean time *increased* between visits by 3.47 s. Mean completion time decreased by 120.7 s and was significantly different ($p < .001$) between visits 1 and 12. No significant differences were observed between the final training visit and any of the follow-up visits (Table 2).

Table 2. Comparison of Visit 12 with follow-up visits for time to complete boat navigation task.

Pair	Variable	*N*	Time to Complete Task, *M* (SD)*	*t* Score	*p* Value	95% CI
1	Visit 12	9	95.54 (12.16)	−0.78	.456	−19.29 to 9.51
	3-month follow-up		100.33 (19.41)			
2	Visit 12	9	98.44 (15.80)	−0.18	.862	−12.30 to 10.52
	6-month follow-up		99.33 (21.98)			
3	Visit 12	16	98.19 (13.22)	0.04	.969	−6.56 to 6.81
	9-month follow-up		98.06 (15.76)			
4	Visit 12	16	98.06 (13.34)	0.43	.674	−5.20 to 7.82
	12-month follow-up		96.75 (15.99)			

Note: Time is in seconds. CI, confidence interval; M, mean; SD, standard deviation.

3.4 Number of Buoys Navigated Successfully

The number of buoys navigated successfully increased over the 12 training visits from a mean of 43.57 to 48.57 (p = .147) (Fig. 2). Number of buoys successfully passed for individual subjects ranged from 35 to 53. Results showed a significant effect for visit number, $F(3.89, 50.60) = 4.372$, p = .004. Post hoc results indicated no significant difference in number of buoys passed for any visit pairs (Table 3).

Table 3. Comparison of Visit 12 with follow-up visits for number of buoys passed.

Pair	Variable	*N*	Buoys Passed, *M* (SD)*	*t* Score	*p* Value	95% CI
1	Visit 12	8	48.75 (1.16)	.55	.598	−0.82 to 1.32
	3-month follow-up		48.50 (1.07)			
2	Visit 12	8	48.63 (1.06)	−1.49	.180	−1.62 to 0.37
	6-month follow-up		49.25 (0.71)			
3	Visit 12	14	48.64 (1.15)	−0.33	.745	−1.07 to 0.79
	9-month follow-up		48.79 (1.25)			
4	Visit 12	14	48.79 (1.05)	−2.59	.022	−1.18 to −0.11
	12-month follow-up		49.43 (0.65)			

Note: CI, confidence interval; M, mean; SD, standard deviation.

3.5 Number of Penalties Incurred

The number of penalties incurred by individual subjects ranged from 0 to 20. Results showed a significant effect for visit number, $F(3.77, 60.43) = 4.060$, p = .006, though post hoc comparisons indicated no significant difference in the number of penalties incurred for any sequential visit pairs. Average number of penalties incurred over the 12 training visits improved, decreasing by 4.82 penalties between visits 1 and 12 (p = .006). Significant decreases occurred between visits 1 and 7 (p = .025), 1 and 8 (p = .013), 1 and 10 (p = .016), and 1 and 11 (p = .013). No significant decreases were observed for any other pairs or the follow-up visits (Table 4).

Table 4. Comparison of Visit 12 with follow-up visits for number of penalties incurred.

Pair	Variable	*N*	Penalties, *M* (SD)*	*t* Score	*p* Value	95% CI
1	Visit 12	9	0.44 (0.53)	−0.45	.665	−1.36 to 0.92
	3-month follow-up		0.67 (1.66)			
2	Visit 12	10	0.30 (0.48)	0.56	.591	−0.31 to 0.51
	6-month follow-up		0.20 (0.63)			
3	Visit 12	15	0.33 (0.49)	0.37	.719	−0.32 to 0.46
	9-month follow-up		0.27 (0.59)			
4	Visit 12	16	0.31 (0.48)	−2.78	.014	−1.43 to −0.19
	12-month follow-up		1.13 (1.02)			

Note: CI, confidence interval; M, mean; SD, standard deviation.

4 Discussion

The results of this study indicate that task-specific sensorimotor skills improved with regular exposure to a navigation task in an immersive VE. Additionally, these skills were retained without practice for up to one year following the training program. Total score and the elements that comprised the total score (time to complete the boat navigation task, number of buoys navigated successfully, and number of penalties incurred) improved as a function of visit number across the 12 training visits. Although significant differences were not observed in sequential visits, there were significant improvements across the visits as a whole.

The greatest improvements in time to complete the task were observed between the first three visits, with smaller improvements thereafter. This is similar to previous work in which two groups showed improvements on a timed motor sequence task between days 1 through 4 of training, reaching a plateau in performance by days 4 through 5 [10]. Other work shows improvements in military operational performance after at least 3 visits using VE training [16], including significant improvements in driving performance of military personnel who had suffered a TBI after 4 to 6 training sessions of simulated driving in a VE [17]. Our results match published work, showing most learning occurs within the first four sessions of training. Work in other areas related to the CAREN has shown that six training sessions is sufficient for motor training [4], but more research is needed. No significant differences in scores, time to complete the boat navigation task, number of buoys navigated successfully, or number of penalties incurred were observed between visit 12 compared with any of the four follow-up visits. This indicates that the task-specific skill was retained long-term and provides support that the 12-visit program over the 6-week period was effective for providing the necessary training to teach and retain this specific skill for up to a year. This matches well with previous reports that suggest there are few declines in performance after a motor skill task is well-learned, even after a long delay with no practice [10, 18, 19]. Although VEs are widely used in military operations training (e.g., flight simulators, infantry immersive trainers), further research demonstrating the effectiveness of training in VEs compared with other types of instruction, such as field-based and classroom-based training, is needed.

The results from this study are useful for comparison with injured populations. Recently, researchers at NHRC and Naval Medical Center San Diego have used the same boat navigation task in the CAREN VE as a method of vestibular physical therapy for wounded warriors with TBI. Preliminary findings show patients who underwent 12 training sessions over a 6-week period started out with significantly lower scores than the non-injured control group, but were able to achieve similar scores by visit 12 [20]. This work provides support for the 12-visit training protocol in the CAREN VE as an effective program for providing task-specific training for patient populations, and it may be used to inform rehabilitation programs for other injuries such as musculoskeletal injury or amputation. Use of VEs for training injured warfighters is not meant to replace traditional therapies, but rather to provide patients with an alternative form of therapy that supports current strategies and is relevant to real-world scenarios [21]. In addition to providing a safe and controlled learning atmosphere for training healthy and injured warfighters, the CAREN platform also provides a tool for measurement and assessment of performance.

5 Conclusions

After training in an immersive VE, the acquisition of a novel skill seems to be quickly acquired and retained in a healthy, non-injured population. Task-specific training in an immersive VE can be useful for warfighters to acquire and practice skills before applying those skills in an operational setting. Task-specific training in the immersive VE may also be useful for rehabilitating injured populations, since specific movements can be practiced while the patient is within a safe, controlled setting. Capabilities of this VE training have implications for returning injured warfighters to duty due to the potential for positive physical and cognitive performance gains. Details of this work can be used to plan duration of training programs in the immersive VE for subjects or patients to obtain maximal performance results.

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