Better Retention of Skill Operating a Simulated Hydraulic Excavator After Part-Task Than After Whole-Task Training

Joey C. Y. So, **Robert W. Proctor**, and **Phillip S. Dunston**, Purdue University, West Lafayette, Indiana, and **Xiangyu Wang**, Curtin University, Perth, Western Australia, and Kyung Hee University, Seoul, Korea

Objective: We examined whether part-task training produces better learning and retention than whole-task training of a trench-and-load task performed on a hydraulic excavator simulator.

Background: For complex perceptual-motor tasks that involve several components and require spatial awareness of the environment, part-task training will be effective if the benefit of being able to focus attention on each component outweighs the cost of integrating the components. We predicted that such would be the case for learning to operate an excavator.

Method: A part-task training group practiced separate Carrier Positioning, Trenching, and Truck Loading modules, whereas a whole-task training group practiced the Trench and Load module, which combines elements from the other modules. The latter module, involving different scenarios, was performed by both groups immediately after training and following a 2-week retention interval.

Results: Production rate on the trench-and-load task was better overall on the retention test than on the immediate test. The part-task group showed improvement on the retention test compared with the immediate test, whereas the whole-task group did not. The part-task group showed higher productivity rates than did the whole-task group on the retention test.

Conclusion: Part-task training on the excavator simulator results in better skill retention than does whole-task training. The benefit of part-task training is likely to be found for other tasks requiring control of implements in various environments.

Application: Part-task training can result in better retention of complex perceptual-motor skills involving several components, even when immediate transfer to the whole task does not show better performance than whole-task training.

Keywords: part-whole training, part-task practice, whole-task practice, simulator training, hydraulic excavator simulator

Address correspondence to Joey C. Y. So, School of Industrial Engineering, Purdue University, 315 N. Grant St., West Lafayette, IN 47907; e-mail: soc@purdue.edu.

HUMAN FACTORS
Vol. 55, No. 2, April 2013, pp. 449-460
DOI:10.1177/0018720812454292

INTRODUCTION

Virtual-reality simulators can be of value when field training involves expensive, logistically difficult, and hazardous tasks, as is the case for operation of heavy construction equipment (Rezazadeh, Wang, Firoozabadi, & Golpayegani, 2011). Commercially available training simulators are modeled after specific models of real equipment, and the equipment manufacturers promote these simulators, which feature different lessons and tasks intended to develop skills in basic machine controls, proper operator technique, and safe job site operation. Much human-factors research has been conducted on simulator training relating to fidelity of flight simulators and design of effective training routines (Koonce & Bramble, 1998), fidelity of driving simulators (Boyle & Lee, 2010), sports expertise (Williams & Ward, 2003), and surgical procedures (Dunkin, 2010; Tan & Sarker, 2011).

However, research on simulator training for operators of construction equipment is limited. Hildreth and Stec (2009) and Hildreth and Heggestad (2010) sought to verify skill development and transfer from motion and zero-motion construction equipment simulators. They compared anxiety levels with those experienced with training on real equipment but did not explore influences from alternative designs of the practice routines. Consequently, proof of the principles and standard curricula for efficient use of construction equipment operator-training systems is still not found in the literature. More in the way of systematic experimentation on use of these virtual-reality systems is needed to demonstrate what factors affect acquisition and retention of skills as well as transfer of those skills to operation of real equipment.

The backhoe loader, for example, is the most versatile machine on construction sites, involved in most projects. Being a skilled operator requires thorough understanding of the machine's capabilities, the principles behind its operation, and thousands of hours of practice (Ober, 2010). Other construction equipment with which a skilled operator must become proficient includes excavators, graders, and dozers. It is crucial to determine effective training for these various machines as well as whether skills at operating one machine transfer to the others. The conditions of practice that help trainees optimize performance are a fundamental issue for skill acquisition (Healy & Bourne, 2012). Because skill acquisition implies an enduring change (Schmidt & Lee, 2011), performance after a retention interval is often used as an indicator of skill acquisition. Skill also implies an ability to perform related tasks effectively, which leads to tests of transfer to other task environments as another measure of skill learning. The goal of any simulator training method is to produce trainees with the requisite perceptual, cognitive, and psychomotor skills, and the effectiveness of alternative methods is evaluated through retention and transfer measures.

