

# Effects of Varied Priority Training on Complex Perceptual-Motor Learning

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## Abstract

We reported results from a study on the effects of different training methods on complex perceptual-motor skill acquisition using a version of the Space Fortress game, which was originally designed to study the acquisition of complex perceptual-motor and cognitive skills in a multi-tasking environment. Participants were randomly assigned to the Fixed Priority (FP) and Varied Priority (VP) training conditions. Action sequences for controlling the spaceship in a frictionless environment using a joystick were analyzed and compared across conditions. Consistent with the previous findings, VP training was in general more successful than FP training. However, we found that VP training benefited participants more in the low performance group than in the high performance group. Participants in the VP training condition showed faster learning of optimal action sequences and faster reduction of suboptimal action sequences. In addition, results showed that in the high performance group, participants in the VP training condition used significantly more optimal action sequences than in the FP training condition. The findings have important implications on how the effectiveness of different training methods can be optimized for people with different cognitive abilities.

**Keywords:** Space Fortress game; Fixed Priority training; Varied Priority training, High performance group, Low performance group.

## Introduction

Effectiveness of training perceptual-motor skills in complex, multi-tasking environments has been an important cognitive science research topic and has been studied for decades. Examples of tasks in complex, multi-tasking environments involved flying a military jet, driving a vehicle, operating a machine, etc. Operators in these environments are required not only to learn the necessary information regarding operation modes, control procedures, regulations and limitations, but also to apply these details under real-time constraints with competing cognitive demands.

Although in complex multi-tasking environments, practice generally improves performance in different training methods, researchers have found that practice time alone is not sufficient to explain differences in effectiveness of these methods. This has directed more focus towards comparing different training methods through computer-based cognitive simulations such as the 'Space Fortress' game (Mane & Donchin, 1989). This kind of synthetic training environment not only allows careful manipulation of multiple variables to carefully tease apart the multiple cognitive processes that interact dynamically to influence

performance, but also allow direct measurement of how performance improves in different training environments.

Among the different training methods, the differences between whole-task training (e.g. learning to steer a bicycle and operate the pedals simultaneously) and part-task training (e.g. separately learning to steer a bicycle and operate the pedals) have been studied most extensively by researchers. In general, research shows that whole-task training is ineffective because the trainee may be overwhelmed by the complexity of the task; while part-task training is ineffective because the trainee may not have sufficient experience in coordinating between different sub-components of the tasks (Ioerger et al., 2003). As a result, a hybrid training method, often called part-whole training, was proposed. Under this approach, the whole task is decomposed into segments. Participants are trained on each of the segments separately before moving to practice the total task as a whole. Although part-whole training has shown to be effective for training in complex, multi-tasking environments (Adams 1987, Wightman & Lintern 1985, Schneider 1985), it still has two problems. First, it is difficult to select the parts to train. Second, by isolating segments, it still suffers from the same problem as in part training, in which training effectiveness may decrease because of the removal of the broader context in which the parts were performed (Gopher et al., 1989).

Varied Priority (VP) training (e.g., Kramer et al., 1995) is a training method that manipulates only the relative emphasis of selected subcomponents in the multi-tasking environment and leaves the whole task intact (Gopher et al., 1989). Gopher et al. showed that systematically varying levels of priorities on attentional control through instruction and feedback could lead to better learning and performance in multi-tasking tasks. They argued that VP training enabled participants to explore different strategies and thus develop a better match between the requirements of the tasks and the efficiency of their efforts. They suggested that participants under VP training condition not only could receive more information on their performance on the emphasized element, but could also learn the costs to performance decrement on the de-emphasized task. As a result, VP training makes people better able to strategically allocate attention to multiple components of the task to comply with the change in emphases during training.

Although benefits of VP training on global performance have been demonstrated through a number of studies, there is still a lack of understanding on the specifics of how it promotes learning of perceptual-motor control. The current

study used a version of the original Space Fortress game to study the impact of VP training on learning a complex perceptual-motor skill. The goal is to understand the impact of VP training on learning of action sequences in a dynamic multi-tasking environment.

