A BEHAVIORAL INTERVENTION FOR REDUCING POST-COMPLETION ERRORS IN A SAFETY-CRITICAL SYSTEM

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Joseph Douglas McDonald

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A BEHAVIORAL INTERVENTION FOR REDUCING POST-COMPLETION ERRORS IN A SAFETY-CRITICAL SYSTEM

Approved by:

Dr. Francis T. Durso, Advisor
School of Psychology
Georgia Institute of Technology

Dr. Eric Schumacher
School of Psychology
Georgia Institute of Technology

Dr. Bruce Walker
School of Psychology
Georgia Institute of Technology

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LIST OF SYMBOLS AND ABBREVIATIONS

α	Alpha Level at Which Statistical Significance is Achieved
CI	Confidence Interval
d	Cohen’s d Standardized Measure of Effect Size
M	Mean
p	Pearson
SD	Standard Deviation
t	T-Statistic
OCU	Operator Control Unit
PC	Post-Completion
PCE	Post-Completion Error
RCO	Remote Control Operator

SUMMARY

A widespread and persistent memory error that people commit on a daily basis is the post-completion error (PCE; i.e., forgetting to complete the final step of a procedural task). PCEs occur in the railroad industry when a locomotive conductor changes the direction of a rail switch but fails to report this change. This particular error could contribute to unsafe conditions as another train traveling on the same track could derail. Although training can help reduce some of the factors leading to unsafe conditions on the rail, research has demonstrated that PCEs are different from other errors of omission in that they cannot be eliminated through training, which makes them a difficult problem to address. Therefore, there is a need to explore new remedial actions designed to reduce PCEs. The current study investigated the effectiveness of a theoretically motivated intervention at reducing PCEs in trainyard operations, where making these errors could be life-threatening. Twenty-eight undergraduates completed trainyard tasks within a high-fidelity simulator. Each participant received the behavioral intervention in one block and no intervention in another. Specifically, participants were required to perform an additional task designed to remind participants of the post-completion (PC) step. The intervention significantly reduced PCE rates in the context of trainyard operations, on average, by 65%. We discuss implications of these results on reducing trainyard accidents, and how this outcome can contribute to the literature on the cause of PCEs.

CHAPTER 1

INTRODUCTION

A widespread and persistent error that people commit on a daily basis is the post-completion error (PCE; Byrne & Bovair, 1997): driving down the road with the lid to the gas cap inadvertently left open, leaving the original in a photocopier, or walking away from a vending machine with the snack but not the change. PCEs can occur when procedural tasks require users to complete an additional step after the main goal has been satisfied. Specifically, users must set up an initial condition, satisfy a goal, and then complete a post-completion step. It may seem plausible that these types of errors are simply the result of some stochastic function of global error rate and are really no more common than other errors of omission. However, previous research has demonstrated that PCEs are systematic procedural errors that occur significantly more often than errors at any other step of a procedure (e.g., Byrne & Bovair, 1997; Li, Blandford, Cairns, & Young, 2008). Given the systematic nature of PCEs, there is a need to understand the underlying mechanisms that give rise to these types of errors, especially in safety-critical systems where procedural slips can be life-threatening. For example, in the railroad industry, if a locomotive conductor changes the direction of a rail switch but fails to report this change, another train traveling on the same track could derail.

PCEs have a unique set of characteristics that set them apart from other procedural errors and make them a difficult problem to address. For example, even experts make these types of errors, suggesting that they cannot be eliminated through training (Blandford, 2000). Furthermore, although PCEs are persistent errors in that they continue to occur even when users possess the required task knowledge, they are also infrequent, which makes them difficult to study in a laboratory setting. However, validated methods of eliciting higher PCE rates in the lab have been developed to investigate how timing of task interruptions, working memory load, motivational factors, and just-in-time reminders affect PCE rates (Byrne & Bovair, 1997; Byrne & Davis, 2006; Li, Blandford, Cairns, & Young, 2008).

Two low-fidelity software programs have been developed to investigate PCEs in a laboratory setting. Li et al. (2008) developed a software program to investigate the effect of interruptions on PCEs. Using their software-based doughnut production task, Li and colleagues found that users who were interrupted just before executing the post-completion (PC) step (i.e., clicking on the “Clean” button) were more likely to make PCEs than if they were interrupted at any other step (Li et al., 2008). Another software program developed by Byrne and Bovair (1997), the “Phaser task,” required users to complete a series of steps to accomplish the main task of destroying an enemy ship. Upon completion of the main task, users were required to turn off the “Tracker” (i.e., the PC task). Byrne and colleagues found that high working memory load, induced by a secondary task, led to significantly more PCEs (Byrne & Bovair, 1997). Another study using the “Phaser task” demonstrated that motivational factors, such as “blame and train” techniques, reprimands, and praise and reinstruction, did not significantly reduce PCE rate relative to a baseline condition (Byrne & Davis, 2006). Similarly, providing a static cue throughout the trial reminding participants to complete the PC step did not lead to a significant reduction in PCEs (Lee, 1992).

Although previous research demonstrated that behavioral interventions that were focused on increasing user knowledge did not help the PCE problem, studies that investigated design changes and task restructuring offered promising results. Chung and Byrne (2008) demonstrated that just-in-time reminders, such as visual cues with dynamic movement displayed immediately before the PC step, significantly reduced the number of PCEs. Additionally, studies that reordered procedural steps of a task to suspend task completion until after the PC step was satisfied (e.g., an ATM machine required users to retrieve their ATM card before cash was dispensed) eliminated PCEs altogether (Blandford, 2000).

Of course, the ideal solution to the PCE problem is to design it out. However, in many instances, a complete re-design is not a feasible option. For example, solving the previously mentioned rail switching problem is complicated by a number of system-level factors that prohibit the re-design of mechanical switches on the rail. However, through the use of an appropriate experimental paradigm, and an understanding of the cognitive constructs associated with forgetting, it is possible to test a theoretically motivated behavioral intervention designed to eliminate PCEs.

One theory explaining why PCEs occur was developed by Byrne and Bovair (1997). Their working memory model of PCEs suggests that PCEs are a result of limited working memory capacity in high workload environments. This computational theory of PCEs is based on the CAPS (Collaborative Activation-based Production System; Just & Carpenter, 1992) cognitive architecture and relies on some underlying assumptions (Byrne & Bovair, 1997). First, the ability to attend to a PC goal is achieved through the activation of the main goal via a direct cognitive link. Second, the underlying mechanism for attending to a goal is similar to other computational models of working memory in that the longer the intention to complete the goal remains in working memory the more activation it receives, and the longer it will remain above activation threshold during the retention period. Third, when multiple goals are active at the same time, the goals compete for activation causing completed goals to drop below threshold faster than they would in the absence of other activated goals. Finally, if a goal falls below the activation threshold before it is time to retrieve it, the goal will be lost and the task related to the goal will be omitted.

In Byrne's theory, the PC goal is viewed as the final subgoal of the main goal, and it only receives activation as long as the main goal is active. Activation of the main goal does not instantly drop below threshold when satisfied, but diminishes at a variable rate, allowing the PC goal to remain above threshold for some time. However, as working memory load increases, activation of satisfied main goals decrease at a faster rate. For this reason, the relatively fast loss of a satisfied main goal in a high workload environment may lead to the loss of still-unsatisfied PC goal (e.g., the goal of retrieving the original copy from a photocopy machine) as it is prematurely pulled below activation threshold. Furthermore, the rapid decrease in activation for an encoded main goal will occur regardless of when the additional tasks are imposed on the individual. Therefore, Byrne's theory suggests that protecting a user from additional tasks at all steps of a procedural task will reduce PCEs. A second theory presented by Li et al. (2008) posits that task interruptions that occur immediately before the PC step are the primary contributing factor to the PCE problem.

Li et al. focused on interruptions that occurred at critical points of procedural tasks in order to explain the underlying mechanisms that give rise to PCEs. According to Li et al., as users gain experience in completing a particular task, they develop a non-declarative cognitive representation that is based on the automatic execution of sequential task steps. Specifically, Li et al. posit that when users practice a task, "cognitive links" develop between proximal steps such that the goal to complete a particular step is automatically cued by the previous step. In this way, completing the first step of a procedure initiates a domino effect such that all of the steps are carried out automatically without much deliberate effort (or cognitive awareness) by the user. A similar automatic cueing mechanism has been described in the context of serial list memory models, in which pairwise associations between adjacent words in a list of words develop over time and account for sequential recall of words (e.g., Lewandowsky & Murdock, 1989). Once "automatic" recall of words or execution of task steps is achieved over time, users rely on the automatic associative cueing mechanism to complete the task; following an interruption, they may no longer have a declarative knowledge structure on which to fall back. Li et al.'s theory was supported by their results; protecting users from interruptions towards the end of a procedural task significantly reduced PCEs. However, Li et al. also observed an interaction indicating that interruptions may not be the only factor contributing to PCEs.

Li et al. observed an increase in PCEs immediately after an interruption, which they took to mean that completion of the PC step depended on the automatic associative cueing mechanism that develops between procedural steps. However, there was also an interaction between the presence or absence of an interruption and the relative increase in PCEs and errors that occur at other steps in the procedure. Specifically, when participants were not interrupted, PCEs were significantly higher than errors at earlier steps in the procedure, which were completely eliminated in the absence of an interruption. Therefore, although interruptions that occur immediately before the PC step may contribute to PCEs, interruptions do not appear to fully explain the PCE phenomenon as PCEs systematically occur in the absence of interruptions. Additionally, a main effect of error type was found such that PCEs were generally significantly higher than any other type of error regardless of interruption position. These results supported the earlier claim by Byrne and others that PCEs are a phenomenon in their own right. Furthermore, because participants in Li et al.'s study did not perform a secondary task, it appears that protecting users from additional tasks does not fully explain the systematic nature of PCEs either, and other possible factors contributing to the PCE problem need to be investigated.

One possible explanation as to why Li et al. and Byrne and Bovair observed significantly higher PCEs than errors at any other step in a procedure revolves around the interruption that occurred immediately before the PC step. Specifically, both studies displayed a false-completion pop-up window immediately before the PC step in order to elicit higher PCE rates, which could be viewed as an additional interruption on top of the task interruption (in Li et al.'s experiment) and secondary task (in Byrne and Bovair's experiment) imposed on participants. As a result, this "double" interruption could have further disrupted the automatic cueing mechanism that Li et al. suggest exists between the PC step and the previous step. In terms of Byrne's working memory theory, the interruption could have increased the user's workload by imposing yet another task on the already overloaded participant. Although it is clear that interruptions that occur immediately before the PC step play a role in changes in PCE rates, it is difficult to speculate how much of the variance in PCE rate was attributable to the additional interruption and how much variance was attributable to the naturally higher probability of making this type of systematic error. Therefore, a more ecologically valid paradigm is required to leverage existing theories and identify additional factors that contribute to the PCE problem in order to develop real-world interventions that reduce PCEs in safety-critical environments.

