Examining the effects of video game training on cortical recruitment of the attentional network

Honors Research Thesis

Presented in partial fulfillment of the requirements for graduation
with honors research distinction in Psychology in the
undergraduate colleges of The Ohio State University

by

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June 2011

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Abstract

We examined the effect of strategy on neural recruitment during video game-play. Fifty participants completed 30 hours of training under one of two training regimes: Fixed Emphasis Training (FET), in which participants practiced all the aspects of the Space Fortress (SF) game at once, or Hybrid Variable Priority Training (HVT), in which participants practiced while prioritizing selective aspects of game play at different times. After 30 hours of training, data indicated a significant advantage for the two training groups relative to a no-training control group. Following training, both groups showed reduced activation in cortical areas involved in attentional control, namely the dorsolateral prefrontal cortex, anterior cingulate cortex, and parietal cortices. The control group continued to show activation in these areas post-training, suggesting that the attentional demands of the task were not reduced for control participants but were reduced for trained participants. These data suggest that training reduced the attentional demands of SF, and this reduction was most evident in the HVT training group.

Keywords: attentional control, variable priority, video game training, young adults

Examining the Effects of Video Game Training on Cortical Recruitment of the Attentional Network

Though the popularity of video games has been widespread since the 1970's (Kent, 2001), it was not until the early 1990's that research recognized the potential of video games to improve various cognitive and perceptual skills (Donchin, 1995). Today, video game-play provides a novel context for the training of a number of basic abilities, including motor control, cognitive control, and memory. Research suggests that video game training is associated with enhanced behavioral performance and skill transference from the virtual gaming environment to the individual's real-world environment (Gopher, Weil, & Bareket, 1994). To elucidate the effectiveness of such computer-based training programs, it is necessary to examine the effects of different training strategies on performance and the neural correlates of these different learning techniques. To this end, the present study investigated the effects of different video game training strategies on behavioral performance and functional brain activity.

In general, video game-play is complex, involving a broad set of skills that must be strategically implemented throughout task performance. Memory, attention, and motor control, for example, are essential to successful game play in many video game genres (Gee, 2003). The habitual exercise of these abilities in a recreational-based, reward-inducing, virtual environment suggests the possibility that video games may have functional significance for players beyond the context of game-play. In fact, extensive research has linked game-play to enhanced visual, spatial, and task motor skills (Green & Bavelier, 2003, 2006, 2007). By rewarding players for fast and accurate reactions, action video games are thought to promote the enhancement of processing speed and hand-eye coordination (Achtman, Green, & Bavelier, 2008). As such, video game players (VGPs) of action video games, particularly first-person shooters, demonstrate better hand-eye motor coordination (Griffith, Voloschin, Gibb, & Bailey, 1983), faster reaction times (Castel, Pratt, & Drummond, 2005), and faster processing speeds (Dye, Green, & Bavellier, 2009) than non-video game players (NVGPs). Habitual video game-play, therefore, is thought to be beneficial for the improvement of certain sensory-motor abilities.

Beyond visuo-spatial and motor abilities, video game-play is also associated with improved cognition. Specifically, VGPs show cognitive advantages over NVGPs in the performance of certain executive functioning tasks. For example, task-switching in VGPs, relative to NVGPs, is associated with lower attentional switching costs, a measure of increased reaction time in trials that require continual shifting of attention in comparison to trials that only involve task repetition. Incurred as a result of the utilization of control processes to switch between attentional sets (Banich et al., 2000; Dove, Pollman, Schubert, Wiggens, & von Cramon, 2000). VGPs are able to shift between attentional sets faster than NVGPS without experiencing a significant trade-off between reaction time and accuracy (Boot, Kramer, Simons, Fabiani, & Gratton, 2008), suggesting that video game-play can result in adaptive use of attentional resources.

The observed relationship between regular video game-play and skill acquisition led to the development of video game training as a way to promote cognitive, sensory, and motor abilities in NVGPs (Boot et al., 2008). Training sessions involve a fixed period of continuous video game-play and a pre- and post-assessment of game performance, along with neuropsychological assessment of functioning. In a study comparing expert VGPs to NVGPs, VGPs were found to be superior to NVGPs in tasks of spatial cognition. NVGPs were assigned to a 10-hour training regimen in which participants practiced playing an action video game, Medal of Honor (Feng, Spence, & Pratt, 2007). Feng and colleagues (2007) found that after 10 hours of training, measures of spatial cognition, particularly mental rotation, were dramatically improved in NVGPs. These findings indicate that video game training significantly improves cognitive ability in NVGPs, and according to Green & Bavalier (2008), training may even be useful for the improvement of other cognitive skills. Although promising, it is uncertain whether the improvement in cognition associated with video game practice is comparable to the baseline cognitive abilities of expert VGPs. Such findings suggest that video game training can effectively improve cognitive skills in novice game-players. In fact, Boot and colleagues (2008) report that extensive video game practice in NVGPs significantly improved game performance, but does not substantially enhance performance on cognitive tasks compared to VGPs. This suggests that fixed practice on a video game does not result in transference to skills outside of the virtual-environment. Given this failure to engender skill transfer in the cognitive domain, extensive practice alone may not be sufficient to produce generalizable effects of video game-play. In fact, training that does not address the components of a complex task, but rather utilizes repeated practice on the complex task, with a single fixed focus does not promote efficiency and transferability. Fixed Emphasis Training (FET) is one in which the focus of the participant is constant and unchanging. This is associated with practice effects, which are not enough to bridge the gap between novices and experts in a complex task and video game performance (Gopher et al., 1989; Boot et al., 2008).

Considering whether training method might influence the effectiveness of video game training, Variable Priority Training (VPT) was developed as an alternative training strategy for skill acquisition. Previous studies have used VPT of attentional control to foster rapid skill acquisition in dual tasks, task-switching (Kramer, Larish, & Strayer, 1995; Gopher, Weil, & Siegel, 1989), and a complex video game (Fabiani, Buckley, Gratton, Coles, Donchin, & Logie, 1989). VPT encourages participants to constantly shift their focus between often overlapping components of a complex or multi-task, thereby fostering a better understanding of the different task components and their relationship to one another. VPT also encourages players to develop new strategies and more efficient tactics for task completion by providing individualized feedback on the game player's performance, a technique considered to be important for learning (Gopher and North, 1977).

In line with the emergence of new video game training methods was the development of more complex video games for the purpose of cognitive training. Space Fortress (SF) was designed by cognitive psychologists in order to study skill acquisition of a complex task (Donchin, 1989). The goal of SF is to navigate a spaceship in a frictionless environment with the intent of destroying the space fortress in the center of the screen, while managing the overlapping motor, working memory, attentional tasks. To achieve a high Total Score, players must learn and excel in all components of the game. Total Score is the sum of the sub-scores Point, Velocity, Speed, and Control. A challenging, multi-task game incorporating cognitive skills, such as motor control, working memory, and attentional/monitoring, SF enables the manipulation of different aspects of cognition.

The utility of VPT as a training strategy is primarily based on its successful implementation in SF. Gopher, Weil, and Bareket (1994) employed SF video game training in a class of Israeli Air Force cadets in flight school. Prior to class enrollment, cadets underwent 10 hours of SF training based on either VPT, or a hybrid version of VPT, which combined part-task training with VPT. In both variations of VPT, cadets completing the pre-enrollment training session demonstrated not only improved behavioral performance on SF after training, but importantly, also enhanced flying ability during actual pilot sessions. This suggests that VPT is associated with a transfer of skill from the video game environment to real-life flight conditions.

In another study, Basak, Boot, Voss, and Kramer (2008) showed that VPT in older adults can potentially improve executive control processes. In this study, a group of older adults were trained with a strategy video game that required fast and strategic decision-making. After five weeks of training, participants showed significant improvements in many executive control functions, including task switching, working memory, and reasoning. The ability of video game training to improve cognitive abilities suggests that video game play is a practical tool that can be used to bolster of cognitive functioning.