## The Space Fortress Game

The Space Fortress game was originally developed to study the acquisition of complex perceptual-motor and cognitive skills in fast-paced multi-tasking environments (Mane & Donchin, 1989). The main objective of the game was to maximize the total scores by shooting missiles at and destroying the space fortress, while maintaining a spaceship within a certain velocity limit and pre-specified boundaries on the screen. Missiles were fired from the spaceship, whose movement was controlled by the participant. In addition to destroying the fortress, the participant had to protect his/her spaceship against damage from the fortress and mine. Participants used a joystick to control the spaceship. Forward movement (thrust) of the stick caused the spaceship to accelerate. Left and right movements caused the spaceship to rotate counter-clockwise and clockwise respectively. Because the spaceship flew in a frictionless environment, it would continue to fly in the direction to which it was pointing unless it was rotated and a thrust was applied. In that case, the spaceship would change its direction of movement. This change of movement was essential not only in controlling the spaceship within boundaries, but also in maintaining its velocity within limits because of the frictionless environment (accelerating in a frictionless environment would lead to higher and higher velocity unless there was a change in flying direction).

Participants were instructed to learn to control and maintain the spaceship within a particular range of velocity and a bounded area on the screen. These two subtasks were reflected by the velocity and control scores respectively, which were continuously updated on the screen. Participants also had to protect the spaceship from being hit by bombs emitted from the fortress and mines that periodically emerged on the screen. Participants could also shoot the mines to gain points. The four subscores: points, control, velocity, and speed added up to the total scores, which were also continuously displayed on the screen.

A cognitive task analysis (Schraagen et al., 2000) was conducted to identify major components of the task and to explicate the hierarchical relationship between internal goals and external cues. Figure 1 shows the overall structure of the cognitive task analysis of the Space Fortress game. The overall objective of the game is shown at the function purpose level. The four major subscores are shown at the abstract function level, and each of the subscores is mapped to one or more generalized functions. These generalized functions were assumed to be the major subgoals that participants had when they were learning to do the task, and they were explicitly taught how to accomplish these subgoals before they began the training. Each generalized function is then mapped to the various state indicators (e.g.,

PNTS indicated the points subscore, CNTRL indicated the control subscore, etc.) at the physical function level, which were continuously updated on the display as participants interacted with the task, and they were directly influenced by moment-to-moment actions (joystick or mouse) executed by the participants at the physical form level.

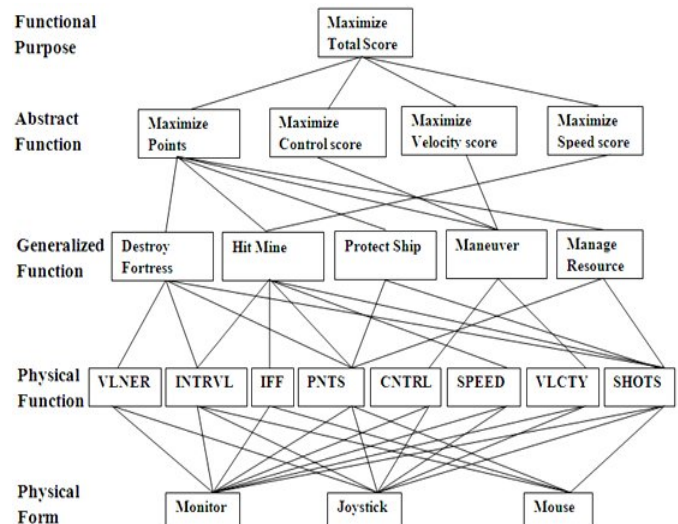


Figure 1: Cognitive task analysis of the Space Fortress game.

In the Fixed Priority (FP) training condition, participants were instructed to give equal weight to the subscores throughout the sessions. In the Varied Priority (VP) training condition, participants were instructed to emphasize one of the four subscores in each game, and the emphasis changed throughout the sessions. Due to space limitation, we will focus on effects of the training conditions on the velocity subscore, which reflected how well the participants could successfully control the velocity of the spaceship. This subscore was also the most predictive of overall performance for all participants.

## Method

### Participants

Thirty-nine participants recruited from University of Illinois community were randomly assigned to either the Fixed Priority (FP) training or the Varied Priority (VP) training condition. Participants had no more than a moderate amount of video game experience.

### Tasks

Figure 2 shows the Space Fortress game display. The starting position of a computer-controlled fortress was centered within two concentric hexagons. And a spaceship controlled by a joystick was located between two hexagons. The fortress rotated to track and fire shots at the spaceship. The small diamond between two hexagons is a shot from the fortress. The arrow is a missile from the spaceship. The

larger diamond is a mine, which appeared every few seconds. The dollar sign indicated an opportunity for bonus.