One real-world situation in which understanding the factors that contribute to PCEs could be life-saving is railroad operations. Trainyards, which can be thought of as relay stations, are composed of a number of connected tracks that are used for breaking down complete trains into individual units (i.e., blocks) so that the blocks can be connected to other trains to be delivered to their final destination. Where two tracks converge, a track switch is used to change the direction in which a train will travel. If trains "run-through" improperly lined switches, the switches could be damaged, which increases the likelihood that another train traveling on the same tracks will derail.

In order to safely operate trains in the trainyard, conductors must remain aware of the alignment of track switches across the yard. Although it is often the case that experienced conductors can see the direction in which a switch is lined as they approach it, and therefore can re-align the switch if needed, there are many blind curves in trainyards that prevent direct line of sight with track switches. For this reason, track switch position can sometimes be difficult to determine. Therefore, conductors communicate with yardmasters who are responsible for assigning trainyard tasks and communicating track conditions to employees working in the trainyard. Communication between conductors and yardmasters related to the position of track switches helps raise conductors' awareness of how track switches are aligned across the yard. Although conductors are trained to report the position of track switches to the yardmaster after they have completed a main task of building or breaking down a train (i.e., a post-completion step), this final step is often forgotten (Ranney & Raslear, 2013). If conductors forget to report the position of track switches to the yardmaster after completing a main task (i.e., a PCE), other conductors working on the same set of tracks may lose awareness of track switch positions. Although conductor workload and interruptions to trainyard tasks may contribute to the PCE problem, another contributing factor could revolve around problems associated with interleaving tasks.

As was the case for the experimental paradigms used in Li et al. and Byrne and Bovair's studies of PCEs, conductors receive multiple task assignments that are performed one after the other, rather than receiving one task assignment at a time. It is possible that Li et al. and Byrne and Bovair observed significantly higher PCEs than errors at any other step in the procedure because users began thinking about their next task (e.g., processing the next batch of doughnuts in Li et al.'s paradigm) before completing the last step of the current task (i.e., the PC step). Li et al. did not address how internal interruptions such as the premature activation of goals for an upcoming task would affect PCEs. However, if one assumes that internal interruptions are equally as disruptive to the associative cueing of adjacent procedural steps as external interruptions, Li et al. would predict an increase in PCEs when users think about future task goals towards the end of their current task.

Byrne and Bovair did not address the issue of interleaving tasks either. However, if one assumes that simultaneously activating a future goal while satisfying the current goal can increase one's workload, Byrne's spreading activation model of working memory would attribute the increase in PCE rates to the additional cognitive load imposed on the user. Therefore, under the previously stated assumptions regarding internal interruptions and increased workload resulting from prematurely attending to an upcoming task, both Li et al. and Byrne would predict an increase in PCE rates for procedural tasks that require the user to move on to another task upon completion of the first. However, workload and interruptions alone do not seem to account for systematically high PCEs. We believe that another factor associated with interleaving tasks contributes to the PCE problem; conductors experience a "sense of closure" for the current task before completing the PC step.

Experiencing a "sense of closure" (Thimbleby, 1990) when a task is thought to be complete has been described in the psychological literature in terms of the Zeigarnik Effect (Van Bergen, 1968; Greist-Bousquet & Schiffman, 1992). The Zeigarnik Effect describes how details of a seemingly completed task are more often forgotten than details of a seemingly incomplete task. Others have described a "sense of closure" in the context of the construction-integration model (Kintsch, 1988), in which "done-it" nodes are activated when most of the steps of a task have been completed and, as a result, the whole task is actively inhibited (Polson et al., 1992). For trainyard conductors, it may be the case that they experience this "sense of closure" when most of the steps for the current task have been completed and, as a result, they forget to complete the post-completion step. Assuming that conductors experience this "sense of closure" prior to completing the PC step, it may be possible to shift conductors' attention back to the "closed" task by reminding them of the PC step after they have moved on to the next task.

Research in memory and recall has demonstrated that an effective way to remind individuals about items that they have forgotten is through the use of associative cues (Tulving & Pearlstone, 1966). For example, Tulving and Pearlstone demonstrated that forgotten words from a list of memorized words were recalled significantly more often when categories associated with the forgotten words were provided as cues. For example, if the word "apple" was forgotten from a list of words, providing the category "fruit" resulted in higher recall of the word "apple." In addition to using word categories as cues, effective associative cues have been observed in various forms, including spatially defined visual cues (Eliassen, Souza, & Sanes, 2003), auditory cues (Weinberger, 2007), and olfactory cues (Gottfried, Smith, Rugg, & Dolan, 2004). In the case of trainyard operations, it may be possible to utilize associative cueing to ensure that track switches are reported after the completion of each task. Our intervention accomplishes this by changing the way in which conductors receive their daily tasks.

For our intervention, conductors will only be given one task at a time. Specifically, we will require conductors to call the yardmaster near the end of their current task (i.e. before moving their train to the departure track) to obtain their next trainyard assignment. Although this requirement will add yet another task for the conductor to perform, which may seem counter-productive to reducing PCEs, it may be true that conductors forget to call in the position of switches because they move on to a new task prematurely. We suggest that internal interference created by directing attention to a future task, and the sense of closure experienced when moving on from a task, is precisely the reason that PCEs occur at a disproportionately higher rate. For this reason, adding a new first step of calling-in to request their next task may help ensure that the PC step of calling-in switch positions for the current task is completed. We predict that forcing controllers to call-in for their next task in a way that reminds them of the still-incomplete PC step could reduce PCEs.

Our intervention requires trainyard workers to call the yardmaster to request their next assignment before the PC step of the current task is complete. Although conductors are forced to move on to the next task when PCEs are likely to occur, this assumes that the act of calling the yardmaster to receive the next assignment will act as an associative cue, reminding the participant to also communicate the position of switches (i.e., the PC step) for the almost-complete current task. In other words, because the acts of calling in for the next assignment and the PC step of calling in the switch positions for the current task share many characteristics (e.g., communicating to the yardmaster, considering switch positions required to complete the next task), the goal of completing the former will share a strong cognitive link with the goal of completing the latter. Although we predict that forcing workers to move on to the next task via a step that is cognitively linked to the PC step of the current task will reduce PCEs, the "modified" versions of the two previously mentioned theories (i.e., Byrne & Bovair, 1997; Li et al., 2008) would predict an increase in PCEs when this additional step is implemented.

CHAPTER 2

METHOD

Participants

Thirty-three volunteers were recruited through flyers posted around the Georgia Institute of Technology campus and through the Georgia Tech Sona Experimental Management System. Participants were compensated $10.50 per hour for each of the 4 hours that they completed and received a bonus of $8.00 for completing the study. Thus, participants who completed the study received a total of $50.00 for their participation. Participants reported normal or corrected-to-normal vision and hearing, spoke fluent English, and were able to operate a remote control device. Four participants did not complete the study and were not included in the analysis. One participant was accidentally given incorrect instructions on the second day of trials and was not included in the analysis. Thus, 28 participants completed the study.

Apparatus and Trainyard Tasks

The study took place in the Cognitive Ergonomics Laboratory at Georgia Institute of Technology in Atlanta, GA. Participants performed sessions in a room with white walls, no wall decorations, and no windows. TrainMaster simulator software was controlled by an Alienware laptop computer with an NVIDIA GeForce GTX 780M Graphics card, and an 18.4 in monitor with a resolution of 1920x1080. A USB remote control device was used to operate locomotives in the virtual environment; a joystick and fixed-function buttons were used to move in the virtual environment and to control various actions needed to perform tasks in the simulator. Instructional slides appeared on a 30 in monitor driven by an Alienware desktop computer.

TrainMaster Simulator and Hardware

The software used for each trial was the TrainMaster Rail Operation Simulation program. This high-fidelity virtual environment is used by railroad companies to simulate various tasks carried out by traditional locomotive engineers and conductors as well as remote control operators (RCOs), who use remote-control devices to control movement of the locomotive (see Figure 1). The operator control unit (OCU) is used by RCOs in remote-controlled freight rail switchyard operations in place of a locomotive engineer operating the engine. Participants used a simulator analog of an OCU to operate the locomotive in the simulated trainyard environment (see Figure 2).

Figure 1. TrainMaster high-fidelity training environment for remote control operators (RCOs) of locomotives. Screen shot displays a trainyard within the virtual environment. The car displayed in blue on the far right is selected, and information specific to that car, as well as task-related information, is displayed below the trainyard environment.

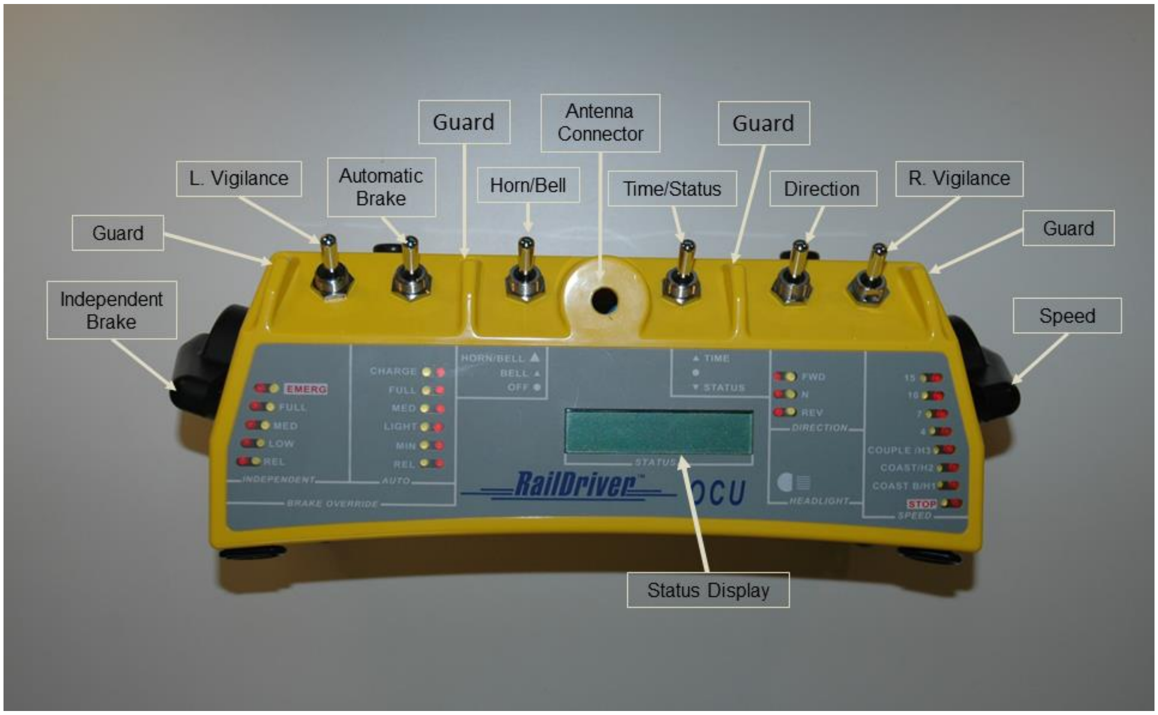


Figure 2. Simulator version of the operator control unit (OCU) used by remote control operators (RCO) to control movement of locomotive in TrainMaster simulator.