To discriminate the effects of VPT with the general effects of simple practice, Boot and colleagues (2010) compared two experimental strategy training protocols, VPT and FET. The VPT group was encouraged to monitor and shift attentional emphasis between the various components of Total Score, whereas the FET group was asked to focus on maximizing the total score while emphasizing all components of the game equally. In order to look at skill transference, Boot and colleagues asked participants to complete a battery of cognitive tasks at pre- and post-assessment. Consistent with previous studies, they found the VPT group learned the task more quickly than the FET group, achieving greater levels of mastery and demonstrating greater skill transference. These findings are consistent with research suggesting that VPT is more effective in enhancing cognitive performance than constant practice (i.e., FET) in tasks where multi-tasking is needed, such as dual task, task switching, and the complex video game SF (Basak et al., 2008; Lee, in review; Voss et al., 2011).

While VPT engenders greater levels of mastery in complex tasks relative to FET (Kramer et al., 1995; Fabiani, et al., 1989; Gopher et al., 1989 ; Boot et al., 2010), the neural mechanisms associated with these differential training strategies are not fully understood. Previous studies have suggested the involvement of distinct learning systems in the consolidation of a learned skill, the declarative and procedural learning systems, each of which is associated with specific brain networks (Myers et al., 2003). The declarative learning system, associated with the medial temporal lobe (MTL) structures, is related to flexibility and the transfer of skills to a novel context (Myers et al., 2003). During game-play, this might involve the ability to efficiently change emphasis between the different components of SF. Characteristic of the declarative learning system is VPT's association with skill transferability, which is observed in the relationship between VPT on SF flight simulation and improvement on actual flying (Gopher et al., 2004). In contrast, the procedural learning system, associated with the basal ganglia and primary motor cortex, is linked to motor performance, fixed learning, and routine behavior (Myers et al., 2003). Consistent with this inflexible learning is the absence of transferable cognitive skills in the FET group.

Evidencing the use of different learning systems based on the strategy implemented, Kantak, Sullivan, Fisher, Knowlton, and Winstein (2010) showed that constant practice (as employed in FET) and variable practice (as employed in VPT) predict reliance on these two different brain networks for the consolidation of learned skills like motor control: variable practice is associated with the MTL in support of declarative learning, while constant practice is associated with the basal ganglia in support of procedural learning. Voss and colleagues (2011) also suggest that during game play, these distinct learning systems associated with the two training strategies uniquely interact with higher-order functional networks such as the attentional network (ATN). The ATN, which includes prefrontal regions (dorsolateral prefrontal cortex, bilateral middle frontal gyri, inferior and superior frontal gyri, and anterior cingulate cortex), supports cognitive processes by facilitating the processing of exogenous stimuli and maintaining attentional control during task performance. Cognitive performance relies on the modulation of neural activity in the ATN such that cortical activation increases in response to task difficulty and cognitive demands. The performance costs associated with cognitively demanding tasks, such as slower reaction time or decreased accuracy (Dove et al., 2000), are reflected by increased cortical recruitment of attentional resources (Banich et al., 2000; Prakash et al., 2009). Voss and colleagues (2011) used functional connectivity analyses to examine the influence of training strategy, either FET or VPT, on the functional interaction of the two learning systems, procedural and declarative, with the ATN. After 20 hours of training, the basal ganglia, associated with the learning system related to FET, and the MTL, associated with the learning system related to VPT, both showed enhanced interaction with the fronto-parietal system of the ATN. The interaction between the MTL and the fronto-parietal system in the VPT group is implicated in the increased capacity of working memory and attention (Craik et al., 1996; Olesen et al., 2004). Therefore, VPT may be more efficiently utilizing their attentional network, suggesting that this training strategy involves more flexible attentional control. In addition, unique to FET, Voss and colleagues observed enhanced interaction between the MTL and the fronto-executive system of the ATN. Given the increased interaction of the basal ganglia with the fronto-parietal system and the MTL with the fronto-executive system in the FET group, it appears that FET participants are concurrently utilizing two different cognitive control systems. Voss and colleagues postulate that this enhanced functional connectivity in two ATN systems indicates a higher cognitive load for FET, which in turn, leads to a reliance on basal ganglia and procedural motor sequences to accomplish game performance. This unique pattern of functional connectivity in the ATN of the FET group is indicative of increased engagement of attentional resources during game-play, which, relative to VPT, suggests the inefficient modulation of neural activity in attentional areas.

To explore this potential explanation, the present study compared the effects of video game training strategies on behavioral performance and functional brain activity in the attentional networks of the brain to determine (1) whether video game training could serve as a tool for training cognitive and neural efficiency on a complex task, and (2) which type of training strategy would be most effective in engendering these benefits. To do this, we implemented a 30-hour video game intervention using SF. We employed a no-contact control group and two types of training groups, an FET group and a Hybrid Variable Priority Training (HVT) group based on a variation of VPT, consisting of VPT in combination with part-task training. The first of its kind, this study employed video game-play during functional magnetic resonance imaging (fMRI) scanning. At pre- and post-intervention, all participants played SF inside the MRI scanner in order to assess functional brain activity during game-play.

Consistent with previous studies, we hypothesized that the training groups (HVT and FET) would out-perform the no-contact control group on SF at post-intervention. Participants in the control group should present with greater activation of the regions comprising the ATN relative to both training groups due to continued attentional demands of the game. Based on the previous literature, we also expect that training with HVT versus FET would result in an increased capacity for attention , which should be reflected in enhanced behavioral performance on SF, along with reduced activation of the ATN. Furthermore, we hypothesized that decreased use of the ATN after training would be correlated to greater improvements in behavioral performance on this complex task.

Methods

Participants

Sixty-six young adults (27 males, 39 females) were recruited from the Champaign-Urbana community via advertisements in the local media, promotional flyers, and announcements throughout the University of Illinois campus. Participants were between 18 and 24 years old and fulfilled a number of inclusionary criteria, including right-handedness, normal or corrected vision, and the absence of any neurological or psychiatric disorders. In order to ensure that all participants were novice video game players, individuals were screened based on their video game playing habits. In particular, those playing video games for more than one hour per week were excluded from the study. Participant demographics for each of the three groups are displayed in Table 1.

Procedure

The present study employed a randomized controlled trial of video game training in which participants were randomly assigned to either a control group or one of the two training groups, HVT or FET. SF was played by all participants at pre-assessment (Time 1) and post-assessment (Time 2). Between Time 1 and Time 2, HVT (n = 22) and FET (n = 23) groups completed 30 hours of practice on SF, while the control group (n = 21) received no further contact with the game until post-assessment.

At pre-assessment, participants viewed a 20-minute instructional video introducing the rules of SF, followed by a quiz, which evaluated participants' relative comprehension of the task procedure. Participants successfully passing this assessment then completed a MRI session in which they played three full games of SF in the scanner.

Post-assessment involved similar procedures as the pre-assessment phase. Participants completed an MRI session, playing three full games of SF in the scanner, using a MRI compatible joystick.

Space Fortress

Space Fortress (SF) was developed by cognitive psychologists as a tool to study complex skills and their acquisition (Donchin, 1989). The game incorporates tasks of motor, memory, multi-tasking, and attentional skills, requiring the player to shift attention between the many components of the game in order to achieve a high score. These overlapping components of the game make it a cognitively demanding task. The complete details of SF are reported in a special issue of *Acta Psychologica (*1989*).*

SF presents within a large hexagon with a fork-like symbol within a second, smaller hexagon in the center of the screen, which represents the space fortress (Figure 1). Flying between the two hexagons is a spaceship armed with 100 missiles, which the player controls. The player's primary goal in SF is to fire missiles from his or her spaceship to damage and destroy the fortress in the center of the screen, while simultaneously avoiding damage to his or her own ship. The fortress rotates and fires missiles at the ship. To destroy the fortress, the player must hit it with 10 missiles, at least 250 milliseconds apart, followed by double clicking on the trigger to impart two missiles in rapid succession that destroy the fortress.

Although the player only starts with 100 missiles, he or she is given the opportunity to earn more. Occasionally, during game-play, a dollar sign ($) symbol will appear on the screen. When this occurs, the player needs to shoot at this target, but only at its second appearance during the trial. If the player correctly shoots at the target after its second appearance, he or she earns bonus missiles. However, if he or she shoots the target at first appearance, points are deducted. This incorporates a monitoring component into the game, requiring participants to be constantly vigilant of the field of play. In addition, players are encouraged to economize their use of missiles because when their supply of missiles reaches zero, three points are deducted for each additional missile shot.