A control panel was shown below the area in which the spaceship and mines flew. It displayed four subscores, including points (PNTS), control (CNTRL), velocity (VLCTY), and speed (SPEED). It also displayed the vulnerability (VLNER) of the fortress, an indicator to identify friend or foe (IFF), an interval (INTRVL) which indicated the time between IFF responses, and shots (SHOTS) which indicated the number of missiles remaining on the spaceship.

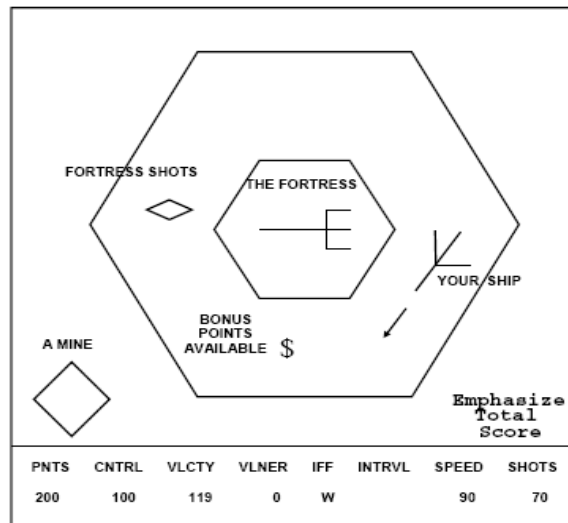


Figure 2: The Space Fortress game display

Participants in both FP and VP conditions initially completed the same three trials of an aiming task to destroy as many mines as possible. This aiming task was designed to demonstrate how to use the joystick to control the spaceship in a frictionless environment. The total aiming score was a function of the number of destroyed mines and the speed with which they were destroyed.

After completing the aiming task, participants in each condition received instructions for the actual Space Fortress game. Participants were instructed that the main objective of the game was to maximize the total score, and this was the same for both conditions. However, participants in the FP condition were told to emphasize each of the four main subscores (points, control, velocity, and speed) equally throughout the whole experiment. On the other hand, participants in the VP condition were told to improve and monitor only one particular subscore while maintaining focus on other subscores in any one of the trials.

## Procedure

All participants completed the training in 10 consecutive days. Each day they did a 2-hour session, with each session consisting of 7 blocks. The first and last blocks are test blocks in which participants are required to emphasize total scores. Participants are told these are not practice blocks.

There were 5 emphasis (practice) blocks between the test blocks. For the VP group, in each emphasis block participants were asked to emphasize some aspect of the game in the order of control, velocity, speed, points, and total score, and every other day, the reverse order. All emphasis conditions were communicated to participants by pop-up windows between sessions. Additionally, for the VP group, reminder text appeared at the corner of the display telling participants what they should be focusing on (see Figure 2). For the FP group, participants did the same amount of trials but are told to always emphasize total score.

## Results

Due to technical difficulties, two participants did not complete all of the tasks. The total score of one participant was 3 standard deviations away from the mean and was excluded from further analysis. We therefore had data from 36 participants in the following analyses.

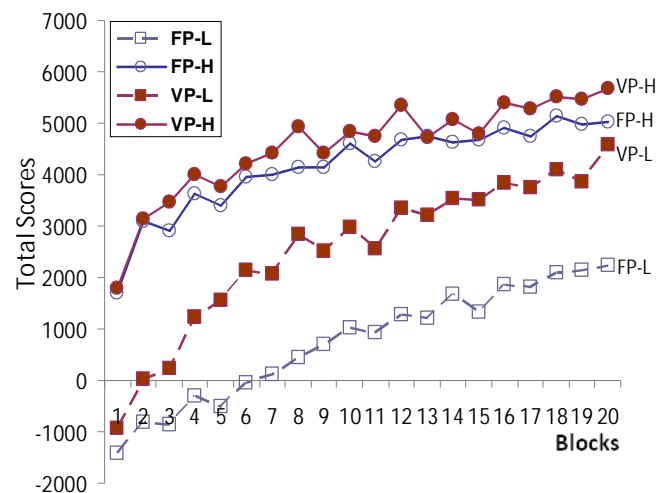


Figure 3: Average total scores across test blocks for the High (H) and Low (L) groups in each condition