The TrainMaster simulator includes a second device for moving and manipulating various elements within the simulated environment from a first-person perspective (see Figure 3). Of the controls available on the device, the joystick and eight buttons (i.e., line switch, deselect, set handbrake, release handbrake, uncouple, aerial, mount, and walk) were used for this study. Participants used the joystick to move their first-person conductor in the simulated environment. A mouse was used to select the locomotive, train cars, and switches found in the simulated environment so that various actions could be applied to those objects. Once an object was selected (i.e., by using the mouse to position the mouse cursor on top of the object and clicking the left mouse button), the object turned blue and the information bar below the virtual environment displayed information specific to that object (see Figure 1).

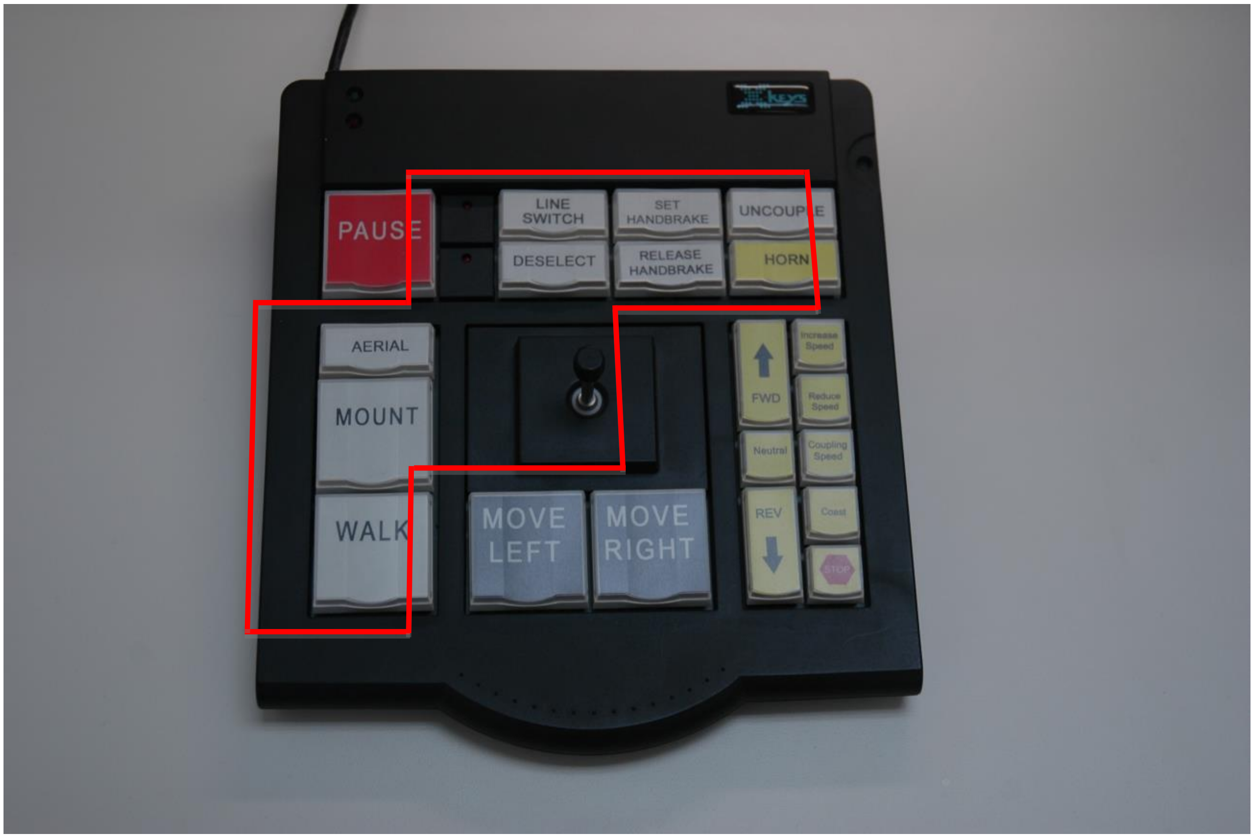


Figure 3. Control device used to move in virtual trainyard environment from a first-person perspective. Controls used for this experiment are outlined in red.

After an object was selected, participants were able to apply specific actions to that object by pressing one of the fixed-function buttons (see Figure 3). For example, if participants wished to set a handbrake on a train car, they first used the mouse to click on the car, which turned the car blue to indicate that it was selected. They then looked in the information bar where they found either "Hand Brake: Applied" or "Hand Brake: Released," which indicated the current status of the handbrake for the selected car. If "Hand Brake: Released" was displayed, and participants wished to apply the handbrake, they pressed the "SET HANDBRAKE" button. Once the handbrake was set to the appropriate position, participants pressed the "DESELECT" button to deselect the train car.

Using a similar procedure, participants used the "RELEASE HANDBRAKE" button to release handbrakes, the "UNCOUPLE" button to separate selected cars from the cars connected to the back of selected cars, and the “LINE SWITCH” button to change the direction that trains could travel at the point of intersecting tracks (see Figure 4 for an illustration of properly and improperly lined switches). Participants used the “AERIAL” button to enter and exit from an aerial view of the tracks. While in aerial view, participants could obtain information about various aspects of the trainyard by clicking on an object and looking at the information bar. However, participants could not change the settings of any objects while in aerial view. For example, by clicking on a switch while in aerial view, participants could obtain information regarding the switch alignment but could not align the switch.

Figure 4. Screen shots from TrainMaster virtual environment displaying a locomotive lined to move towards the viewer. The top image displays an improperly lined switch and the bottom image displays a properly lined switch

Participants used the “MOUNT” and “WALK” buttons to mount or dismount the locomotive, respectively. Mounting and riding the locomotive were useful while moving the locomotive across long distances as walking within the simulated environment was inefficient.

Main Task Development

Two categories of simulator trainyard tasks were developed for this study: (1) building a train out of blocks of train cars (i.e., “Building Task”), and (2) breaking down a train into individual blocks of train cars (i.e., “Breaking Down Task”). These task categories were chosen to represent the types of jobs performed in a trainyard.

For the Building Task, participants used two classification tracks to build trains out of blocks of train cars located on two of the four classification tracks (e.g., tracks 304 and 305) of an activated RC zone (see Figure 5). See Table 1 for the steps required to complete the Building Task.

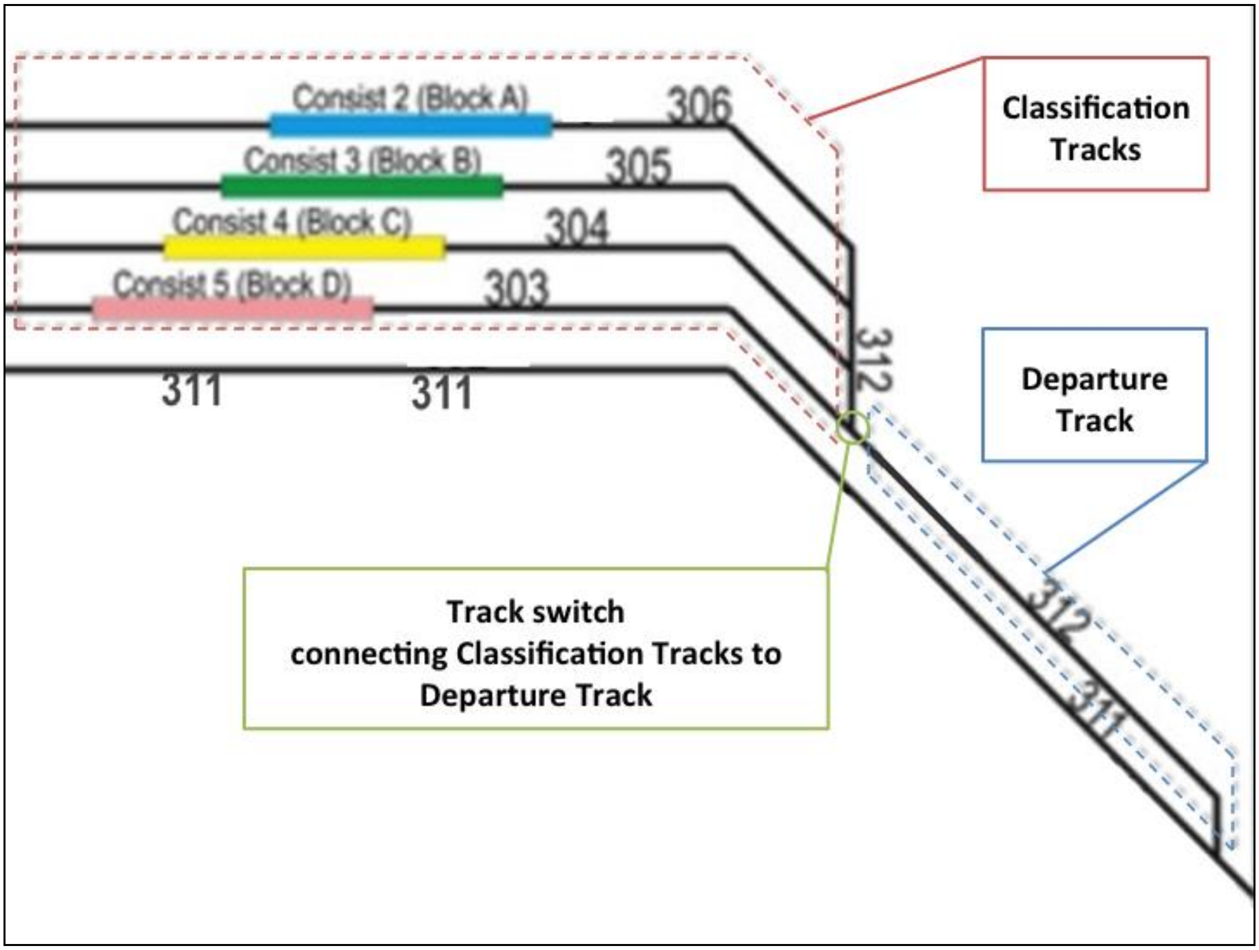


Figure 5. Track diagram of simulator trainyard. Initial positions of blocks of cars are displayed on tracks 303, 304, 305, and 306. Classification Tracks (i.e. tracks 303, 304, 305, and 306) are outlined by a dotted red line and the Departure Track (i.e. track 312) is outlined by a dotted blue line. The location of the track switch connecting the Classification Tracks to the Departure Track is identified with a green label.

Table 1

The list of steps required to complete the simulator Building Task. Note that an additional step (i.e., communicate the position of switches in the trainyard) was imposed on participants after the main task of building a train had been completed. This final step is the PC step.