Periodically, a mine will appear on the screen as a diamond-shaped figure with a letter in the middle, and it behooves the player to promptly identify the mines and destroy them, because no damage can be done to the fortress while a mine is present. Two types of mines exist, friend mines and foe mines. When friend mines are identified and hit with a missile properly, the mine will “energize” and damage the fortress by crashing into it. Foe mines, when identified and destroyed, will transfer their damage to the fortress. Before each block, participants are asked to remember three letters, which will identify the foe mines, and all other letters will be friend mines. When a mine appears, it will actively pursue the player until it is identified and destroyed. If either of these mines, friend mines or foe mines, is not handled correctly, this damage will be transferred to the player’s spaceship.

Arguably, the most difficult component of SF is controlling one’s spaceship. The ship flies in a frictionless environment with no brakes, so the player must exercise slight, precise movements of the joystick. If the ship is not carefully controlled, it will leave the vicinity of the large hexagon and fall into hyperspace. In addition, the ship must be in constant motion in order to avoid being hit by the missiles of the fortress.

The player's Total score is the sum of four sub-scores: Points, Speed, Velocity, and Control. To accumulate a Control score, the player must keep his or her aircraft within the large hexagon. Falling into hyperspace results in a negative Control score. To accumulate a Velocity score, the player must carefully control his or her aircraft. This is accomplished by maintaining a slow speed, using subtle, controlled movements of the joystick. As mentioned before, this is a challenging motor task because the aircraft has no brakes and is flying in no gravity. The Speed sub-score rewards the player based on his or her ability to deal with mines rapidly, first by identifying the mine as friend or foe, and then reacting accordingly. However, if a mine is misidentified, the damage that the mine endures will be transferred to the ship and the player will receive a deduction in Speed. Lastly, the Point sub-score is rewarded to players for shooting and destroying the space fortress in the center of the screen. Players are penalized if they improperly execute the series of missile launches required to destroy the fortress, and if the fortress' missiles hit the ship.

Training Groups

After familiarization with SF, participants in the training groups engaged in fifteen 2-hour training sessions of under HVT or FET. During the training sessions, a PC computer with a 19-inch color LCD screen was used for game-play of SF and data collection. Participants inputted responses using a computer mouse and a Logitech Attack 3 Joystick. All FET sessions began and ended with three test trials of SF, and consisted of thirty 3-minute practice rounds of SF, totaling

36 games. FET participants received no formal strategy training and were simply instructed to concentrate on obtaining as high a total score as possible, while focusing on the different components of SF equally.

In contrast, HVT sessions involved both part-task training and VP training. A combination of part-task and VP training (combined session) was used in the first five sessions, while pure VP training was used in the last ten sessions. During the first hour of the combined sessions, part-task training was employed, in which players practiced a specific component of SF that was presented separately from the rest of the game. For example, in a given game during part-task training, participants might be presented with the task of just navigating the ship or just aiming and firing. During the second hour of the combined sessions, participants in the HVT group were instructed to employ VP training. In here, participants played SF in its entirety with the goal of focusing on the specific skill that was previously learned in the part-task training and scoring as high a total score as possible on that particular component. Two test trials of SF were presented at the beginning and end of every session as well as after part-task training. During all test trials, HVT participants were told to accumulate a high total score. For the remaining 10 sessions, pure VPT was employed.

Behavioral Analyses

To analyze the effect of video-game training on improvement on SF game performance, quantified by total score across all four components, we conducted a series of repeated-measures ANOVAs with time as the within-subjects factor and group as the between-subjects factor. For both the ANOVAs, gender was included as a covariate in the analyses in order to account for gender differences, which previous research has shown to exist in video game performance (Feng et al, 2007; Terlecki & Newcolbe, 2005). Firstly, to examine the influence of training on game performance, we merged the two training groups into one and examined if any kind of training on the SF game was associated with improvements in total game score, relative to the control group. For this, we conducted our first repeated-measures ANOVA with time (Time 1, Time 2) as a within-subjects factor and group (Control, Training) as a between-subjects factor.

In order to examine the influence of training strategy on game improvement, we conducted a second repeated-measures ANOVA with time as a within-subjects factor and training strategy as a between-subjects factor (HVT, FET). Total score at pre-assessment and post-assessment was analyzed using a repeated-measures ANOVA with time (Time 1, Time 2) as a within-subjects factor and group as a between-subjects factor. All behavioral data were analyzed using SPSS 17.0 for Mac.

fMRI Data Acquisition and Task Parameters

Participants were scanned in a 3 Tesla Siemens Allegra head-only scanner at the Beckman Institute for Advanced Science and Technology on the University of Illinois campus. Structural T1-weighted images were acquired using a 3D MPRAGE (Magnetization Prepared Rapid Gradient Echo Imaging) protocol with 144 contiguous axial slices, collected in ascending order, echo time (TE) = 3.87 ms, repetition time (TR) = 1800 ms, field of view (FOV) = 256 mm, acquisition matrix 160 mm 192 mm, slice thickness = 1.3 mm, and flip angle = 8°.

Functional T2* weighted images were acquired using a fast echo-planar imaging sequence (EPI) with Blood Oxygenation Level Dependent (BOLD) contrast (64 x 64 matrix, 3.4

x 3.4 x 4.0 mm voxel size, TR = 2000 ms, TE = 25 ms, and flip angle = 80°). Using a MRI-compatible joystick, all participants completed three full runs of the SF game during MRI scanning at pre-assessment and post-assessment. Presentation of SF during the MRI session was based on a block design consisting of two 30-second blocks of active game-play and two 30-second blocks of passive viewing, interspersed with 10-second fixation periods and 4 second of instructions. A total of 115 volumes were collected for each functional run. A depiction of the SF MRI task design is presented in Figure 2.

fMRI Pre- and Post-Processing

Neuroimaging data were analyzed using FSL 4.1 and FEAT (fMRI Expert Analysis Tool). Images were corrected for motion using a rigid-body algorithm in MCFLIRT, and smoothed with a Gaussian high-pass filter of 100 seconds. Structural T1-weighted images were skull stripped using a robust deformable brain extraction technique (BET). The skull-stripped images for each participant were transformed to a standard Montreal Neurological Institute (MNI) space and then spatially registered to each participant's high-resolution scan. All participants, as mentioned above, played three full runs of the SF game. Given that participants were required to play a video game with a MRI-compatible joystick inside the fMRI scanner, we noticed significant motion for many participants across different runs of the game. For each participant, we decided to exclude one run with the lowest signal to noise ratio (SNR) and motion greater than 1 functional voxel space (3.475 mm) in 10 or more volumes. Final analyses were conducted with two runs of the SF game for each participant at pre-training and post-training.

Following pre-processing, the functional data collected during the presentation of the SF game were convolved with a double-gamma function to model the response for each condition (active game playing and passive viewing). This first-level analysis, done separately for each participant for the two functional runs, resulted in voxel-wise parameter estimate maps for the entire brain for each condition (active, passive), and for the direct comparison between the conditions (Active>Passive). These parameter estimate maps and variance maps from the two functional runs were then aggregated within subject (across the two functional runs) for greater statistical power, using ordinary least squares (OLS) in FSL's FEAT tool. This was done separately for Time 1 and Time 2 to examine recruitment in cortical regions during active game play before and after the intervention for each individual participant.

Finally, the mean individual-level statistical maps from the two time-points were then forwarded to a third-level fixed effects, individual-level longitudinal analysis, to examine the influence of training on neural recruitment during active game playing and passive viewing separately for each individual participant. This was done using OLS in FSL's FEAT tool. This third-level analysis resulted in statistical maps representing activation during active game playing and passive viewing at pre-training, post-training and the contrast between the two time-points. The final fourth-level, mixed-effects analysis that considered between-subject variation was conducted using FLAME (FMRIB's Local Analysis of Mixed Effects) to locate regions of cortex that showed an influence of training on the recruitment of the attentional network during active game play. For this, we examined the contrast of Active>Passive game playing for the three groups of participants and for the direct contrast between the controls and the training groups. All maps were thresholded at a voxel-wise z-score of 2.33 ($p<0.01$) and a cluster-wise threshold of $p<0.05$.