Based on previous findings that VP training had different benefits for low and high ability participants (Gopher et al., 1989), we performed a median split on the total scores of the first test block to identify the High (H) and Low (L) performance groups in each condition. Figure 3 shows the total scores for each group across the 20 test blocks. Analysis of Variance (ANOVA) showed a significant main effect of blocks ( $F(19, 627) = 106.946, p < .001$ ), H-L ( $F(19, 627) = 106.946, p < .001$ ), but not for conditions (FP vs. VP). However, there was a significant interaction between blocks and H-L ( $F(19, 627) = 3.891, p < .001$ ), and between blocks and conditions ( $F(19, 627) = 1.745, p < .05$ ). Participants in the High and VP groups learned significantly faster across blocks than the Low and FP groups, respectively. The three-way interaction conditions  $\times$  HL  $\times$  blocks was marginally significant ( $p = 0.18$ ).

The results showed that, in general, VP training was more successful than FP training. Interestingly, the difference was

larger in the Low performance group, in which participants started with a much lower score and was consistently lower throughout the 20 test blocks. In fact, Figure 3 shows that for the High performance group, participants in the VP condition were only slightly better than those in the FP conditions. However, for the Low performance group, the total scores for participants in the VP condition increased to almost the same level as the High performance group at the last block, but participants in the FP condition had a much lower total score even after 20 hours of training.

### Analysis of Action Sequences

To further understand the effects of VP training on perceptual-motor skill acquisition, action sequences were extracted from the game and compared across conditions. The game was designed such that clockwise rotation of the spaceship was better than counter-clockwise direction. Participants were informed of this optimal strategy upfront before the training began. To study how well participants learned to use this optimal strategy, we focus on the analysis of the number of clockwise rotation (CW), counter-clockwise rotation (CCW), and thrust (T) actions across blocks. Given that participants were instructed to control their spaceships by clockwise rotation, it was expected that participants would performed more CW and fewer CCW actions across blocks. In addition, given that the velocity score would decrease when velocity of the spaceship was too high, it was also expected that the number of T actions would decrease across blocks.

**First-order Action Sequences** Figure 4 shows that the number of T (thrust) actions in each condition. ANOVA showed significant main effect of H-L ( $F(1, 33) = 26.313$ ,  $p < .001$ ), but not for conditions. The interaction between conditions and H-L was marginally significant ( $F(1, 33) = 3.849$ ,  $p = .058$ ). As shown in Figure 4, participants used significantly fewer T actions in the High than the Low group. Participants in the FP-L group used much more T actions than those in the VP-L group, but the difference was much smaller between the FP-H and VP-H groups. ANOVA also showed that the main effect of blocks was significant ( $F(19, 627) = 3.331$ ,  $p < .001$ ), confirming the obvious downward trend, suggesting that participants were successful in reducing the use of thrust in controlling the spaceship. The interaction between blocks and H-L was also significant ( $F(19, 627) = 3.859$ ,  $p < .001$ ). The interaction between blocks and conditions and the three-way interaction was not significant.

Figure 5 shows the number of CCW (counter-clockwise) actions across 20 test blocks. ANOVA on the number of CCW actions showed significant main effects of conditions ( $F(1, 33) = 6.842$ ,  $p < .05$ ) and H-L ( $F(1, 33) = 28.116$ ,  $p < .001$ ). The interaction between conditions and H-L was also significant ( $F(1, 33) = 5.08$ ,  $p < 0.05$ ). The main effect of blocks and the interaction between H-L and blocks was significant ( $F(19, 627) = 11.306$ ,  $p < .001$  and  $F(19, 627) = 3.161$ ,  $p < .001$  respectively). However the interaction between conditions and blocks was not significant, nor was the three-way interaction.

Participants in the FP condition and Low group used significantly more CCW actions than the VP condition and High group, respectively. As shown in Figure 5, the number of CCW actions in the FP-L group was significantly higher than the VP-L group, but there was almost no difference between the FP-H and VP-H groups.