One dimension of training is that of practice conditions (Raymond, Healy, & Bourne, 2012). A key issue for training, including that conducted with simulators, is whether the trainee should practice the task as a whole or in parts that are later combined (Holding, 1965). The effectiveness of part-task training depends on the nature of the whole task and characteristics of the component part tasks (Goettl & Shute, 1996; Healy, Schneider, & Bourne, 2012; Murray, 1981). Some results also suggest that the relative effectiveness of whole- and part-task training varies by the type of skill (e.g., cognitive, perceptual-motor) required for the task (e.g., Gopher, Weil, & Siegel, 1989; Peck & Detweiler, 2000). For example, Lim, Reiser, and Olina (2009) investigated the effects of part- and whole-task training on acquisition and transfer of the cognitive skill of preparing a grade book using a spreadsheet. Their results indicated that whole-task training facilitated acquisition and transfer of such skill. The possible benefits of whole-task training include enabling learners to integrate the knowledge and skill components and to coordinate them in performance of the complete task (van Merriënboer & de Croock, 1992).

However, part-task training has also been shown to be beneficial in several settings (e.g., Whaley & Fisk, 1993; Wightman & Lintern, 1985). For example, using a cognitive-prediction task, Naylor and Briggs (1963) provided evidence that a complex task with loosely interrelated components benefits from part practice. As another example, Newell, Carlton, Fisher, and Rutter (1989) showed for a perceptual-motor video game called *Space Fortress*, an advantage of part practice in facilitating overall task performance because of the use of "natural" response components in each part. Part-task training also has been used to teach technical skills, such as laparoscopic surgical procedures (Beaubien & Baker, 2004; Sprick, Owen, Hein, & Brown, 2011), and team performance skills for pilots using PC-based flight simulators (Jentsch & Bowers, 1998). Part-task training allows trainees to practice their technical and teamwork component skills to predefined standards without being distracted by irrelevant information and other aspects of the task (Ewy et al., 1987; Frederiksen &White, 1989).

Unlike the more widely studied flight and driving training simulators, which focus training on the tasks of navigating and maneuvering vehicles, construction equipment operation requires attention to tasks of cutting, moving, and processing material by means of specially designed machine "implements" (Tatum, Vorster, Klingler, & Paulson, 2006). Bernold (2007) cited efficient handling of the implement as a key indicator of operator skill. Thus, heavy-equipment training simulators should be designed to promote development, appraisal, and transfer of the complex perceptual-motor skills involved in both navigation and the efficient handling of the implements to accomplish productive work (Wang & Dunston, 2005).

In this study, a simulated hydraulic excavator, one of the most common pieces of heavy construction equipment, was used to compare training methods for performing a specific construction task, *trench and load*. This task requires that the operator position the excavator between a dump truck and trenching area, dig soil from the trench, and then dump the soil into the truck. These task components are performed in sequence, enabling comparison of part-task training on the components with whole-task training. The former allows attention to be focused on the respective components rather

Figure 1. Simulator setup.

than being distributed across them. If the benefits of learning each component without distraction from other task requirements outweigh the costs associated with having to integrate those components when transferred to the whole task, then part-task training should yield better learning than whole-task training. Customarily, transfer and retention tests are used separately to evaluate skill learning. In the present experiment, though, we examined transfer to the whole-task both 5 min after the training and after a 2-week retention interval.

METHOD

Participants

For this study, 42 Purdue University students (24 males and 18 females, distributed evenly across the part- and whole-task groups), ages 19 to 34 years (M = 23.5, SD = 2.8), volunteered to participate. All were right-handed, were physically capable of operating the simulator, and had no experience operating construction equipment. They received $20 for their participation after completion.

Apparatus

All tests were performed with the use of Simlog's PC-based Hydraulic Excavator Personal Simulator, which simulates a Caterpillar 320CL hydraulic excavator. This system was installed on a desktop computer with a 19-in. LCD Dell color monitor, speakers to each side of the monitor, and original equipment manufacturer joystick controls (see Figure 1). Participants were presented with a virtual scene from the perspective of a person in the excavator cabin. They controlled the virtual excavator via the joysticks, which mimic the controls of an actual excavator. Each joystick could move in four directions: up (forward), down (backward), left, and right. There was a button on the top of each joystick. The button on the left control, called the "horn button," was used to end a trial of a task; the button on the right control, called the "travel-mode button," was used to shift control function of the joysticks from carrier driving to bucket motion and vice versa.

Experimental Task and Design

The experiment involved three phases: training, immediate test, and retention test. All phases involved training modules provided as part of the simulator software. Participants were randomly assigned to one of the two training-method groups: part task and whole task.