Regions of Interest Analysis

The above discussed whole-head fourth-level analysis resulted in statistical maps that demonstrated cortical recruitment in the Active>Passive contrast for the Control>Training groups. Regions of interest (ROI) in this statistical map were identified to firstly examine associations with behavioral improvement on the SF game. Secondly, in addition to examining changes in brain activation patterns as a function of video game training, we also examined if training strategy had a differential influence on cortical recruitment. Percent signal change in ROIs generated through the Control>Training contrast (Figure 3) was also examined for differences between HVT and FET groups.

Results

Behavioral Results

The effect of training on behavioral performance was examined using a repeated-measures ANOVA with time (pre-training, post-training) as a within-subjects factor and group (control, training) as a between-subjects factor. We found a main effect of time ($F(1, 63)= 15.3$, $p< 0.001$), indicating that all groups had significant improvement in total game score from Time 1 to Time 2, along with a significant Time x Group interaction ($F(1, 63)= 37.9$, $p<0.001$), suggesting that training across both strategies was beneficial for behavioral performance in the SF game, relative to the control group (Figure 4).

To examine whether HVT as a training strategy was related to greater levels of game mastery in comparison to FET, we contrasted HVT and FET using a repeated-measures

ANOVA, using the average total score from SF at Time 1 and Time 2 as a within-subjects factor and group as a between-subjects factor. We found a main effect of time (*F*(1, 42)= 19.21, *p*<0.001) as well as a significant Group x Time interaction (*F*(1, 42)= 5.61, *p*<0.05), which indicated a greater benefit on SF game performance for the HVT group relative to the FET group. This suggests that a training strategy combining part-training with variable priority is more beneficial than practice alone on the SF game (Figure 5).

Neuroimaging Results

In order to examine the effects of training on neural recruitment during active game play, we conducted a whole-brain analysis contrasting brain activation during the Active > Passive condition at Time 1 > Time 2, separately comparing the control group to the training groups. A contrast of the control group and the training groups (Control>Training) showed decreased activation of the prefrontal, temporal, occipital, and parietal cortices, and then basal ganglia for the training groups at post-assessment compared to pre-assessment, but not for the control group Specifically, in contrast to the training group, the control group continued to recruit several cortical regions, including, the bilateral MFG, bilateral SFG, the OFC, intracalcarine cortex, motor cortex, cingulate gyrus, caudate, putamen, and right middle temporal gyrus (Figure 3). Of these areas, the left SFG, OFC, left MFG, and right MFG, regions primarily associated with the ATN, were identified as sites of peak activation (Table 4). In line with our hypotheses, these results demonstrate that video game training, in comparison to the control condition, results in a reduced need for activation of attentional areas during game-play (Figure 6). Statistical peaks in this contrast were taken to create regions of interest, which were then examined for differences in cortical recruitment as a function of strategy (HVT compared to FET) and for correlations with performance data. Specifically, statistical peaks were identified in the bilateral MFG, left SFG and the OFC during the Control>Training contrast, and a 14-mm region of interest was created to examine changes in recruitment of these regions as a function of strategy effects.

As seen in Figure 7, the HVT group showed greater reduced activation than the FET group at Time 2 relative to Time 1 for all regions of interest; however, significant reductions in activation were noted for the right MFG ($t(43) = 2.35$, $p< 0.05$) in comparison to FET after training. This finding suggests that individuals in the FET group require continued activation of the prefrontal cortices in order to meet the demands of the SF game, whereas individuals in the HVT group seem to require less activation of the regions traditionally comprising the attentional network in response to training.

Correlation of behavioral performance to neural activity

To examine the relationship between behavioral performance and neural activity, we conducted a series of partial correlations between improvement in total score and percent signal change in the bilateral MFG, left SFG, and OFC, using gender as a covariate. As seen in Table 5, a general negative trend was found for activation across all ROIs, implying that a reduction in the prefrontal cortices was indeed related to higher total score improvement in SF. Decreased activation in the right MFG was significantly correlated ($r = -0.27$, $p<0.05$) to improvement in performance and percent signal change, such that participants with the greatest improvements in SF total score also showed the greatest reduction in the right MFG (Figure 8). Overall, these findings suggest that video game training may be useful in enhancing performance on a complex behavioral task and may correspondingly optimize the use of attentional resources.

Discussion

The present study, employing the video game SF as a context to study multi-tasking and skill acquisition in a complex task, investigated the effects of two types of training strategies in enhancing performance and neural recruitment during video game-play. A 15-session randomized controlled trial of video game training was implemented, using a no-contact control group and two types of training groups, HVT and FET. In line with our hypotheses, we found that video game training enhanced behavioral performance on a complex task and concurrently reduced the neural demands of SF in areas associated with greater attentional control. In addition, comparing the two training strategies, we found greater training-related improvements associated with HVT relative to FET. Based on these results, video game training is proposed as an effective means of improving cognitive and neural functioning.

Extensive research supports the utility of video games as a cognitive training tool to enhance behavioral performance (Fabiani et al., 1989; Gopher et al., 1994; Boot et al., 2010). Corroborating these findings, our study reports that repeated exposure to SF leads to higher levels of game mastery in novice video game players. Across all three groups, participants showed improvement in behavioral performance from pre- to post-training, indicating a beneficial effect of basic practice on a complex task (Newell & Rosenbloom, 1981). Confirming our predictions, we also found greater improvement in behavioral performance for both training groups, relative to the control group, evidencing the efficacy of video game training strategies in facilitating skill acquisition. A further comparison of HVT and FET at post-assessment revealed that the effects of video game training vary as a function of the particular training strategy employed. While both training groups resulted in improved behavioral performance, HVT uniquely promoted greater skill acquisition and superior performance on a complex task. This provides new evidence for the distinct advantage of HVT over FET as a training strategy, a comparison which has previously been unexamined.

To investigate the neural mechanisms associated with video game training, we also examined the influence of training strategy on functional brain activity, particularly in areas of the attentional network. Given that training strategy, particularly HVT, was expected to reduce the attentional demands associated with game-play, we predicted an attenuation of neural activity in areas of the prefrontal and parietal cortices as a result of training. Confirming this hypothesis, we found reduced activation in cortical regions involved in attentional control for the training groups relative to the control group, and also for HVT relative to FET. Specifically, the control group specifically exhibited continued activation in regions of the frontal cortices, as well as, the right middle temporal gyrus, cingulate gyrus, motor cortex, and the basal ganglia. This suggests that the poorer performance of the control group relative to the training groups may, therefore, be related to ineffective control of the joystick during game-play, greater effort in multi-tasking between the different components of the game, and a general enduring need for cortical recruitment in support of task-focused performance. In comparison, the reduced activation of such regions observed in the training groups relative to the control group at post-training represents training-related optimization of neural recruitment during game-play. Whereas game performance on SF led to a persistent taxing of the attentional network in control participants, individuals in the training groups demonstrated successful performance on a complex task using minimal allocation of attentional resources. Our findings, therefore, substantiate the ability of video game training to effectively diminish the cognitive demands of a complex task.

To assess the differential influence of the two video game training strategies on game performance and neural recruitment, we examined differences between the HVT and the FET groups. As predicted, we found continued activation of attentional areas for FET post-training, which might reflect the increased functional connectivity of the basal ganglia with the fronto-executive and fronto-parietal networks (Voss et al., 2011). This inefficient use of two different cognitive control networks may underlie the FET group's poorer behavioral performance (Voss et al., 2011) and their enduring reliance on attentional resources to meet the demands of SF. In comparison, the HVT group demonstrated a reduction in the cortical recruitment of the ATN, as expected based on HVT's association with declarative learning (Kantak et al., 2010; Voss et al., 2011), which is characterized by cognitive flexibility and increased capacity for working memory and attentional load (Foerde et al., 2006; Olesen et al., 2004). The HVT group's ability to modulate limited attentional resources corresponds to their exceptional performance on SF, when compared to FET. Thus, our study shows that the attentional costs of multi-tasking, exemplified in lower scores in SF and continual activation of the ATN after training (Dove et al., 2000; Gazzaley et al., 2005), are more pronounced for HVT than FET, a finding which predicates the employment of this particular cognitive training strategy (uniquely involving variable emphasis on different task components combined with basic part-task practice) as a useful approach to improving cognitive functioning. Based on the significant association between game score improvement and decreased activation of the right MFG, we also suggest that such reductions in cortical recruitment, observed in the HVT group, are indeed related to improved performance on SF. Since, decreased recruitment of the cortical regions comprising the

ATN has important implications for behavioral performance, an effective cognitive training tool is one which concurrently hones behavioral skills and optimizes the neural circuitry of attention.