Building Task
1. Read task assignment to determine which classification tracks will be used during the task
2. Align track switches to gain access to classification tracks
3. Set the locomotive to the reverse position using the OCU direction toggle
4. Move the locomotive to the first block of cars (e.g., "block D" located on track "303") using the OCU speed control
5. Stop the locomotive 50-250 feet from the cut of cars to complete the "safety stop"
6. Attach the locomotive to the cut by setting the OCU speed control to "COUPLE"
7. Stop the locomotive once it is coupled to the cut and set the direction of the locomotive to neutral using the OCU speed control and OCU direction toggle, respectively
8. Remove any handbrakes that are applied to cars in block D by left-clicking on the car (using the mouse) to view the status of the handbrake, and pressing the "RELEASE HANDBRAKE" fixed-function button to release the handbrake if needed
9. Mount the locomotive by pressing MOUNT on the control device and using the joystick to walk towards the locomotive
10. Set the locomotive to the forward direction using the OCU direction toggle
11. Move the locomotive (along with the attached "block D") past the switch connecting track 303 and track 304 to track 312 using the OCU speed control
12. Stop the locomotive on track 312 and set the direction of the locomotive to neurtral using the OCU speed control and OCU direction toggle, respectively
13. Dismount the locomotive by pressing WALK on the control device
14. Line the swith connecting track 303 and track 304 to track 312 for movement onto track 304 by clicking on the switch lever (see Figure 4) and pressing LINE SWITCH on the control device
15. Mount the locomotive by pressing MOUNT on the control device and using the joystick to walk towards the locomotive
16. Set the locomotive to the reverse position using the OCU direction toggle
17. Move the locomotive (along with the attached "block D") to "block C" located on track 304 using the OCU speed control
18. Stop the locomotive (along with the attached "block D") 50-250 feet from "block C" to complete the "safety stop"
19. Dismount the locomotive by pressing WALK on the control device
20. Couple "block D" to "block C"
21. Set handbrakes on the first two train cars by pressing SET HANDBRAKE on the control device
22. Uncouple the locomotive from the train cars by clicking on the locomotive and pressing UNCOUPLE on the control device
23. Mount the locomotive by pressing MOUNT on the control device and using the joystick to walk towards the locomotive
24. Move the locomotive past the switch connecting track 303 and track 304 to track 312 using the OCU speed control
25. Stop the locomotive on track 312 and set the direction of the locomotive to neutral using the OCU speed control and OCU direction toggle, respectively
26. **[PC step]** Communicate (i.e., report out loud) the position of switches in the trainyard

For the Breaking Down Task, participants broke down complete trains into two blocks of cars. Participants executed the reverse of the process used to build a train in the Building Task in that they started with a completed train and deposited two blocks of train cars onto two classification tracks.

Four tasks were created for each category, for a total of eight tasks, with variations in specifics of the task across the four representative tasks. For example, for the “breaking down a train” task, four scenarios were created in which the simulated environment was identical across scenarios, but the block of train cars that was to be broken down and the position within that block in which the cut was to be made differed. Participants referred to task assignment sheets (see Appendix A) to know which cars to separate to break down a block and a train car list (see Appendix B) to know where those cars were located within the respective block.

Post-Completion Step and Post-Completion Errors

As illustrated in Table 1, each of the two main tasks can be thought of as a series of sub-task steps. The final sub-task step for each of the main tasks was to communicate the final position of the switches (i.e. the PC step). In the field, RCOs are instructed to communicate to the yardmaster (who is in charge of the activated RC zone) the position in which they left each of the track switches. In this experiment, participants accomplished this by saying out loud “reporting the position of track switches” when they felt that they had accomplished the trainyard task. If participants failed to report the position of track switches at the end of a task, a PCE was recorded for that task. Therefore, at the end of every task, there was an opportunity for participants to make a PCE.

In the real world, train operators use radios to communicate with yardmasters. This study focused only on the communication of switch positions. Specifically, participants communicated to experimenters by speaking out loud while seated at the trainyard simulator.

Main Task Delivery

Four of the eight tasks were randomly selected for day one sessions, and the order in which the tasks were presented on their respective days was determined by random assignment. Additionally, the order of the selected tasks were verified to ensure that the position in which train car blocks were left after completing a task did not interfere with subsequent task assignments. If a conflict were identified (e.g., if the first task required participants to deposit cars on track 303 and the second task required participants to access a block of cars on track 303 located behind the block of cars deposited during the first task), random assignment was used to determine a new order of tasks. This process was repeated until a plausible sequence of four tasks was selected for each of the two trial sessions. Because the sequence in which tasks were presented had to be carefully planned, the order in which tasks were presented was necessarily consistent across participants.

Safety Violation Feedback

While performing trainyard tasks, participants received real-time feedback regarding safety violations (including variables such as walking too close to the end of a block or walking or standing in between tracks for too long) in the form of a popup window (see Figure 6).

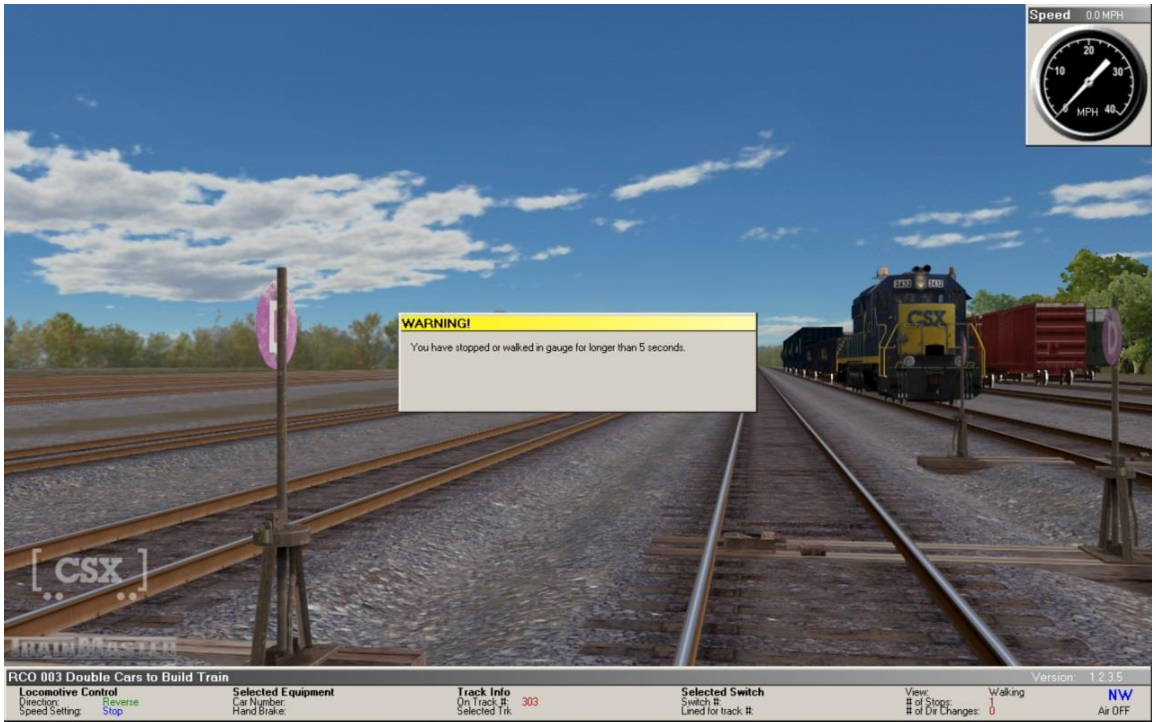


Figure 6. Safety violation displayed to participants in real-time as the violation occurs.

Procedure

Training

At the beginning of the first session, participants signed consent forms and confirmed scheduled session times for each of the four consecutive sessions of the study. The first two sessions (i.e., first two days of 1 hr sessions) were training sessions (see Table 2 for a complete list of activities included in these training sessions).

Table 2

The first two days of the experiment in which participants were trained on the simulator and the trainyard tasks. Activities are listed by day along with the associated completion time in minutes.

Training	Activity	Time (minutes)
Day 1	Consent form and session scheduling	5
	Simulator controls: PowerPoint presentation and practice	15
	Task 1 instructions: PowerPoint presentation	10
	Task 1 participant run through: replica trainyard felt board	5
	Performance feedback on Task 1 run through	5
	Task 2 instructions: PowerPoint presentation	10
	Task 2 participant run through: replica trainyard felt board	5
	Performance feedback on Task 2 run through	5
		60
Day 2	Participant practice on trainyard task: In simulator	15
	Performance fedback on trainyard task	5
	Participant practice on trainyard task: In simulator	15
	Performance fedback on trainyard task	5
	Participant practice on trainyard task: In simulator	15
	Performance fedback on trainyard task	5
		60

During the first session, participants were instructed on how to use the trainyard simulator and how to complete the trainyard tasks of building a train and breaking down a train. Specifically, following session scheduling, participants completed training on the simulator control devices: the OCU device, joystick, fixed-function buttons, and mouse. The 15 min simulator training consisted of a PowerPoint presentation, hands-on experience with each of the control units, and a simplified trainyard task. Specifically, participants controlled the locomotive within the simulator to attach (i.e. “couple”) the locomotive to a block of train cars.

Following simulator training, participants were trained on each of the two trainyard task categories (i.e. building a train and breaking down a train) using a felt board replica of the trainyard environment (including train tracks, blocks of train cars, locomotive, and track switches; see Figure 7). Training for each task consisted of a PowerPoint presentation describing the task instructions in detail and an exercise in which participants completed the task using the felt board replica of the trainyard environment. The tracks on the felt board were connected in the same formation (and the locomotive and train cars were placed in the same starting locations) as was found in the trainyard tasks completed within the simulator during trial sessions. These exercises enabled experimenters to verify that participants understood the train-related tasks before they completed these tasks using the simulator and OCU. This was important because these task exercises were used to ensure that participants did not commit errors simply because they did not understand what they were expected to accomplish.