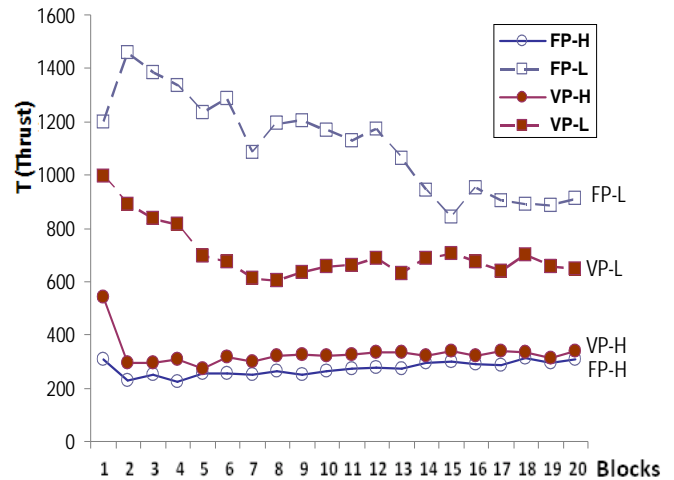


Figure 4: The number of T actions across test blocks for the High (H) and Low (L) groups in the Fixed Priority (FP) and Varied Priority (VP) conditions.

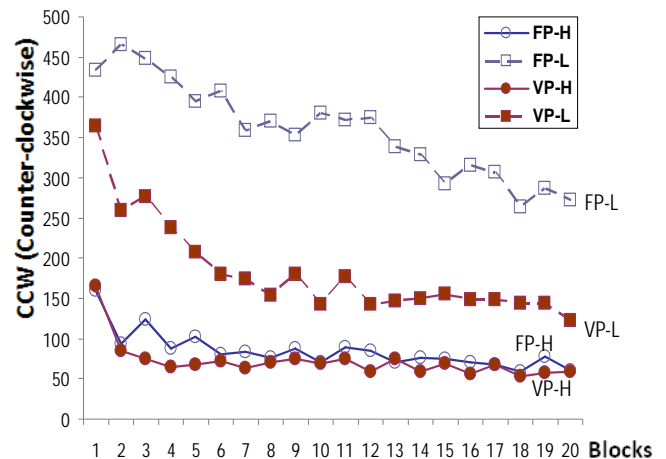


Figure 5: The number of CCW actions across test blocks for the High (H) and Low (L) groups in the Fixed Priority (FP) and Varied Priority (VP) conditions.

The overall behavioral patterns shown in Figure 4 and 5 were very similar, both showing that the number of “suboptimal” actions decreased across test blocks. However, similar to the improvements in total scores (Figure 3), participants in the High performance groups did not differ between conditions. On the other hand, participants in the Low performance groups showed a large difference: the FP-L group used significantly more “suboptimal” actions than the VP-L group. This pattern of results again supported the notion that VP training was more effective than FP training for the Low performance group. Apparently, participants



who were already good at controlling the joystick did not benefit much from either training method.

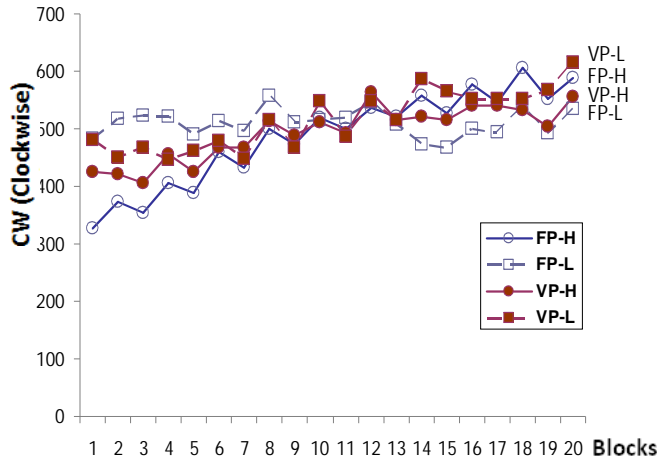


Figure 6: The number of CW actions across test blocks for the High (H) and Low (L) groups in the Fixed Priority (FP) and Varied Priority (VP) conditions.

Figure 6 shows the number of CW (clockwise) actions across test blocks. ANOVA on the number of CW actions showed that main effects of conditions, H-L and their interaction were not significant. However, the main effect of blocks was significant ( $F(19,627)=10.210, p<.001$ ). The interaction between conditions and blocks was significant ( $F(19,627)=2.358, p<.001$ ). As shown in Figure 6, although all participants used more CW actions across test blocks, the improvement differed across conditions. The improvement was bigger in the VP than the FP condition in the Low performance group, but not in the High performance group. Results again supported the notion that VP training was more effective to learn the optimal strategy to control the spaceship. Overall, we see that participants not only learned to reduce the number of actions needed to control the spaceship, but also learned to use more effective actions and reduced the use of suboptimal actions.