The part-task group performed separate Carrier Positioning, Trenching, and Truck Loading modules. The objective of the Carrier Positioning module was to learn to position the tracks by driving the hydraulic excavator in the forward direction. In each trial (simulation exercise), the target position of the hydraulic excavator was indicated by a pair of red "wire-frame" outlines of the same size and shape as the excavator tracks. The outlines changed color (from red to green) as the tracks "fit in." For each trial of the Trenching module, the bucket was empty and the excavator was positioned at one end of the trench to be dug, ready for digging (in "bucket-motion mode"), and the boundaries of the trench were marked in red. In the Truck Loading module, the trainees had to partially load the articulated truck by dumping the contents of the bucket of the hydraulic excavator. Each trial began with the bucket full and positioned to the side of an empty truck.

The whole-task group performed the Trench and Load module, which combined elements from the Carrier Positioning, Trenching, and Truck Loading modules. For each trial, the excavator bucket was empty, and the excavator was positioned some distance away from the trench to be dug (target area indicated by a red rectangle on the ground), with an empty articulated dump truck

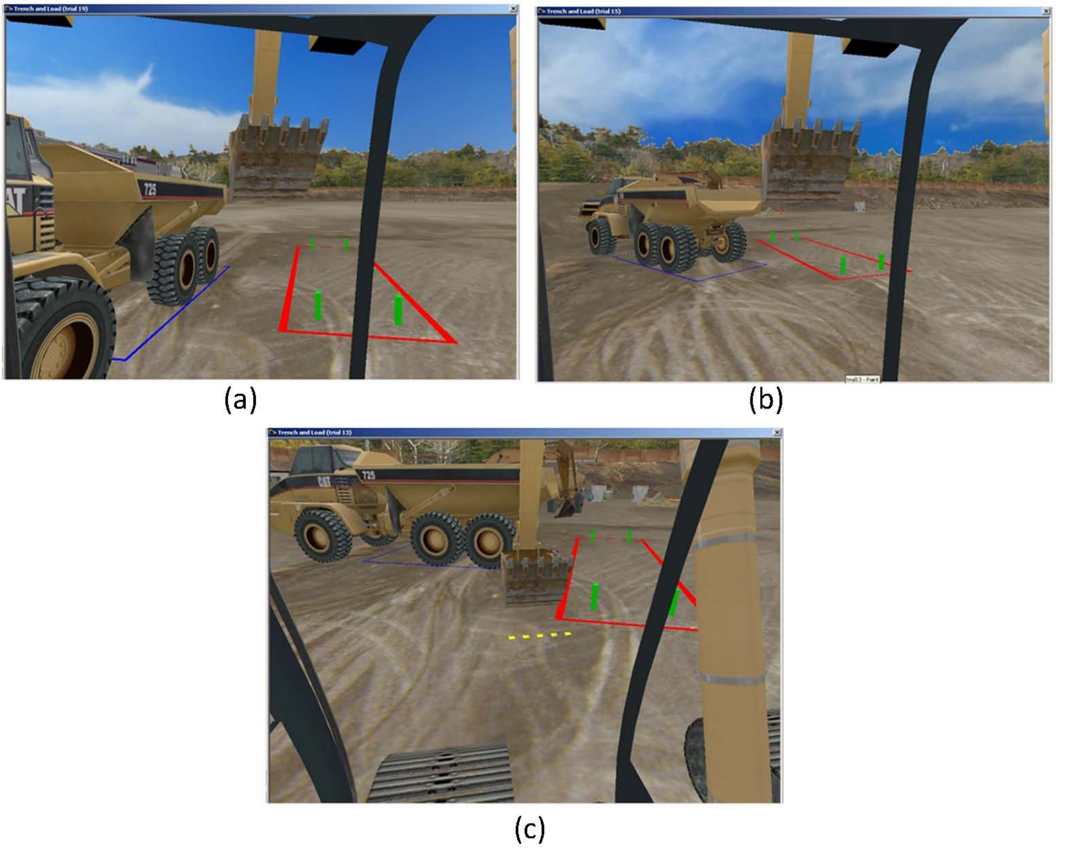

Figure 2. Screen captures from the three trench-and-load scenarios distinguished by excavator position relative to the truck: (a) front, (b) back, and (c) side. (a) The excavator was positioned beside the front of the truck where the view of the back of the truck was inhibited (Trial 2). (b) The excavator was positioned to load directly into the back of the truck (Trial 3). (c) The trenching area was at the rear and perpendicular to the truck (Trial 13). The actual displays were in color.

ready for loading near the trench area. For all modules, the execution time was the elapsed time from the beginning of a trial until the participant activated the horn button on the left joystick to terminate the trial after finishing the transfer of six buckets to the truck. A "Results" window was then displayed until the user activated the horn button again to start the next trial.