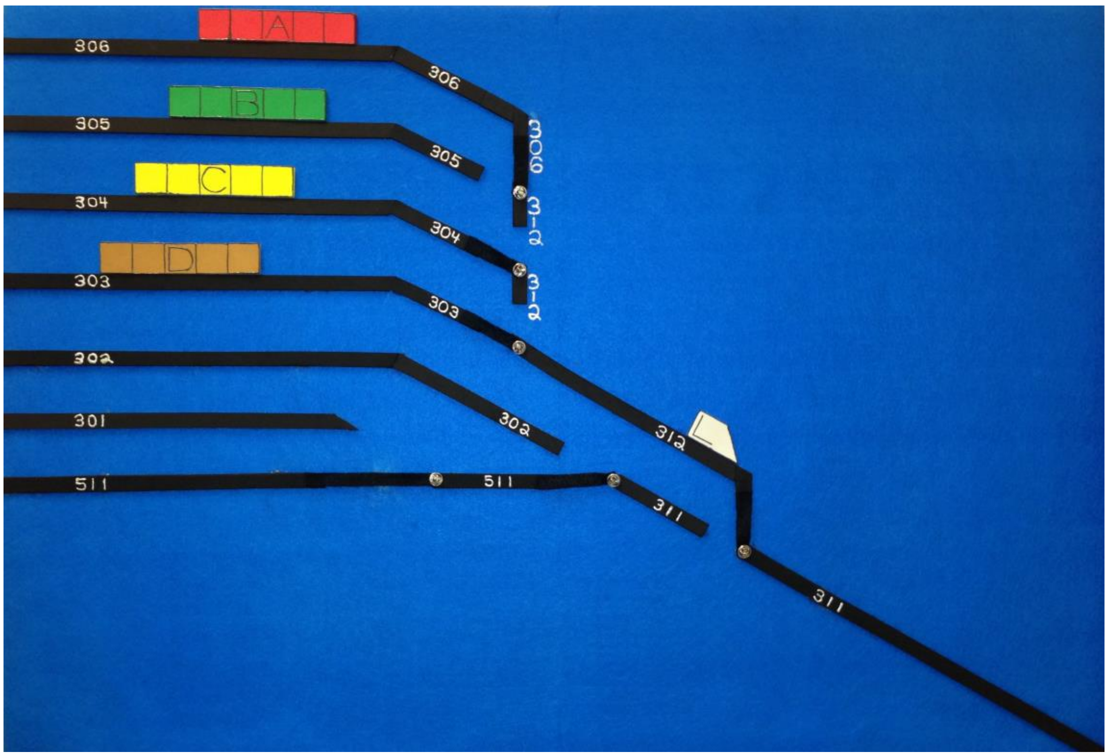


Figure 7. Felt board replica of trainyard environment (including tracks, track switches, blocks of train cars, and locomotive) used during participant training.

On the second (final) day of training, participants completed task exercises within the simulator. Participants completed two to three trainyard tasks using the simulator and control devices. All participants completed at least one task of building a train and one of breaking down a train.

Feedback During Training

Following each of the felt board exercises in day one and the simulator exercises in day two, participants were given feedback regarding procedural errors related to the task. Specifically, if participants performed procedural steps out of order (e.g., if they uncoupled a block of cars before applying handbrakes), failed to initialize steps that require initialization (e.g., they moved the OCU speed control from stop to coupling speed without first pressing the vigilance switch), or failed to complete the PC step of reporting track switch positions at the end of the task, then the experimenter provided feedback on these errors. Specifically, experimenters told participants what they did wrong, how to correctly perform the step (or steps) that were performed incorrectly, and showed participants the correct steps. Participants were required to commit fewer than three errors in one task and to report the position of track switches (i.e., the PC step) on at least one of the previously described exercises to move on to trial sessions. It was important to ensure that participants reported track switches at least once during training so that, during trial sessions, failing to report track switches could not be due to participants not knowing that this step was necessary. One participant did not show up for a training session and was not allowed to continue the study. This participant was one of the previously mentioned participants removed from the study for not showing up to a session. All participants who attended both training sessions met the performance criteria during training and moved on to trail sessions.

Trial Sessions

Trial sessions took place on day three and day four of the experiment. Participants completed two 1 hr trial sessions (in addition to two days of training) in one week. No more than one session was completed in one day. Each session contained two to four trainyard tasks, depending on how many tasks participants were able to complete in a 1 hr session. If questions were asked during the trial sessions, the experimenter reminded the participant that, as discussed during training, “training is complete and I will not be able to answer any questions for the rest of the study.” If the 1 hr allotted session time ended while a participant was still completing a task, the experimenter stopped the session by entering the room and informing the participant that the session was over. If the participant was currently working on a task when the session time expired, the task was not scored.

Task assignments were given to participants on sheets of paper (see Figure 8 for an example; see Appendix A for all task assignment sheets). Each participant was in the experimental condition for one day of trial sessions and the control condition for the other. To control for the possibility of sequence effects, the order in which participants received each condition was counterbalanced. The way in which participants received task assignment sheets was varied.

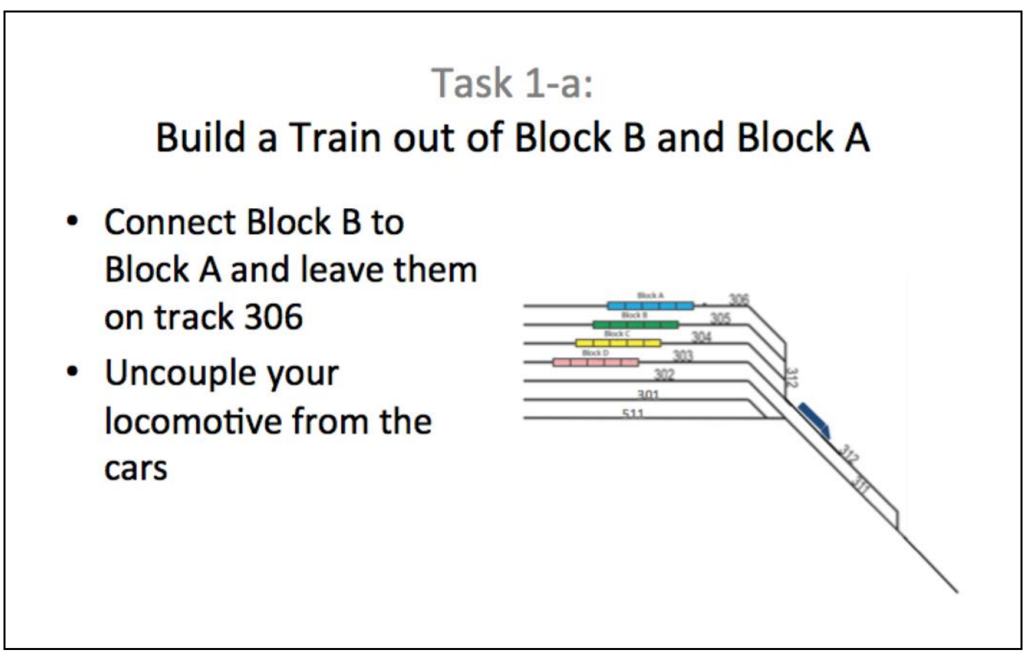


Figure 8. An example of a trainyard task assignment used by participants to build trains and break down trains in the trainyard simulator.

Experimental Condition

In the experimental condition, the experimenter gave participants one task assignment sheet at a time. Specifically, after reading the experimental session instructions (see Appendix C), the experimenter gave the participant the first task assignment sheet and informed the participant that they will be given one task assignment sheet at a time. The experimenter instructed participants to report completion of the task by saying out loud "Reporting completion of task. Requesting next task." After hearing the request, the experimenter entered the room and gave the next task assignment sheet to the participant.

Control Condition

In the control condition, the experimenter gave participants all of their tasks assignment sheets at the beginning of the session. Specifically, the experimenter read the control session instructions (see Appendix D), placed the stack of all four task assignment sheets (the order of which corresponded to the order in which the tasks were to be completed, with the first task appearing on the top of the stack) on the table next to the participant and informed participant that the task assignment sheets were all of the assigned tasks for the day. The experimenter instructed participants to complete the task assignments and bring the task assignment sheets to the experimenter after they had completed the tasks.

Recording Post-Completion Step Communications

The experimenter sat directly outside of the experimental room, and the door was left open to ensure that all communications could be heard and recorded. Participants reported position of track switches (i.e., the PC step) by stating out loud, "reporting position of track switches." Experimenters recorded the total number of trainyard tasks completed during the session and the number of times participants reported the position of track switches.

Design

The experiment was a within subjects design, with two levels of the independent variable. The independent variable was whether or not participants were required to request their next task from the dispatcher (Yes, the intervention; No, the control). Conditions were counterbalanced across participants. The dependent variable was PCE rate, which was obtained by dividing the total number of opportunities to make a PCE in one session (i.e., up to four opportunities to make a PCE) by the total number of PCEs made in the session (i.e., 0-4 PCEs).

CHAPTER 3

RESULTS

Data were analyzed using SPSS 21.0. Each reported statistic was tested at $\alpha = .05$. Analysis focused on proportion of PCEs. Differences in the control and experimental conditions were examined using paired samples t-tests. Effect sizes are expressed in both original units and standardized Cohen's d values. Unless otherwise stated, data from 28 participants were included in analysis.

The number of opportunities to make PCEs differed across participants and across trial sessions because participants completed two, three, or four trainyard tasks per 1 hr trial session. Because the base of opportunity to make PCEs differed across participants and across trial sessions, the data did not meet the assumptions of parametric statistical tests and an arcsine transformation was performed on the data before subjecting the data to statistical analysis. See Table 3 for mean number of opportunities to make PCEs, mean number of PCEs made, and mean proportion of PCEs in original units for the control and intervention conditions. Also presented in Table 3 are mean proportions of PCEs in transformed data values for each condition.

Table 3

Opportunities to make PCEs, number of PCEs made, and proportion of PCEs for the control and intervention conditions expressed in original units. Proportion of PCEs for the control and intervention conditions after arcsine transformation.

	Original Units			Transformed Data
	Opportunity for PCEs	PCEs	Proportion of PCEs	Proportion of PCEs
Condition	*M*	*M*	*M* (*SD*)	*M* (*SD*)
Control	3.43	2.39	0.69 (0.43)	1.07 (0.67)
Intervention	3.50	0.79	0.24 (0.41)	0.38 (0.64)

PCE rate was substantially higher in the control (M = 0.69, SD = 0.43) than in the intervention (M = 0.24, SD = 0.41), t(27) = 5.37, $p < .001$, d = 1.06, 95% CI [.27, .62]. Furthermore, analysis on transformed data confirmed the significant difference in PCEs between the control and intervention condition, t(27) = 5.37, $p < .001$, d = 1.06, 95% CI [.17, .67]. Thus, the intervention across all participants reduced PCE rates by 65%. When we excluded the seven participants who did not make an error in the control condition (and therefore did not need an intervention) the means were 0.92 (0.17) and 0.33 (0.45), for control and intervention respectively, a drop of 0.59 points and a percentage reduction similar to the overall group (64%).

CHAPTER 4

DISCUSSION

Our hypothesis that requiring participants to call experimenters near the end of a task to request their next assignment would result in a reduction in PCEs was supported by the intervention reducing PCEs rates by 65%. Neither existing theory could easily predict the reduction in post-completion errors. In fact, existing theories would have predicted an increase in PCEs. Li et al. would have attributed the increase to the disruption caused by performing the additional step of requesting the next task assignment on the automatic cueing mechanism. Byrne's model would seem to argue that adding an additional task for the operator to perform would increase operator workload, causing an increase in PCE rates. Indeed, because our intervention moved participants on to a subsequent task before the PC step of the current task was performed, one might think that the final step of tasks would easily be omitted. However, it was not.