The addition of neuroimaging techniques provides insight into the influence of video game training on changes in neural activity during a complex task. Another particular strength of this study is the inclusion of a no-contact control group and a non-VPT training group, which previous SF studies have not considered. This is particularly useful because it serves to clarify the once convoluted distinctions between the behavioral and neural characteristics of VPT-based training (HVT) and simple practice effects (FET). However, for future studies of this nature, a shorter intervention might better display the accelerated learning rate observed under the HVT regimen (Lee et al., in review), which is not presented in the current study. Since differences in behavioral performance between HVT and FET were predominant after 10 hours of training, we suspect that 30 hours of video game training may be excessive (Lee et al., in press). Although a comparison of the training groups in this study indicates a significant advantage for participants in the HVT group, this advantage could potentially be augmented with a shorter training period. Therefore, future studies examining changes in neural recruitment post shorter periods of training would be critical to understanding the dose-response relationship between training and neural recruitment.

Previous studies of attentional and executive control have established that cortical recruitment of the ATN is responsive to task demands (Banich et al., 2000; Dove et al., 2000). However, the role of this additional neural activation has been disputed, with some studies suggesting that activation may serve a compensatory function (Davis et al., 2008), while others argue that excessive ATN activation is related to diminish performance on a cognitive task (Gazzaley et al., 2005; Prakash et al., 2009). The aging literature, for example, has associated extensive cortical recruitment in older adults with poorer performance on a cognitive task (Prakash et al., 2009). Although the efficacy of VPT as a means to improve executive control in older adults has previously been examined (Basak et al., 2008), the implementation of a randomized controlled trial similar to the one used in the present study could shed light on the neural correlates associated with improved executive function in older adults. Thus, a video game training intervention using older adult and other clinical populations represents a potentially interesting and valuable study for future investigations.

In summary, the present study provides evidence for the ability of video game training to enhance performance on a complex task and correspondingly decrease cortical recruitment of attentional resources. Based on behavioral and neuroimaging evidence, we conclude that HVT, relative to FET, may facilitate greater mastery of a complex task and neural adaptation in response to task difficulty. In general, video game training signifies a novel and promising avenue to improving cognition and maximizing efficiency in neural recruitment, thereby making it a plausible tool for use with clinical populations in the future.

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Table 1

Demographics of Participants in the Control Group and Training Groups

	HVT	FET	Control Group
N	22	23	21
Age	21.91 (2.77)	20.88 (2.06)	21.44 (2.52)
Gender	Male= 9 Female= 13	Male= 8 Female= 15	Male= 10 Female= 11
Years of Education	15.52 (2.19)	14.68 (1.85)	15.28 (2.25)

Note: The training groups were Hybrid Variable Priority Training (HVT) and Fixed Emphasis Training (FET).

Table 2

Repeated Measures ANOVA Comparing Total Score at Time 1 and Time 2 for the Control Group and the Training Groups

	Sum of Squares	df	Mean Square	F(1,63)
Time	14,993,264	1	14,993,264	15.40**
Time x Gender	10,878,543	1	10,878,543	11.18**
Time x Group	35,423,613	1	35,423,613	36.39**

Note: Gender was used as a significant covariate. Group was used as a between-subjects factor. The groups are the control group and the training groups. Time was a within-subjects factor.

** indicates p-value < 0.001; * indicates p-value < 0.05

Table 3

Repeated Measures ANOVA Comparing Total Score for Training Groups at Time 1 and Time 2

	Sum of Squares	df	Mean Square	F(1, 42)
Time	17,291,253	1	17,291,253	18.80**
Time x Gender	10,109,094	1	10,109,094	10.99*
Time x Group	4,340,106	1	4,340,106	4.72*

Note: Gender was used as a covariate. Group was a between-subjects factor. The groups were HVT and FET. Time was a within-subjects factor.

** indicates p-value < 0.001; * indicates p-value < 0.05

Table 4

Statistical peaks of cortical regions recruited during the Active>Passive condition at Time2>Time1 contrasting the control group with the training groups (Control>Training).

Anatomical Region	Label	Max z-Stat	MNI Coordinates		
			X	Y	Z
Left Superior Frontal Gyrus	Lt. SFG	3.61	13	65	49
OrbitoFrontal Gyrus	OFC	3.1	72	62	56
Left Middle Frontal Gyrus	Lt. MFG	3.69	39	82	27
Right Middle Frontal Gyrus	Rt. MFG	3.18	51	70	68

Table 5

Correlation Matrix Relating Improvement in SF Score to Percent Signal Change in the ROIs

	Lt. SFG	OFC	Lt. MFG	Rt. MFG	Imprv. in TS
Lt. SFG	1	0.47**	0.82**	0.73**	-0.12
OFC		1	0.43	0.43**	-0.12
Lt. MFG			1	0.73**	-0.19
Rt. MFG				1	-0.27*
Imprv. in TS					1

Note: Lt. SFG, left superior frontal gyrus; OFC, orbitofrontal cortex; Lt. MFG, left middle frontal gyrus; Rt. MFG, right middle frontal gyrus; Imprv. in TS, improvement in total score in Space Fortress from Time 1 to Time 2. ** indicates p-value < 0.001; * indicates p-value < 0.05

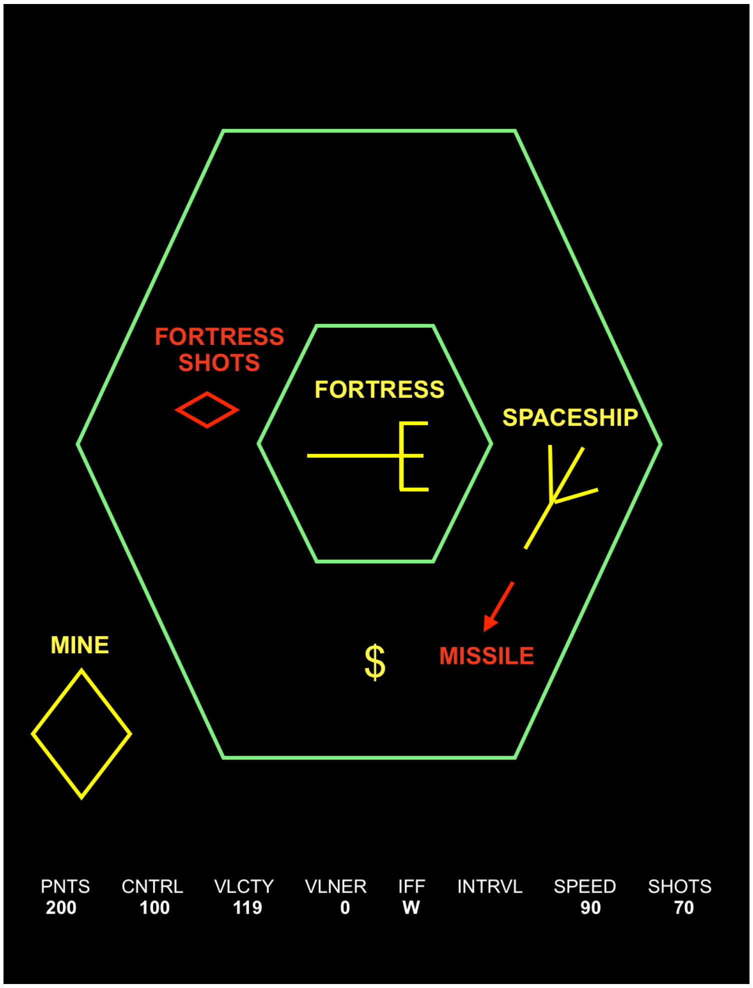

Figure 1. Schematic representation of Space Fortress. In the bar underneath the game, players monitor their total score and various sub-scores. SHOTS is the number of missiles that remain in the player's inventory.