For the immediate and retention tests, three specific trials (Nos. 2, 3, and 13 from the Simlog's Trench and Load module set), with different trenching locations and loading-truck positions (loading from the back of the truck with the trench nearly parallel to the truck, from beside the front of the truck with the trench parallel to the truck, and from the side with the trench at the rear and perpendicular to the truck; see Figure 2), were presented randomly and tested in a secondary analysis. These distinct configurations were representative of the full set that is programmed into the simulator and therefore were selected for task consistency and to reveal their influence on performance, since they differ in how they facilitate visual comprehension of the task. The factors and levels studied were two sessions (immediate, retention), six trials (1 to 6) within each session, and two training methods (part task, whole task). Sessions and trials were within-subject factors, whereas training method was a between-subjects factor.

Several performance parameters were recorded, including execution time (elapsed time since the beginning of the trial), volume removed from the trench (amount of material dug within the trench target), volume transferred to truck (amount of material dumped into the truck body), number of bucket slams (incidence of the hydraulic cylinder reaching its limit when opening or closing the bucket), and number of collisions (of the bucket with the ground, a part of the excavator, or the truck). Bucket slams and collisions were counted separately because they indicate fundamentally different aspects of performance, fine control and spatial awareness, respectively.

Procedure

Task introduction and control familiarization. Participants were informed of the study's aim and that the goal was to obtain the highest productivity with fewest errors. The first phase of experimentation, skill acquisition, involved two parts. Part 1 started with an introductory lesson that described the parts and basic functions of the excavator and the corresponding operation of the joystick controls, followed by practicing the Control Familiarization module. In Part 2, participants performed part-task or whole-task practice. Part 1 lasted approximately 20 min.

In the introductory lesson, formal instruction was provided to introduce participants to the excavator simulator controls and their functions. Both groups received an audiovisual presentation about hydraulic excavator basic control functions. The presentation explained the excavator's components that the operator could control—cabin, boom, stick, and bucket—and introduced the eight movements of those components with corresponding joystick movements.

After the introduction, participants were seated at the simulator and performed Simlog's Control Familiarization module to learn the necessary perceptual-motor skills to perform later prescribed tasks. The module provided a command for each trial that instructed the participant to perform one of the eight component actions described previously. For example, if a command "Activate Swing Left" appeared at the top of the display, the participant had to read it, recall the appropriate control action, and then move the correct joystick accordingly. A summary of results appeared after the function was activated to the required extent correctly. The participant then pressed the "Next" button to begin the subsequent trial. Each participant had to complete 50 trials.

Part- and whole-task training. In Part 2, participants in the whole-task group completed three instances of the trench-and-load task, each of which had a specific excavator position relative to the truck body while digging: Back (Trial 1), side (Trial 6), and front (Trial 9) were selected and practiced in the same order by all participants. In each task, participants were to align the excavator with the trenching area and then dig and transfer six buckets of soil to the truck. To maintain an equivalent amount of time on training, the part-task group performed the first 3 trials of practice on the Carrier Positioning module, the first 3 trials (6 buckets per trial) of the Trenching module, and the first 18 trials (3×6) of the Truck Loading module.

Immediate test (Session 1). After the training session, participants received a 5-min break and then were asked to execute a whole-task performance (trench-and-load task). They were given six trials of the task with each of the three excavator positions relative to the truck body, presented in random sequence. In each trial, participants were told to drive and position the excavator until it aligned with the trenching area and then to dig and transfer six buckets to the truck. The six test trials were different from the three trials during practice for the whole-task group. A summary of results, built into the simulator software, appeared at the end of each trial. It included execution time, volume removed from the trench, volume transferred to truck, number of bucket slams, and number of collisions.

Retention test (Session 2). Participants returned to perform a retention test 2 weeks after completing Session 1. The retention test was conducted in the same manner as the immediate test in the primary session, with participants asked to perform the whole task again. As in the immediate test, a summary of results appeared at the end of each trial.

RESULTS

Control Familiarization

Mean execution time and error rate of the four control functions of the excavator for the Control Familiarization module as a function of

TABLE 1: Mean Execution Time and Standard Deviation in Seconds and Number of Errors for Different Basic Control Functions of the Controls Familiarization Module

	Execution Time				Number of Errors			
	Whole Task		Part Task		Whole Task		Part Task	
Function	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Bucket	4.12	2.02	3.64	0.91	6.24	5.52	4.76	3.73
Stick	3.61	1.20	3.61	1.07	3.71	4.19	3.90	5.58
Boom	3.76	1.76	3.53	0.87	4.48	4.70	4.57	4.91
Swing	2.58	0.63	2.66	0.57	1.48	3.50	0.67	1.39

Note. Swing motion (left or right) was found to be significantly faster and to display less error rate than the other control functions (*p*s < .001).