We suggest that the significant decrease in PCE rates occurred because the additional step was related to the PC step of the current task in that participants used the same communication method (i.e., they reported to the experimenter) to complete this additional task as they had for the PC step of the current task. In this way, the new first step of a task (i.e., requesting the next task from the experimenter) served as a reminder to complete the final step of the current task (i.e., report the position of track switches). In other words, the additional step served as an associative cue to complete the possibly forgotten PC step. Furthermore, as supported by our results, we do not believe that the forgotten steps of the current task are purged and unable to be recovered, as Byrne would suggest, or cannot be brought to conscious awareness, as Li et al. would suggest. Rather, the associative cue acts as a reminder to re-open a closed task and review the steps that could have been omitted.

Previous studies have identified task interruptions (Li et al.) and high operator workload (Byrne & Bovair) as contributing to the PCE problem. However, in these previous studies, high PCE rates were observed even when task interruptions and additional tasks were removed, suggesting that there are other unidentified factors that contribute to the systematic PCE problem. We believe that PCEs were observed in the absence of secondary tasks and interruptions because users experience a premature "sense of closure" towards the end of a task (Van Bergen, 1968; Kintsch, 1988; Thimbleby, 1990; Greist-Bousquet & Schiffman, 1992), which contributes to their tendency to move on to the next task and abandon any unsatisfied steps in the current task. Furthermore, even if the previous task was "closed," should there be a lingering sense that the previous task was not completed (Greist-Bousquet & Schiffman, 1992), immediately moving on to the next task would not allow conductors the opportunity to "open" the "closed" task by reviewing the previous task in memory. We believe the possibility of reviewing a closed task accounts for the instances when the PC step is remembered, which could not easily be explained by Byrne's workload theory or Li et al.'s interruption theory. Our intervention facilitates the review of the "closed" task by pointing conductors to the last step of the previous task via an associative cue.

One alternative explanation for the observed difference in PCE rates in the control and experimental conditions would be that participants in the control condition might have read all of the task assignments at the beginning of the session and prior to beginning their first task, which could result in overloading their working memory. In other words, the relatively high PCE rates for the control condition could have been due to the high workload that participants may have imposed on themselves by activating future goals in memory, which, as Byrne would suggest, interferes with the goal of completing the current task. However, there are two reasons that high workload could not be the only factor contributing to high PCE rates.

First, if participants in the control condition experienced higher workload due to holding multiple upcoming tasks in working memory, it is likely that PCE rates would be the highest for the first task, when participants had three remaining tasks to complete, and would decrease the further along they were in the session as there would be fewer future task assignments to interfere with the current task. However, we did not observe such a trend of decreasing PCE rates on later tasks. Second, according to Byrne's workload-based PCE explanation, after the goal for the current task had dropped below threshold in a high workload situation, it would not be possible to recover the uncompleted steps. However, this was clearly not the case in our study. Therefore, we do not believe that simply overloading participants in the control condition by giving them four task assignments at the same time is the most likely explanation.

A second alternative explanation for the effectiveness of our intervention at reducing PCEs is that preventing participants in the experimental condition from completing the study without calling the experimenter for their next task, and not the associative cue itself, reduced PCEs. In other words, because participants were prevented from immediately moving on to the next task after finishing the current task, the pause that occurred after completing a task could have allowed them to review the "closed" previous task, and remember to complete the PC step. In this way, there could have been nothing special about the additional step of requesting the next task. However, it was often the case that participants requested the next task before reporting the position of track switches. We believe this is strong evidence against the explanation that participants remembered the PC step on their own, and for the plausibility of the communication with the experimenter serving as an associative cue to revisit the PC step.

Although we believe that forcing participants to request their next task before moving on with the study, it might seem like a logical next step to simply force participants to report the position of track switches instead. This modification could be thought of as a behavioral analog to functionality built into technology that prevents the user from moving forward without completing the PC step (Blandford, 2000). However, in our real-world example, this would require the yardmaster to ensure that conductors report track switches before giving conductors their next assignment, which would create another opportunity for error, this time on the part of the yardmaster. Because our intervention forces conductors to slow down and also serves as a reminder to complete the current task, it addresses the PCE problem at the level of the user, and does not rely on the yardmaster, who is removed from the actual work of building and breaking down trains, to correct the problem.

As our results would suggest, associative cueing can be used to "re-open" a "closed" task and help ensure that valuable steps that promote the safe operations of trains in a trainyard, such as reporting the position of task switches, will be completed by conductors. Furthermore, even if contributory factors such as high workload or task interruptions are present at the time of the PC step, possibly contributing to the likelihood that the PC step will be forgotten, it is possible that the PC step is still likely to be recovered with our intervention as conductors are cued to revisit the final step after they have completed the main task. Although previous theories would suggest that interruptions and high task load inevitably increase PCEs, if designed in the right way, interventions that leverage the operator's ability to revisit previous tasks may be a good solution for ensuring that critical steps are remembered.

Our participants were undergraduate students, which always brings into question the transferability of results to the target population. However, although our sample was not taken from the target population, the fact that the effect of the intervention on PCE rates was robust to participants who performed poorly on the main trainyard tasks is important because it speaks to the overall effectiveness of the intervention even though the main task may have been more difficult for some than others.

Although our intervention did not completely eliminate PCEs for every participant, the significant reduction in average PCE rate should greatly contribute to a decrease in run-through switches in general. Although we do not believe that failing to report the position of track switches is the sole cause of run-through switches, when this error occurs in conjunction with other problematic system-level factors, run-through switches are likely to occur. In other words, especially when other factors that contribute to run-through switches are present, our behavioral intervention could reduce the likelihood that a catastrophic event will occur. Because post-completion errors have been found to be a particularly difficult issue to address (Blandford, 2000), our intervention could go a long way in increasing the resilience of safety-critical systems, especially when implemented along with other system-wide preventative measures. Finally, not only was the intervention effective at reducing PCEs, it does not require any changes to technology which would be prohibitive in trainyard operations.

APPENDIX A

TRAINYARD TASK ASSIGNMENT SHEETS

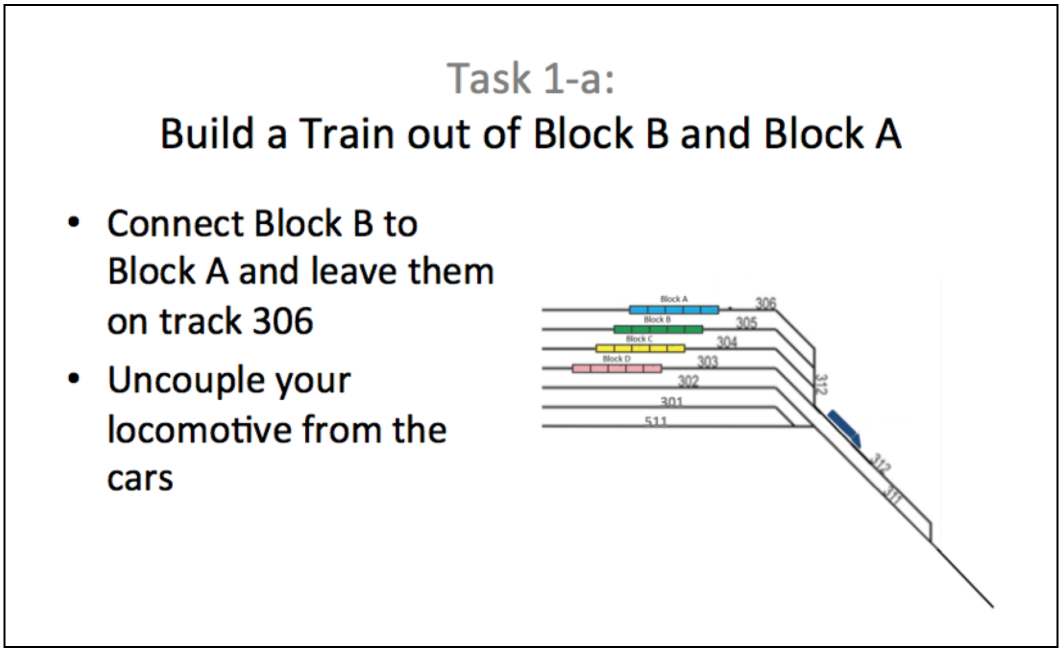


Figure 9. Task assignment sheet used by participants during trial 1 on day 1 of trial sessions.

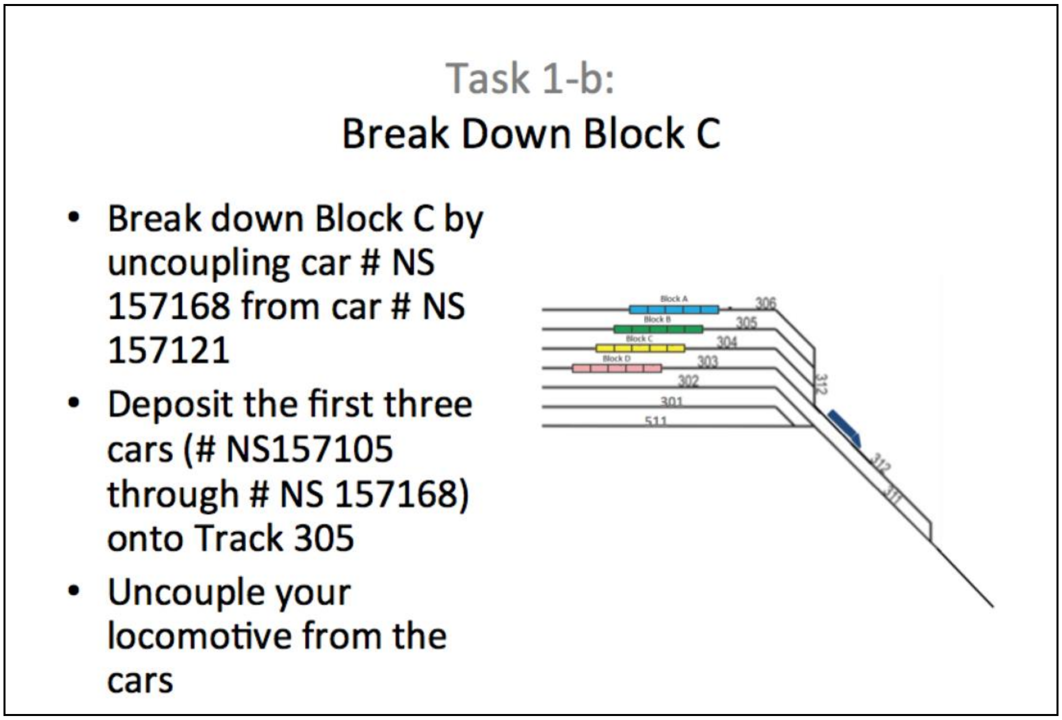


Figure 10. Task assignment sheet used by participants during trial 2 on day 1 of trial sessions.