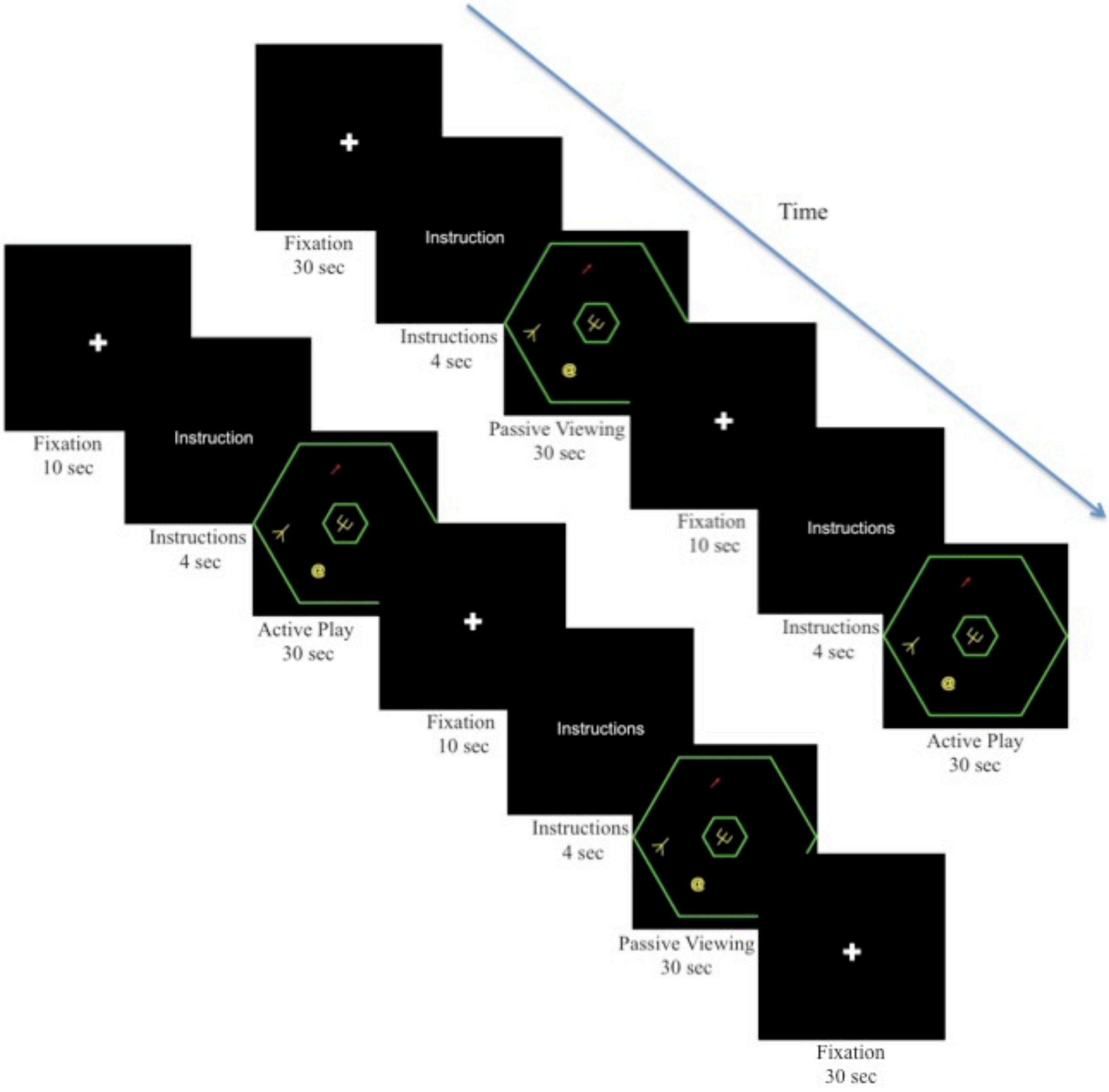

Figure 2. Graphical description of the SF MRI task design with blocks of active play and passive viewing interspersed with fixation periods.

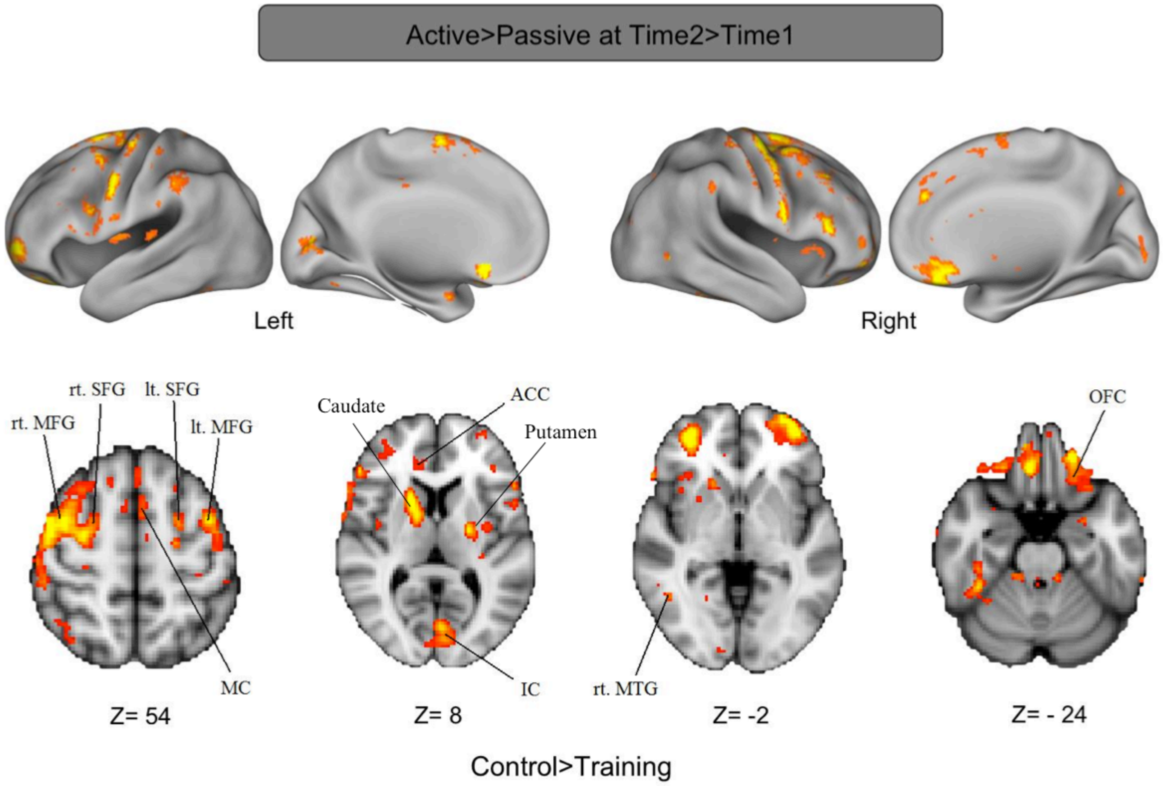

Figure 3. Cortical activation in the Active>Passive, Time 2>Time 1, and Control>Training contrast. Regions observed in this contrast include the bilateral MFG, bilateral SFG, the OFC, intracalcarine cortex (IC), motor cortex (MC), cingulate gyrus, areas of the basal ganglia, and right middle temporal gyrus.