TABLE 2: Whole-Task Group: Mean Production Rate (m^3/hr), Number of Collisions, and Number of Bucket Slams for the Three Practice Trials

Practice Trial	Production Rate	Collisions	Bucket Slams
1	29.64 (15.04)	2.24 (3.99)	7.14 (3.84)
2	40.00 (15.64)[a]	2.00 (2.19)	6.43 (2.68)
3	38.03 (11.61)[a]	1.57 (2.11)	5.57 (2.56)

Note. Standard deviations shown in parentheses.
[a]Production rate improved significantly in the second (p = .001) and third (p = .007) trials compared to the first trial.

training group are shown in Table 1. ANOVAs with training group as a between-subjects factor and control function as a within-subject factor were conducted on these measures. For the within-subject terms of the reported ANOVAs, the Huynh-Feldt correction for violations of sphericity was applied, and the adjusted degrees of freedom are reported when appropriate. Control function had a significant effect on execution time, $F(2.67, 109.35) = 17.10$, $p < .001$, and error rate, $F(2.42, 99.34) = 8.18$, $p < .001$. Bonferroni multiple-comparison tests showed that participants activated the swing motion (left or right) faster than the other control functions (*p*s < .001), with a lower error rate (*p*s < .05). Training group showed no main effect or interaction for either measure, *F*s < 1.0, indicating that the groups were similar in performance prior to receiving the training.

Training

The total training time for the whole-task method was the sum of execution times for the three trials of the trench-and-load task. Similarly for the part-task method, the total training time was the sum of the execution times for all trials of the three part tasks: carrier positioning, trenching, and truck loading. A one-way ANOVA revealed no difference in total training time between part-task (M = 1,624 s) and whole-task (M = 1,635 s) training, $F < 1.0$.

Production rate (m^3/hr) in the trench-and-load task was the total volume transferred from the trench to the truck, divided by the time spent on trenching and loading (i.e., total execution time minus the time on carrier positioning). The production rate (across six bucket loads), number of collisions, and number of bucket slams in the three practice trials for the whole-task group are shown in Table 2. A one-way ANOVA showed a practice effect on production rate, $F(2, 40) = 10.13$, $p < .001$, which was lower in the first trial (29.6 m^3/hr) than in the second and third trials (*M*s = 40.0 m^3/hr and 38.0 m^3/hr). No significant difference was found across practice trials for number of collisions, $F < 1.0$, and bucket slams, $F(2, 40) = 2.11$, $p = .134$.

TABLE 3: Part-Task Group: Mean Time (in Seconds) for Carrier Positioning and Productivity (m^3/hr) for Trenching and Truck Loading During Training

Practice Trial	Carrier Positioning[a]	Trenching	Truck Loading
1	71.62 (9.48)	47.89 (3.67)	82.18 (42.68)
2	92.43 (14.18)	47.76 (5.41)	136.65 (38.70)
3	59.48 (7.92)	48.86 (4.85)	142.59 (54.35)
4			142.11 (50.53)
5			121.31 (50.81)
6			160.41 (50.45)
7			170.85 (63.51)
8			154.85 (42.55)
9			133.14 (58.53)
10			188.69 (56.14)
11			160.98 (64.73)
12			141.02 (75.20)
13			96.01 (57.59)
14			128.75 (57.72)
15			131.29 (36.15)
16			142.98 (66.12)
17			136.52 (55.76)
18			200.50 (54.42)[b]

[a]Significant differences attributable mainly to truck position differing for each trial.
[b]Significant increase from 82.18 m^3/hr in the first trial to 200.50 m^3/hr in the last trial.

Table 3 includes the descriptive statistics of the three component tasks performed by the part-task group. For the Carrier Positioning module, the time to position the excavator differed across the three trials, $F(2, 40) = 3.63$, $p < .05$, mainly because the truck position was different for each trial. The Trenching module showed no difference in mean productivity across the three trials, $F < 1.0$. Finally, for the Truck Loading module, mean loading production rate ranged from 82.2 m^3/hr in the first trial to 200.5 m^3/hr in the last trial, $F(17, 340) = 2.23$, $p < .005$.

Immediate and Retention Tests

A mixed-design ANOVA was used to test the effects of session (immediate, retention), trial (1 to 6), and training method (part task, whole task) on production rate as a function of training group. An initial analysis for a gender difference yielded $F < 1.0$, so gender was not included in the ANOVA. The results showed main effects of session, $F(1, 40) = 41.76$, $p < .001$, with production rate being lower for the immediate test than for the retention test (Ms = 58.3 and 75.5 m^3/hr), and trial, $F(5, 200) = 45.04$, $p < .001$, showing an increase in performance across the trials within a session. The main effect of training method was not significant, $F(1, 40) = 2.36$, $p = .132$.