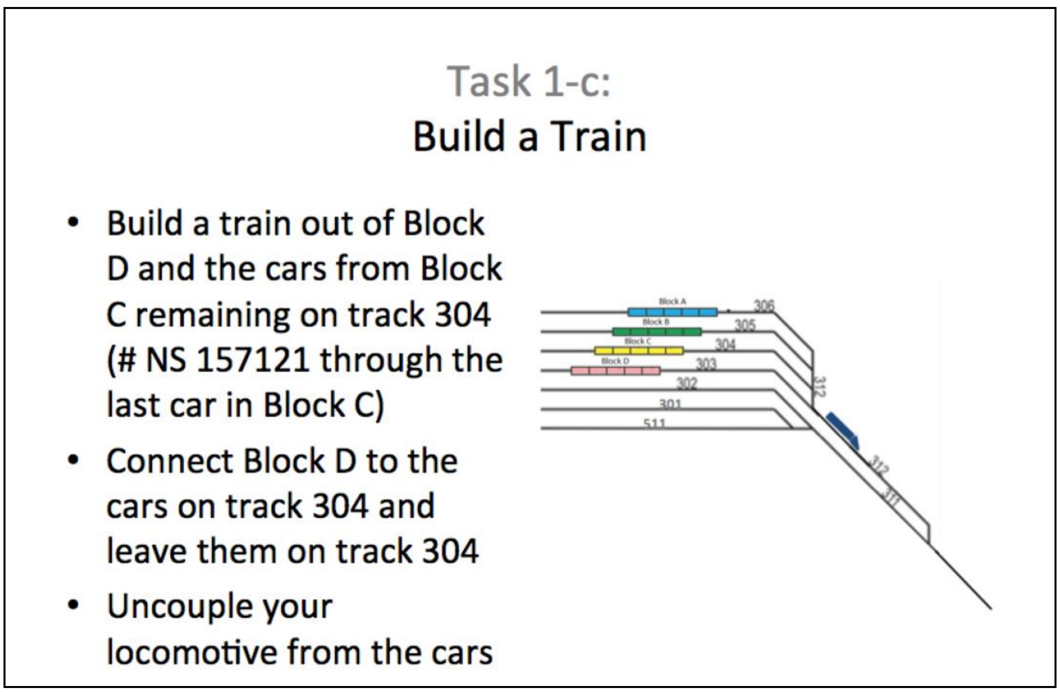


Figure 11. Task assignment sheet used by participants during trial 3 on day 1 of trial sessions.

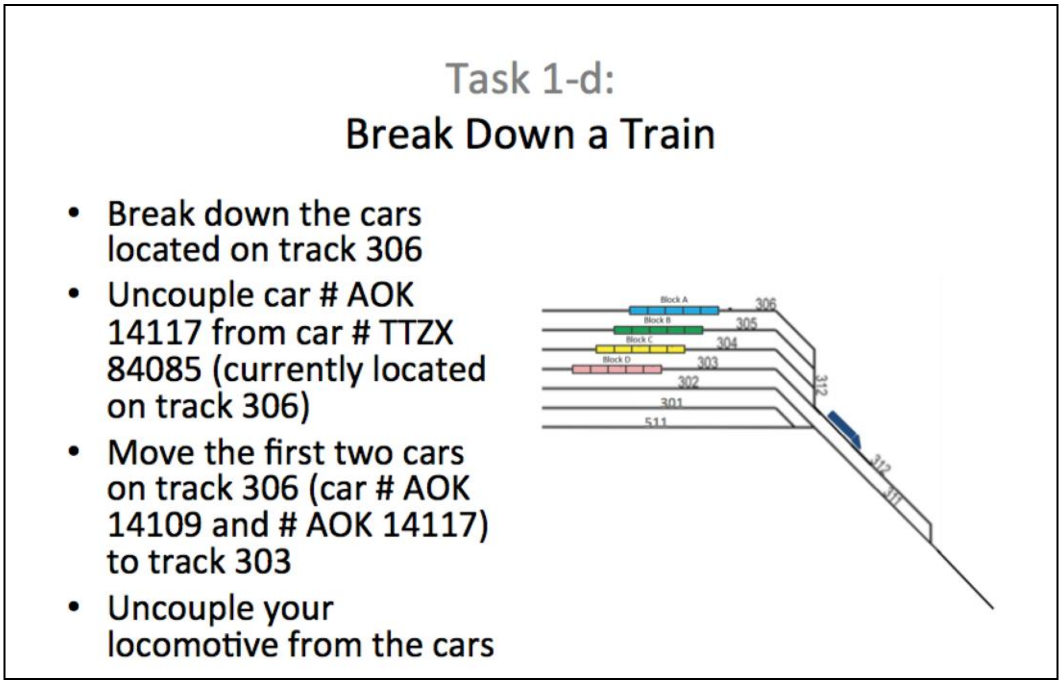


Figure 12. Task assignment sheet used by participants during trial 4 on day 1 of trial sessions.

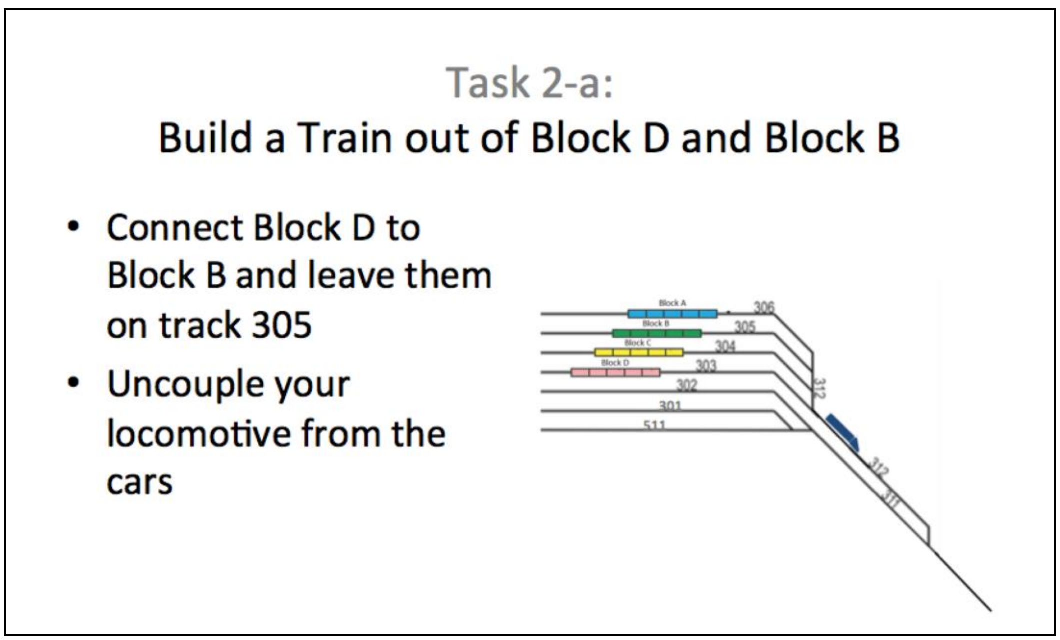


Figure 13. Task assignment sheet used by participants during trial 1 on day 2 of trial sessions.

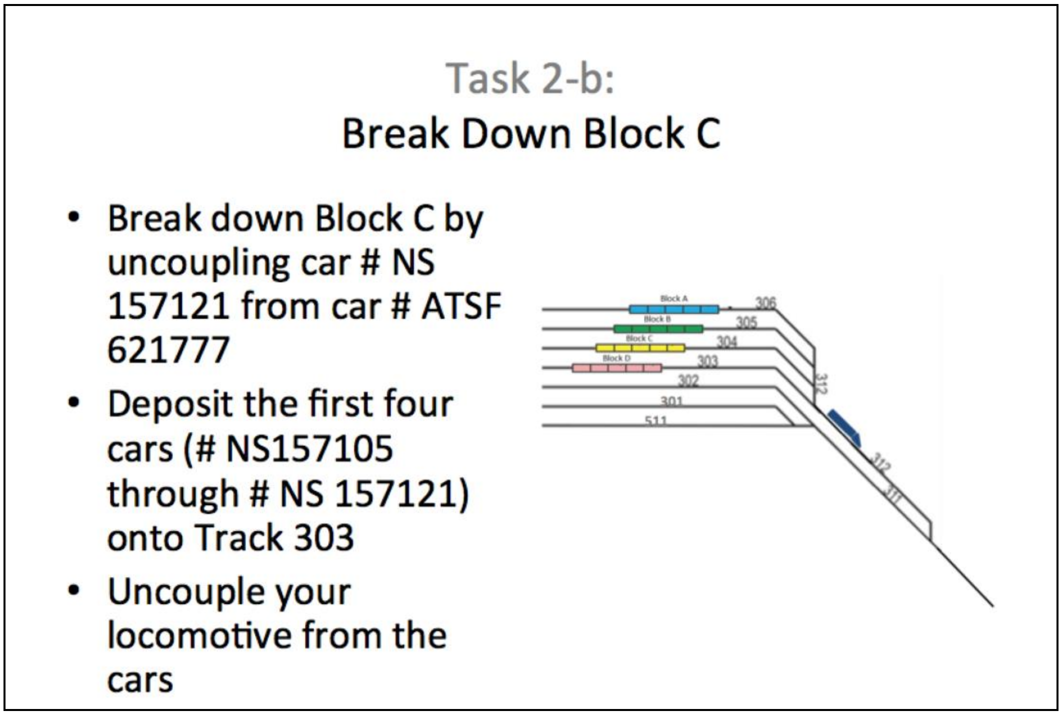


Figure 14. Task assignment sheet used by participants during trial 2 on day 2 of trial sessions.

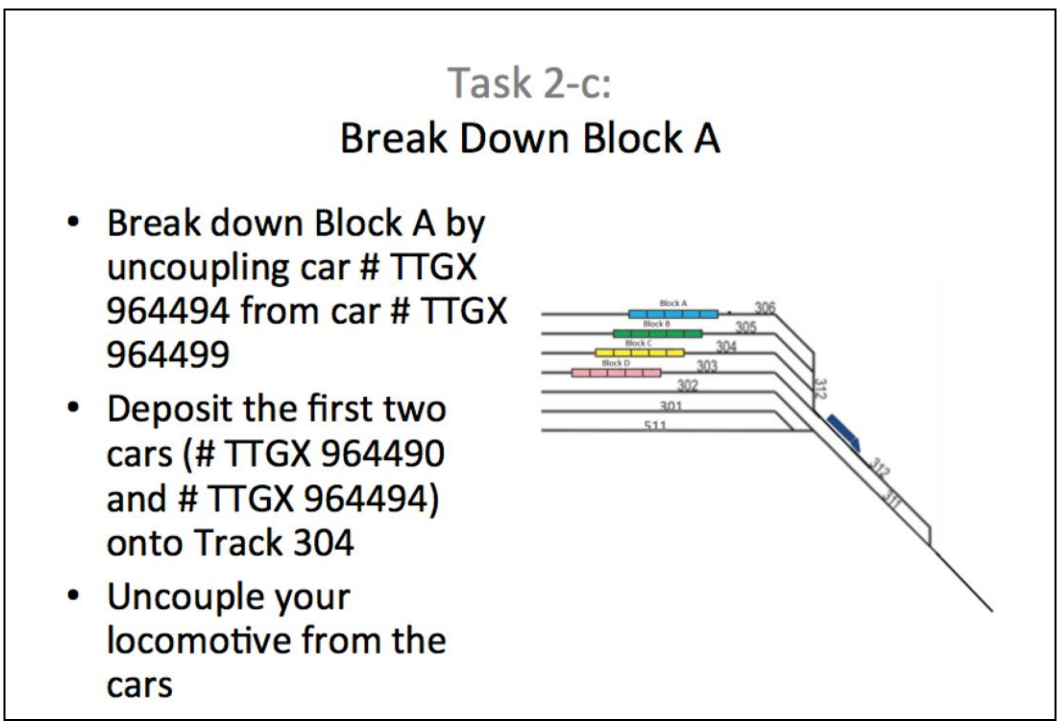


Figure 15. Task assignment sheet used by participants during trial 3 on day 2 of trial sessions.