**Higher-order Action Sequences** We also extracted the transitions between actions to investigate further how the different training conditions influence learning of these higher-order action sequences. We extracted all second and third order transitions among the three actions CW, CCW, and T (e.g., CW-CW indicates a clockwise rotation followed by another clockwise rotation). There were a total of 9 second order and 27 third order transitions. None of the third order transitions showed significant differences between conditions. Due to space limitation, we will focus on two most frequent second-order transitions that showed significant differences between conditions.

Figure 7 shows the number of CW-T (clockwise-thrust) actions across test blocks. One major function of this action sequence was to change direction of the spaceship, and to control the spaceship to rotate in a clockwise direction and aim (and fire) at the fortress or mines to gain more points. ANOVA on the number of CW-T actions showed that the main effects of conditions (FP vs. VP) was marginally

significant ( $p=.085$ ). Three-way interactions blocks x conditions x H-L was significant ( $F(19,627) = 2.178, p<.005$ ). No other effect was significant.

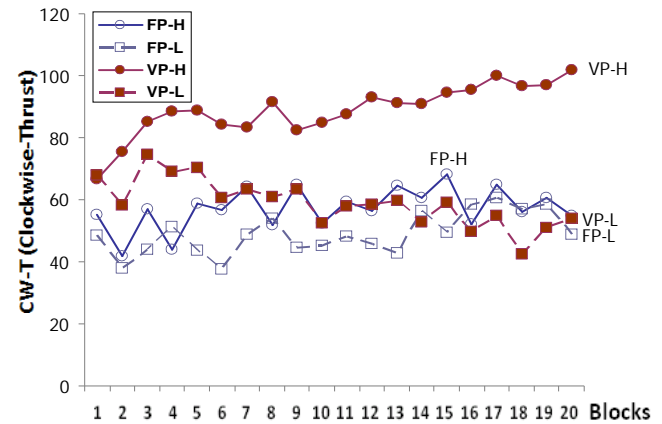


Figure 7: The number of CW-T actions across test blocks for the High (H) and Low (L) groups in the Fixed Priority (FP) and Varied Priority (VP) conditions.

Figure 7 clearly shows that the three-way interaction was caused by the higher number of CW-T in the VP-H group. Although we did not see major differences between the VP-H and FP-H in previous analyses, the higher number of CW-T showed that participants in the VP-H group not only were successful in controlling the spaceship (like the FP-H group), but they were also better at chunking the actions required to control and aim than the other groups.

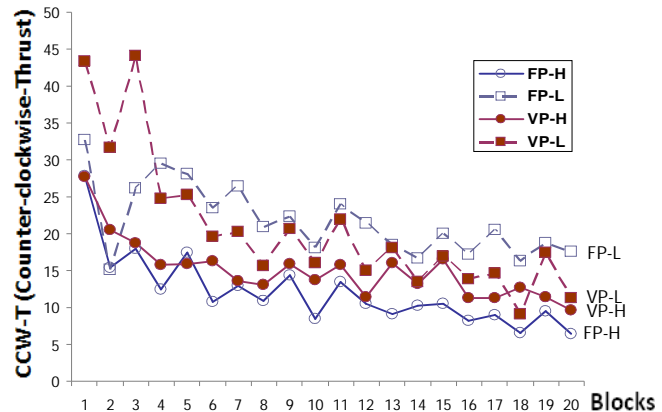


Figure 8: The number of CCW-T actions across test blocks for the High (H) and Low (L) groups in the Fixed Priority (FP) and Varied Priority (VP) conditions.

Figure 8 shows the number of CCW-T (counter-clockwise-thrust) actions across test blocks. CCW-T allowed participants to rotate in a counter-clockwise direction (which was suboptimal) and aim at the fortress or mines. ANOVA on the number of CCW-T actions showed that the main effect of H-L, and the two-way interaction blocks x conditions were marginally significant ( $p=.054$  and  $p=.108$  respectively). The main effect of blocks was significant ( $F(19,627) = 11.804, p<.001$ ), so was the three-

way interaction blocks x conditions x H-L ( $F(19,627) = 1.620, p < .05$ ). Results showed that participants were better at reducing the use of the suboptimal action sequences, and this improvement was faster for the VP-L than the FP-L group.

## Conclusion and Discussion

The current results in general provided further support for the VP training method for perceptual-motor skill learning in complex, multi-tasking environments. In the Space Fortress game, perceptual-motor skill learning (controlling the spaceship) was the most difficult and critical skill for performance. The total scores across test blocks showed that for the High performance group, participants in the VP condition were only slightly better than those in the FP conditions. However, for the Low performance group, participants in the VP condition were much better than those in the FP condition.