However, all two-way interactions were significant (see Figures 3A through 3C). For Session × Training method, $F(1, 40) = 17.84$, $p < .001$, separate ANOVAs for each session showed that the difference between the training methods was not significant for the immediate test, $F < 1.0$, but the part-task group had better performance than the whole-task group on the retention test, $F(1, 40) = 17.71$, $p < .001$. The Trial × Training method interaction, $F(5, 200) = 2.36$, $p < .05$, indicates that averaged across sessions, the part-task group showed a larger improvement in performance across trials than did the whole-task group. Finally, the Session × Trial interaction,

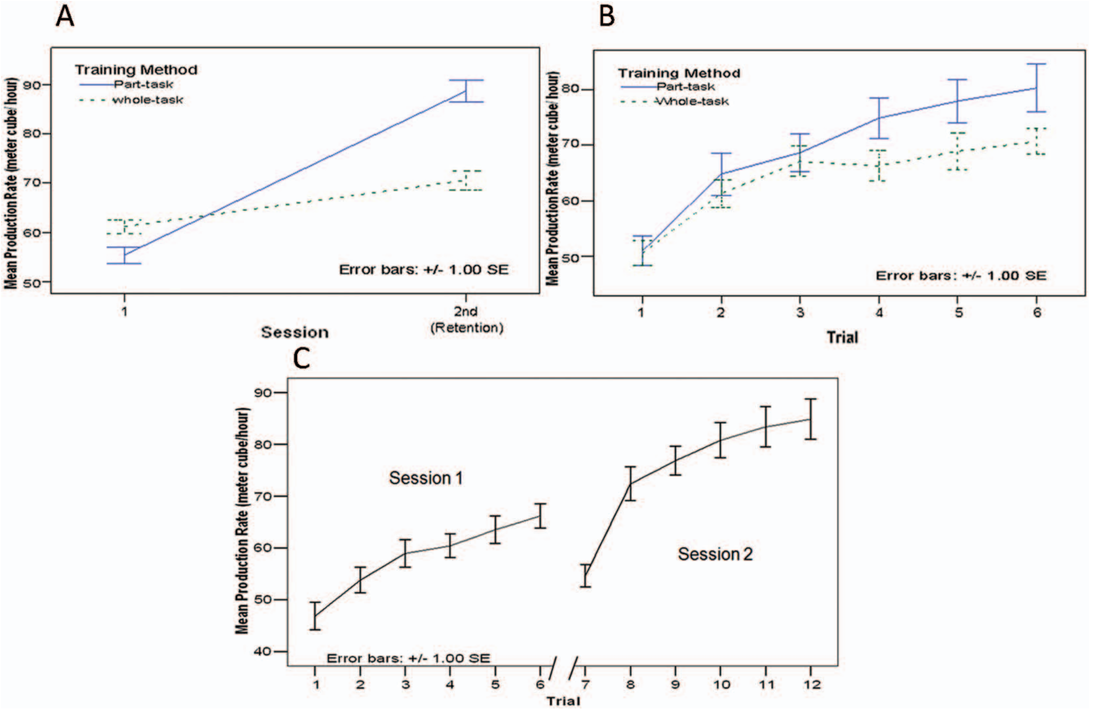

Figure 3. Two-way interactions: (A) Session × Training Method; (B) Trial × Training Method (each data point is a mean of corresponding Sessions 1 and 2 trials); (C) Trial × Session (trials indicated as 7 through 12 represent 1 through 6 for Session 2).

$F(5, 200) = 3.55$, $p < .005$, illustrates that the increase in performance across trials was larger in the retention test than in the immediate test, mainly because of a dip in productivity on the first trial of the retention test.

Although the three-way interaction was not significant, $F(5, 200) = 1.15$, $p = .337$, a plot of the data by all three variables (training group, session, and trials) depicts most clearly the pattern of results (see Figure 4). The part-task group began with less productivity than the whole-task group on the first trial (42 m^3/hr vs. 51 m^3/hr), but their performance improved across the trials, equaling that of the whole-task group in Trials 4 through 6 of the first session. The retention test, 2 weeks later, showed an initial performance decrement on the first trial for both groups, but the part-task group showed a higher production rate than the whole-task group throughout the session (the production rates being 96 m^3/hr vs. 74 m^3/hr for the respective groups on Trial 12).