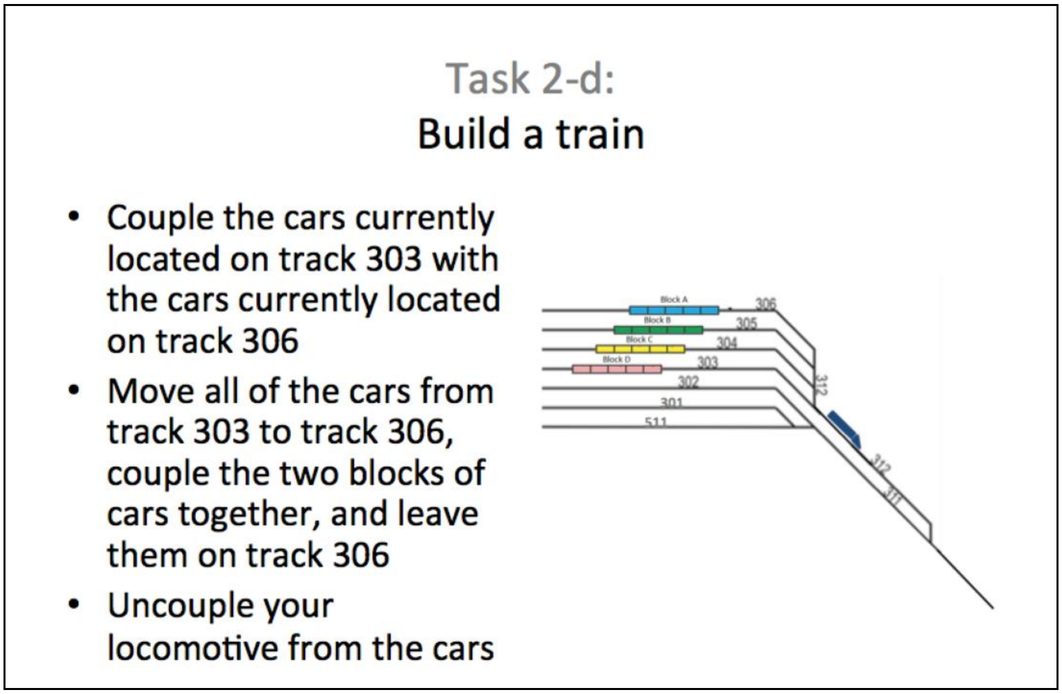


Figure 16. Task assignment sheet used by participants during trial 4 on day 2 of trial sessions.

APPENDIX B

TRAIN CAR LIST

Trainyard Car List - Howells Yard

Block A – Track 306		
Sequence Number	**Car Number**	**Weight (tons)**
001	TTGX 964490	032
002	TTGX 964494	032
003	TTGX 964499	032
004	TTGX 964483	032

Block B – Track 305		
Sequence Number	**Car Number**	**Weight (tons)**
001	AOK 14109	100
002	AOK 14117	100
003	TTZX 84085	030
004	UP 273195	030
005	NDYX 162	030
006	NATX 866567	100

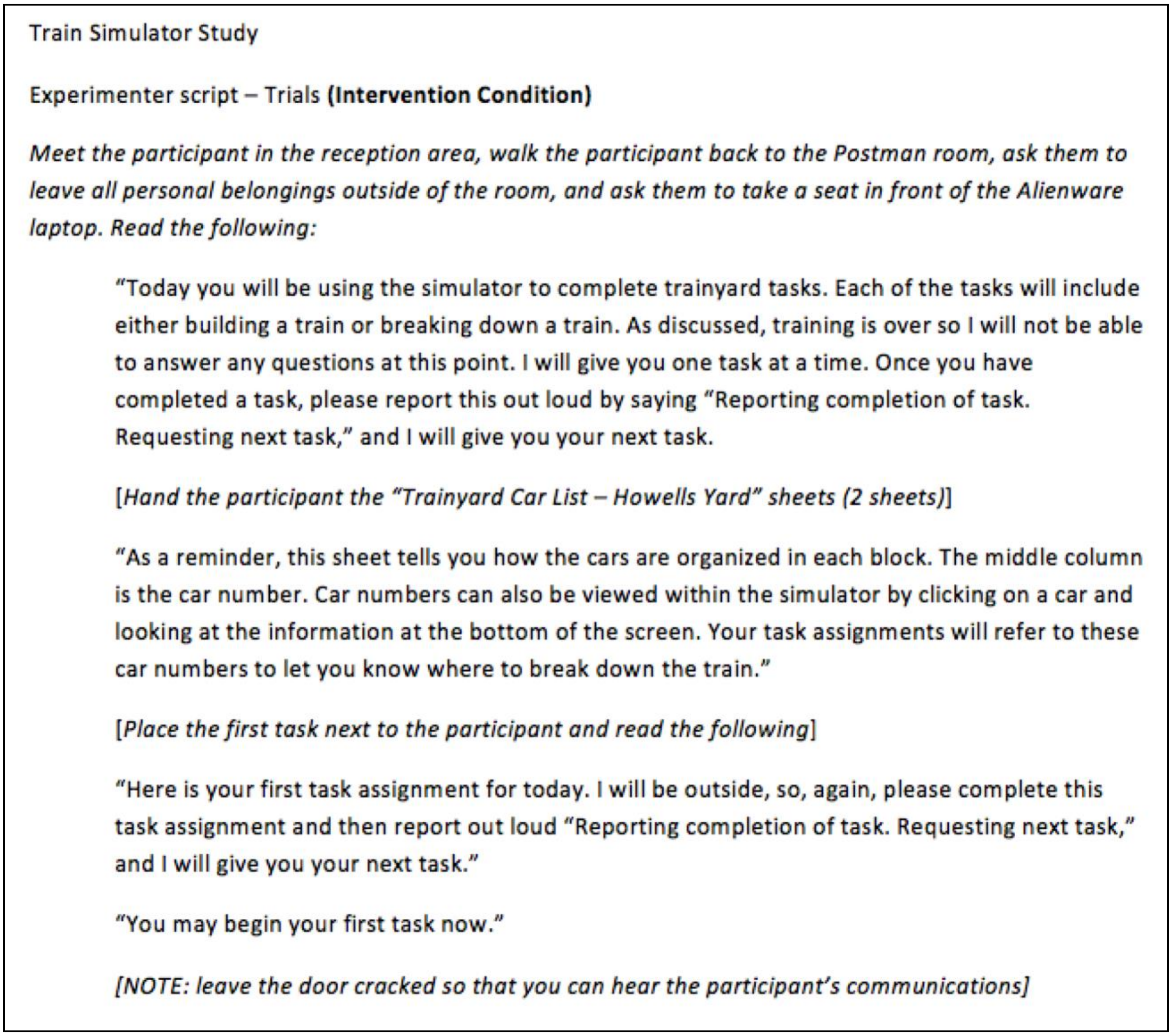
Block C – Track 304		
Sequence Number	**Car Number**	**Weight (tons)**
001	NS157105	030
002	NS 157142	030
003	NS 157168	030
004	NS 157121	030
005	ATSF 621777	107
006	ATSF 621769	107
007	MP 794705	100
008	MP 794722	100
009	MP 367748	032
010	TTX 940284	030
011	UP 901081	030
012	UP 901055	030

Block D – Track 303		
Sequence Number	**Car Number**	**Weight (tons)**
001	FURX 310112	030
002	FURX 310105	030
003	MRL 35061	030
004	MRL 35082	030
005	MRL 35077	030
006	GATX 610012	100

Figure 17. Train car list used by participants to know where to break down trains.

APPENDIX C

SESSION INSTRUCTIONS READ BY EXPERIMENTER



Train Simulator Study

Experimenter script – Trials **(Intervention Condition)**

Meet the participant in the reception area, walk the participant back to the Postman room, ask them to leave all personal belongings outside of the room, and ask them to take a seat in front of the Alienware laptop. Read the following:

> "Today you will be using the simulator to complete trainyard tasks. Each of the tasks will include either building a train or breaking down a train. As discussed, training is over so I will not be able to answer any questions at this point. I will give you one task at a time. Once you have completed a task, please report this out loud by saying "Reporting completion of task. Requesting next task," and I will give you your next task.
>
> [*Hand the participant the "Trainyard Car List – Howells Yard" sheets (2 sheets)*]
>
> "As a reminder, this sheet tells you how the cars are organized in each block. The middle column is the car number. Car numbers can also be viewed within the simulator by clicking on a car and looking at the information at the bottom of the screen. Your task assignments will refer to these car numbers to let you know where to break down the train."
>
> [*Place the first task next to the participant and read the following*]
>
> "Here is your first task assignment for today. I will be outside, so, again, please complete this task assignment and then report out loud "Reporting completion of task. Requesting next task," and I will give you your next task."
>
> "You may begin your first task now."
>
> *[NOTE: leave the door cracked so that you can hear the participant's communications]*

Figure 18. Experimental session instructions read by experimenter.

Train Simulator Study

Experimenter script – Trials **(Control Condition)**

Meet the participant in the reception area, walk the participant back to the Postman room, ask them to leave all personal belongings outside of the room, and ask them to take a seat in front of the Alienware laptop. Read the following:

> "Today you will be using the simulator to complete trainyard tasks. Each of the tasks will include either building a train or breaking down a train. As discussed, training is over so I will not be able to answer any questions at this point, so please continue through the tasks on your own."
>
> [*Hand the participant the "Trainyard Car List – Howells Yard" sheets (2 sheets)*]
>
> "As a reminder, this sheet tells you how the cars are organized in each block. The middle column is the car number. Car numbers can also be viewed within the simulator by clicking on a car and looking at the information at the bottom of the screen. Your task assignments will refer to these car numbers to let you know where to break down the train."
>
> [*Place all of the trainyard tasks next to the participant and read the following.*]
>
> "Here are all of your task assignments for today. Please complete only one task assignment at a time. When you finish a task, please flip to the next one and complete it."
>
> "Please bring me all of your papers after you have completed all of the tasks. You may begin your first task now."
>
> *[NOTE: leave the door cracked so that you can hear the participant's communications]*

Figure 19. Control session instructions read by experimenter.

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