CW actions were designed to be better than CCW actions in the game, and T actions were expected to decrease across test blocks to obtain a higher velocity score. Therefore CW actions were identified as optimal first-order action sequence, and T actions, CCW actions, and CCW-T actions were separated into suboptimal action sequences. All participants used more CW actions (optimal) across test blocks, and similar to the improvements in total scores, the increases in CW actions were bigger in the VP than the FP condition in the Low performance group, but not in the High performance group. The results of T actions, CCW actions, and CCW-T actions showed that the number of suboptimal action sequences decreased across test blocks, and participants in the VP-L group used much fewer suboptimal action sequences than those in the FP-L group, but the difference was much smaller between the FP-H and VP-H groups. In addition, the analysis of CW-T action sequences showed that participants in VP-H group not only could successfully control the spaceship, but also perform better at chunking the actions required to control and aim than the other groups.

Research has shown that VP training is often better than whole-task, part-task, and part-whole training because VP training not only can reduce task complexity but also can keep the task components as a whole. Our results showed that VP training was more effective for people who started off with a lower performance level. Given that the Space Fortress game is a difficult task that requires efficient attention allocation strategies, it was possible that performance were largely limited by cognitive resources available to the individuals. Participants in the Low performance group were therefore likely reached the resource limits earlier than the High performance group. Given that under FP training, the trainees have to simultaneously split their resources over different subcomponents, but under VP training, the trainees can invest all resources in one subcomponent at one time and then shift to other subcomponents in other trials, participants in the VP group would therefore more likely able to practice each subcomponent with more resources available, and thus would more likely to acquire better action sequences than in the FP group.

In addition to more resources available for each subcomponent, experiences of how different subcomponents were dynamically related to each other were also important in the game. Under FP training, participants received feedback based on the total score that represented the sum of subcomponents (control, velocity, speed, points); while under VP training, participants received feedback on different subcomponents in different trials. Thus, in VP training, participants obtained more diverse feedback and a wider range of experiences of different attention allocation strategies than the FP group. In other words, not only did participants in the VP group able to learn to improve each subcomponent better, they were also more likely to learn when and how to shift attention to different subcomponents and experience the performance consequences. Participants in the VP group would therefore more likely learn to acquire the better action sequences than in the FP group.

In general, participants in the Low performance group tended to benefit most from the VP training, as they showed the biggest overall improvement through faster learning of optimal action sequences and reduction of suboptimal action sequences. However, even in the High performance group, participants were better at acquiring complex action sequences in the VP condition. Our studies complement previous research by showing exactly how the training method has an impact on the acquisition of optimal action sequences in a complex multi-tasking environment, and highlight how the method interacts with the initial learning ability of participants, which is important for realistic training consideration. Future research will further investigate the effectiveness of different training methods for people with different cognitive profiles to understand how these methods can be optimized for them.

## References

- Adams, J.A. (1987). Historical review and appraisal of research on learning, retention and transfer of human motor skills. *Psychological Bulletin* 101, 41-77.
- Gopher, D., Weil, M., & Siegel, D. (1989). Practice under changing priorities: An approach to training of complex skills. *Acta Psychologica*, 71, 147-179
- Ioerger, T.R., Sims, J., Volz, R.A., Workman, J., and Shebilske, W.L. (2003). On the Use of Intelligent Agents as Partners in Training Systems for Complex Tasks. *Proceedings of the 25th Annual Meeting of the Cognitive Science Society (CogSci'03)*.
- Kramer, A.F., Larish, J.F., & Strayer, D.L. (1995). Training for Attentional Control in Dual Task Settings: A Comparison of Young and Old Adults. *Journal of Experimental Psychology: Applied*, 1 (10), 50-76.
- Mane A., & Donchin, E. (1989). The space fortress game. *Acta Psychologica*, 71, 17-22.
- Schneider, W. (1985). Training high performance skills: Fallacies and guidelines. *Human Factors* 27, 285-301.
- Schraagen, J. M., Chipman, S. F., & Shalin, V.L. (2000). *Cognitive Task Analysis*. Mahwah, NJ: LEA.
- Wightman, D.C. and G. Lintem. (1985). Part-task training for tracking and manual control. *Human Factors* 27, 267-284.