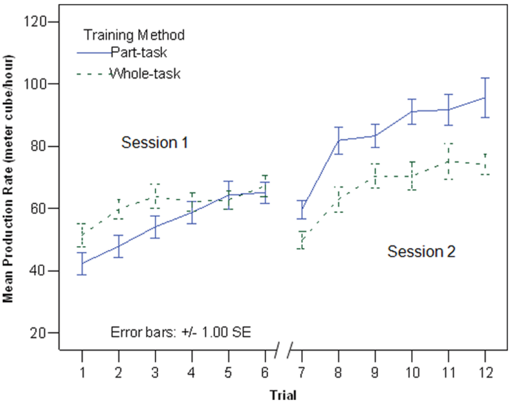

Figure 4. The performance of all trials in each session for the two training methods.

Another ANOVA was conducted with trench-and-load scenario (for which the position between the truck and the trenching area differed) as a factor, along with session and

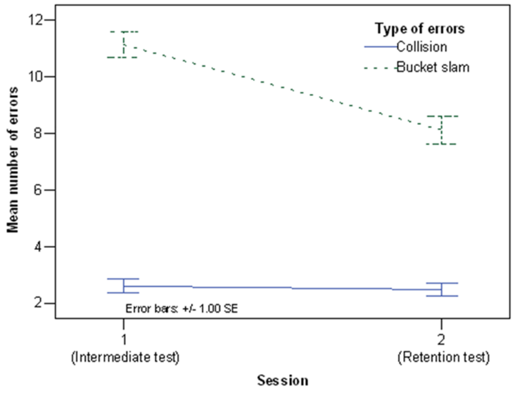

Figure 5. Two-way interaction plot of Error × Session on number of errors.

training group. Scenario was significant, $F(2, 80) = 8.63$, $p < .001$, but did not interact with the other factors: Productivity was higher when loading at the back of the truck ($M = 70.8$ m^3/hr) than from the front or side (Ms = 64.0 m^3/hr and 65.9 m^3/hr; ps < .01).

A mixed-design ANOVA tested the effects of session, scenario, error type (bucket slams, collisions), and training method on total number of errors. Error type had a significant effect, $F(1, 40) = 117.96$, $p < .001$. The number of bucket slams ($M = 9.6$) exceeded the number of collisions ($M = 2.5$). A session main effect, $F(1, 40) = 23.33$, $p < .001$, indicated that more errors were made in the immediate test than in the retention test (Ms = 6.9 and 5.3). Scenario was significant as well, $F(2, 80) = 8.55$, $p < .001$, with fewer collisions and bucket slams made when the excavator was located at the rear but aligned perpendicular to the side of the truck ($M = 5.3$) than when loading from beside the front or from the back (Ms = 6.2 and 6.7; ps < .05). The only other significant effect was the Error Type × Session interaction, $F(1, 40) = 23.35$, $p < .001$. Participants showed fewer bucket slams in the retention test than in the immediate test (ps < .001), whereas the number of collisions remained low for both sessions (see Figure 5).

DISCUSSION

During the training phase of the study, performance improved for both whole- and part-task practice groups. In the immediate test, the part-task group initially performed worse on the whole task than did the whole-task group, but within a few trials, performance for the two groups was similar. This result pattern is similar to that found by Frederiksen and White (1989) for the *Space Fortress* task, which also involves complex perceptual-motor skills, and is to be expected because part-task training allows acquisition of only the component skills. Integration of those skills cannot occur until put in the whole-task context. Both groups showed a higher production rate at the 2-week retention test than at the initial test, suggesting that the skills acquired during the initial practice were retained. This result is consistent with Speelman and Kirsner's (2001) finding that when old skills are executed in the context of new tasks, the old skills continue to improve if stimulus conditions have not changed.

A decrease in production rate on the first trial of the retention test was evident. This decrease may reflect a warm-up decrement associated with recollecting the old skills (Schmidt & Lee, 2011) or a "fast, transient dimension of adaptation" (Newell, Mayer-Kress, Hong, & Liu, 2009). Regardless, the part-task group showed significant improvement in the retention test compared with the initial test in the first session, whereas no significant difference between the two sessions was found for the whole-task group. Moreover, the part-task group obtained higher productivity rates than the whole-task group in the retention test. This pattern is similar to that observed in some motor-learning studies, whereby effects of a training variable are more evident after a retention interval of several days than shortly after practice (e.g., Schmidt, Young, Swinnen, & Shapiro, 1989).