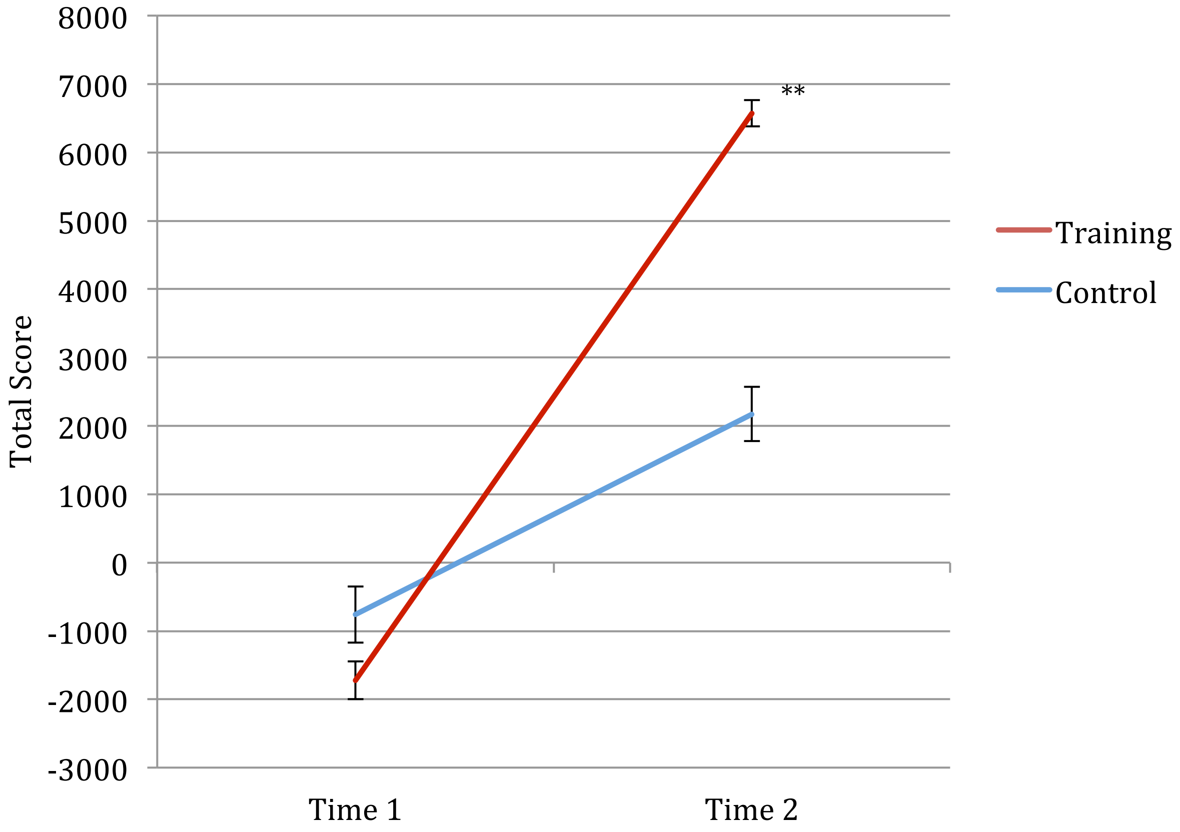

Figure 4. Graph of the average total score in SF at Time 1 and Time 2 for the control and training groups. **indicates p-value < 0.001.

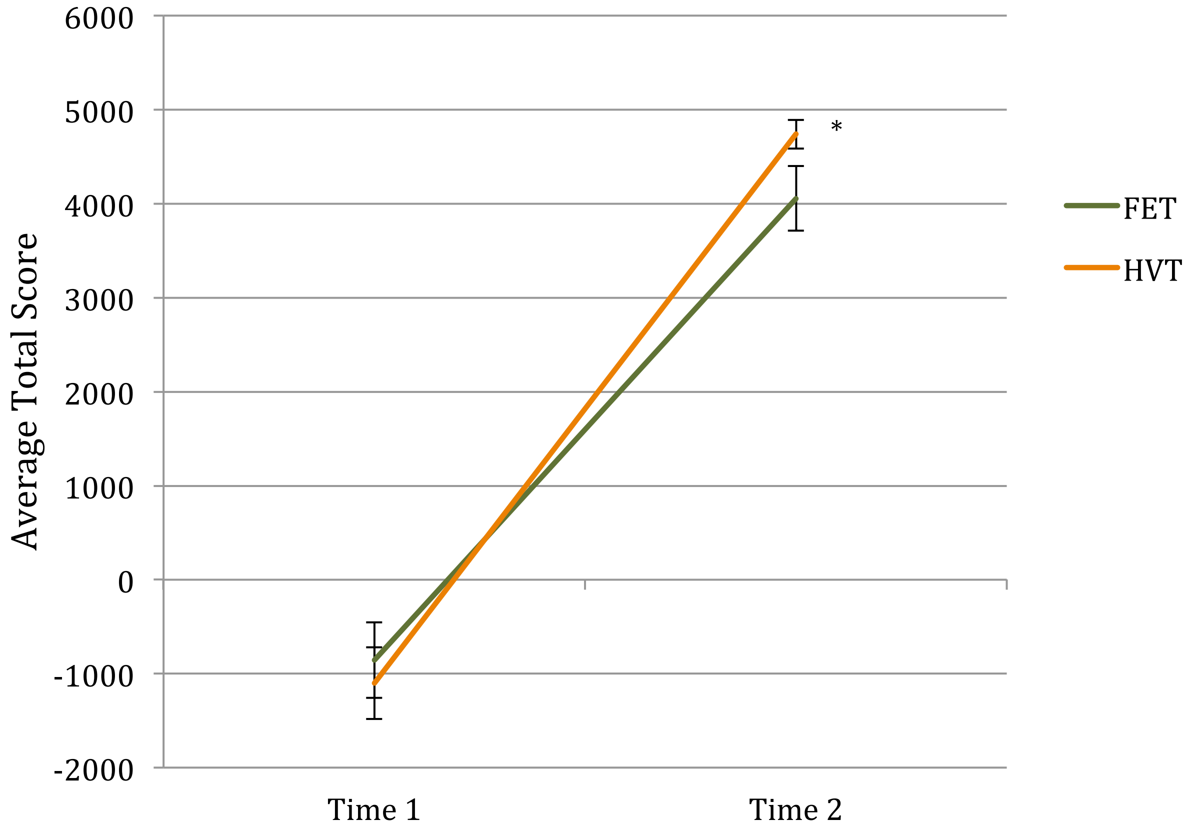

Figure 5. Graph of the average total score in SF at Time 1 and Time 2 for HVT and FET.
* indicates p-value < 0.05