Although all participants who received part-task training indicated at the end of Session 1 that they experienced some initial difficulty combining the part tasks to accomplish the whole task, the skill at the part tasks they acquired enabled better performance after the coordination required for the whole task was learned. Such benefit of part-task training appears to apply generally to complex perceptual-motor tasks of which vehicle control is only a part (e.g., Gopher et al., 1989; Mane, Adams, & Donchin, 1989) and technical skills, such as laparoscopic surgical procedures involving control of implements (Beaubien & Baker, 2004).

Regarding the trench-and-load scenario, the production rate was highest when the excavator was positioned at the back of the truck, next highest when the truck was positioned perpendicular to the trenching area and the excavator loading the truck from the side, and worst when the excavator was positioned and loading from beside the front of the truck. This result is likely because both back and perpendicular scenarios provided clearer views for dumping when transferring the soil from the trench to the truck. In the front scenario, participants were unable to ascertain exactly the width and the back of the truck, which would increase the chance of dumping the soil over the other side or poorly positioning the bucket before opening it. Therefore, participants have better cues when transferring the soil to the truck in the back and perpendicular scenarios. The front scenario's disadvantage may be exacerbated in the virtual environment because of a lack of binocular depth cues. Such scenarios, in which limitations in the training medium may inhibit skill development, might be catalogued and investigated in future research.

Compared with bucket slams, the number of collisions was small and insignificant, regardless of training method, session, or trench-and-load scenario. The number of bucket slams was reduced in the retention test, indicating that participants were still improving at bucket control. This finding again supports Speelman and Kirsner's (2001) finding that old skills continue to improve if task conditions are not altered, since the participants were performing the same task as that in the immediate test. Regarding the trench-and-load scenario, the back scenario with the highest production rate did not benefit from avoiding bucket slams, but the least number of bucket slams occurred with the trench at the rear and perpendicular to the truck and the excavator loading from the side. To maximize production rate, participants needed to minimize the execution time to complete the trench-and-load task. In contrast, greater accuracy in joystick movement to control the bucket, stick, and boom was obtained at the cost of speed: The higher the accuracy in joystick control, the longer the execution time and the lower the production rate.

CONCLUSION

Part-task training provided better skill retention and larger improvement than did whole-task training for a trench-and-load task on a simulated hydraulic excavator. This benefit of practice was evident mainly in the retention test conducted 2 weeks later, although we cannot discern whether this benefit is attributable to retention or to the continuation of practice beyond the initial six trials of the immediate test. It seems reasonable to assume that the better skill evidenced by the part-task group in the retention session would transfer to operation of a real hydraulic excavator in the field, but more direct evidence of such transfer is needed to confirm this assumption.

The commercially available training simulators for heavy construction equipment feature different lessons and tasks to train proper operator technique, machine controls, and safe operation in a virtual job site, but hardly any experimental evaluations of the influences on perceptual-motor skill learning are available to users of these systems. Consequently, more investigation of the principles and curriculum that make for efficient use of the construction equipment operator training systems is needed in the future. How these systems should be used to demonstrate the successful acquisition of skills and transfer of those skills to the operation of a variety of pieces of construction equipment is also of interest.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation Grant CMMI-0700492. Opinions, findings, conclusions, or recommendations presented in this article are those of the authors and do not necessarily reflect the views of the National Science Foundation.

KEY POINTS

- Part- and whole-task training methods for performance of a trench-and-load task carried out on a simulated hydraulic excavator were compared.
- Part-task training provided better performance than did whole-task training in a session

conducted 2 weeks after the initial acquisition and test session, with the former method showing significant improvement in that session that the latter did not.

- Performance was found to vary across the specific trench-and-load scenarios, with the implication that performance was worse for conditions in which the depth cues of the natural environment were not depicted accurately in the virtual environment.
- The benefit of part-task training found in the present study likely applies more generally to tasks composed of subtasks involving complex perceptual-motor skills.

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Joey C. Y. So received her master's degree from City University of Hong Kong in 2009. She is currently a doctoral student in the School of Industrial Engineering at Purdue University, where she specializes in human factors.

Robert W. Proctor received his PhD from the University of Texas at Arlington in 1975. He is currently a distinguished professor of psychological sciences at Purdue University, with courtesy appointment in the School of Industrial Engineering, where he specializes in basic and applied human performance.

Phillip S. Dunston received his PhD from North Carolina State University in 1995. He is currently a professor of civil engineering at Purdue University, where he specializes in advanced technology applications for construction equipment and visualization.

Xiangyu Wang received his PhD from Purdue University in 2005. He is currently a professor in the School of Built Environment at Curtin University. He is also affiliated with the Department of Housing and Interior Design at Kyung Hee University, Seoul, Korea. He specializes in virtual technology applications in architecture, engineering, and construction.

Date received: October 25, 2011
Date accepted: June 12, 2012