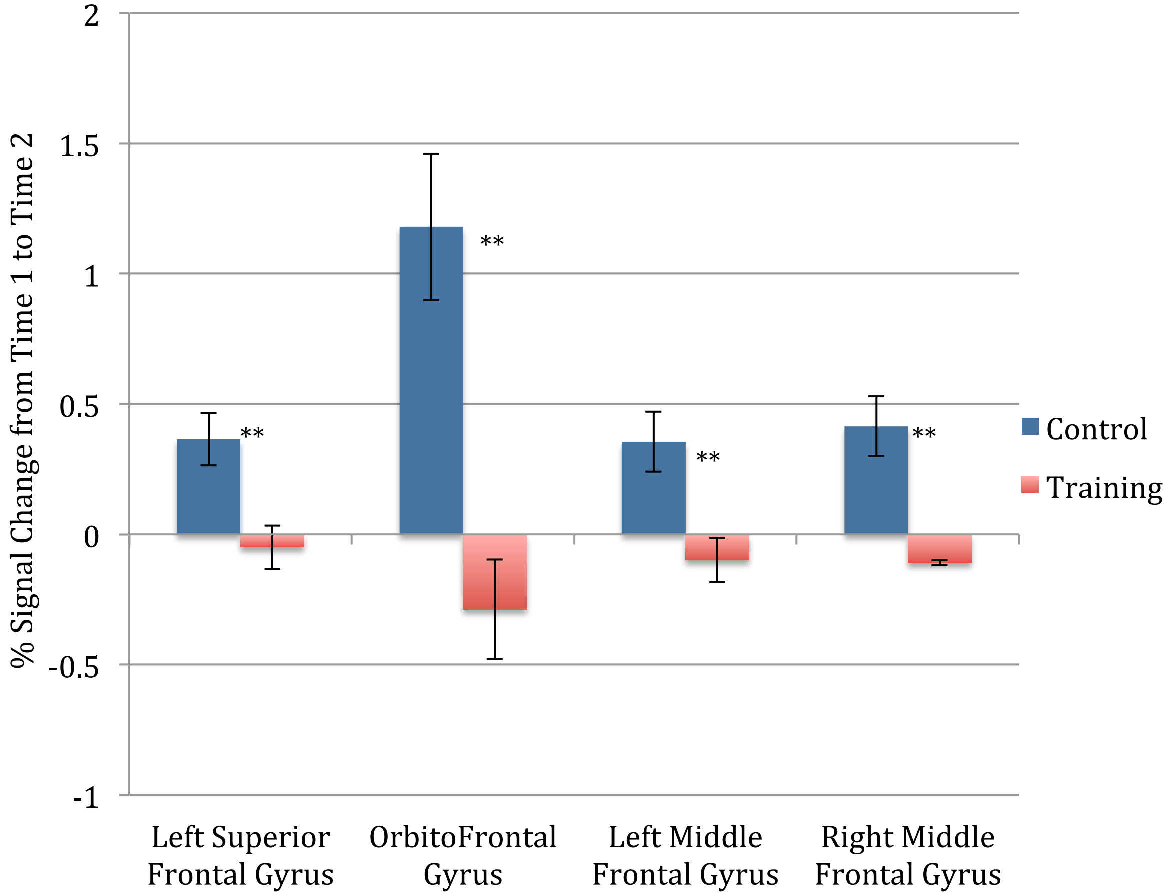

Figure 6. Graph representing the percent signal change in the cortical regions comprising the ATN based on the contrast map of Active>Passive, Time 2>Time 1, and Control>Training. **indicates p-value < 0.001

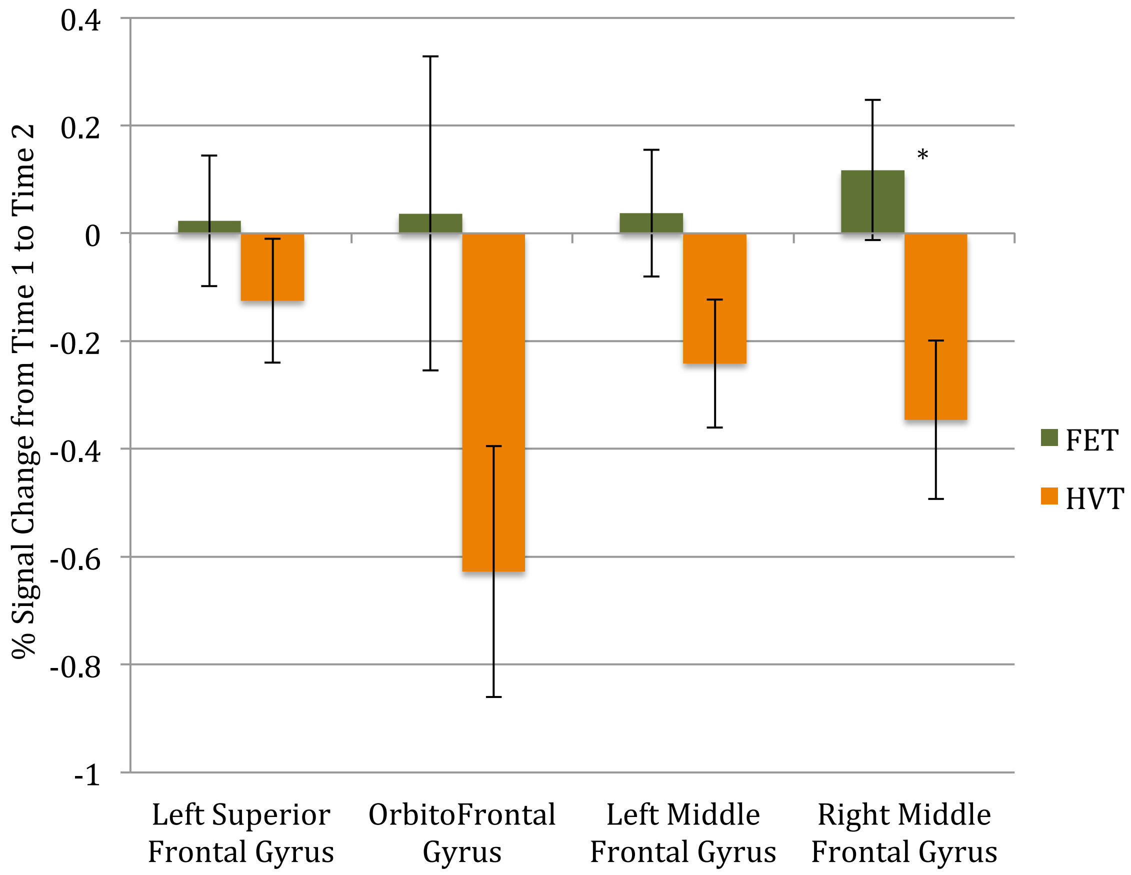

Figure 7. Graph representing the percent signal change in the cortical regions comprising the ATN based on the contrast map of Active>Passive, Time 2>Time 1, and Control>Training for HVT and FET. *indicates p-value < 0.05

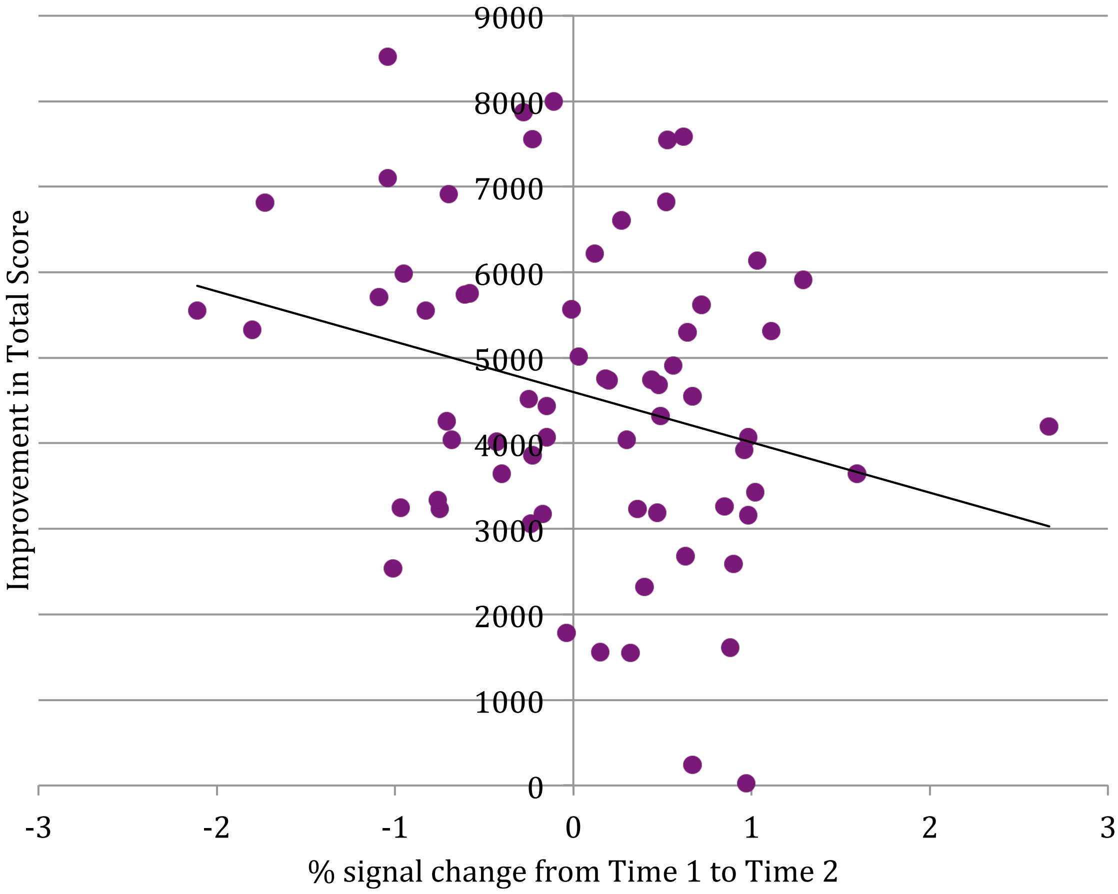

Figure 8. Scatterplot representing the correlation between change in activation in the right MFG from Time 1 to Time 2 and improvement in total score for all participants. $R^2 = 0.073$