THE EFFECTS OF ACTION VIDEO GAME TRAINING ON VISUAL SHORT-TERM MEMORY

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ABSTRACT

The ability to hold visual information in mind over a brief delay is critical for acquiring information and navigating a complex visual world. Despite the ubiquitous nature of visual short-term memory (VSTM) in our everyday lives, this system is fundamentally limited in capacity. Therefore, the potential to improve VSTM through training is a growing area of research. An emerging body of literature suggests that extensive experience playing action video games yields a myriad of perceptual and attentional benefits. Several lines of converging work provide evidence that action video game play influences VSTM as well. The current study utilized a training paradigm to examine whether action video games cause improvements to the quantity and/or the quality of information stored in VSTM and whether these VSTM advantages extend visual working memory (VWM). The results suggest that VSTM capacity is increased after action video game training, as compared to training on a control game, and that some limited improvement to VSTM precision occurs with action game training as well. The VSTM improvements seen in individuals trained on an action video game are not better accounted for by differences in motivation or engagement, differential expectations, or baseline differences in demographics as compared to the control group used. However, these findings do not appear to extend to measures of VWM, nor to verbal working memory. In sum, action video game training represents a potentially unique and engaging platform by which this severely capacity-limited VSTM system might be enhanced.

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CHAPTER 1

INTRODUCTION

The ability to maintain task-relevant visual information over a brief delay after direct visual input has been removed (i.e., visual short-term memory—VSTM) is critical for learning new skills, solving novel tasks, and acquiring new knowledge (e.g., Alloway, Gathercole, & Elliott, 2010; Alloway, Gathercole, Willis, & Adams, 2004; Gathercole & Pickering, 2000; Logie, 2011). Visual short-term memory is the fundamental process that allows us to sustain attended information across saccades and other visual interruptions, to compare objects or scenes based on visual features, and to navigate the visual world. Because VSTM is crucial to so many basic actions and processes that guide behavior, research has begun to focus on potential ways to improve this essential system. The current study focuses on a novel approach to training VSTM through the use of action video game play. This approach is seated in two main areas of literature. First, there is a vast literature regarding individual differences in VSTM and how these individual differences are linked to various aspects of visual attention. Second, in the past decade, an emerging body of research has supported the notion that experience playing action video games enhances a range of perceptual and attentional skills. As will be discussed below, considering these two areas of research together suggests that action video game training may be an exciting and effective new method for training VSTM.

One important feature of VSTM, especially with regards to training, is its fundamental capacity limitation. Though there is much debate surrounding the nature of the capacity limitation, as discussed in the following section, VSTM capacity has commonly been estimated at approximately three or four items (Cowan, 2001; Luck & Vogel, 1997). Despite consistency in the literature about the approximate capacity of VSTM, it is also well documented that VSTM capacity varies widely among individuals (Astle & Scerif, 2011; Cowan et al., 2005; Cusack, Lehmann, Veldsman, & Mitchell, 2009; Vogel, McCullough, & Machizawa, 2005). One exciting implication of these known individual differences in VSTM is the prospect of using this information to inform the potential remediation of VSTM. Considering how crucial VSTM is to guiding behavior, investigating how various factors influence individual differences in VSTM capacity and examining the potential to enhance VSTM through training is an important endeavor.

In the sections that follow, I will discuss the current literature surrounding investigations of VSTM, including competing theories concerning what factors limit its capacity and an examination of the relationship between individual differences in VSTM and attention. The basic research into the nature of VSTM and its relationship to specific aspects of visual attention provides key insights into the features of VSTM that may respond to training interventions. After consideration of the foundational findings, I will describe the alternative approaches that have been used to target VSTM enhancement, concluding with a discussion of the relevant findings from studies using action video game play as a training intervention.

Models of VSTM Capacity

Several models of VSTM capacity have been proposed, and the debate among these various models has permeated the literature for some time now. Using a change detection paradigm, in which observers are asked to determine whether a change was present between a memory array and a test array of items, separated by a retention interval, Luck and Vogel (1997) originally proposed that VSTM was object-based because capacity was estimated to be approximately 3-4 objects regardless of the number of features contained in each object. This model suggests that VSTM is limited by a fixed number of slots with each slot containing one integrated object percept, and that individual variability can arise either through differences in the number of slots one possesses or from differences in controlling access to these slots (Cusack, et al., 2009; Fukuda & Vogel, 2009; McNab et al., 2008; Vogel, et al., 2005). Despite evidence for Luck and Vogel's slots model of VSTM, there are also contradictory results (Davis & Holmes, 2005; Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Wheeler & Treisman, 2002).

One alternative model suggests that VSTM capacity is not a fixed number of items, but instead a limited resource that is spread over the entire visual scene (Bays & Husain, 2008; Palmer, 1990; Wilken & Ma, 2004). According to this model, the proportion of resources allocated to each item in the visual scene determines the precision with which it is remembered. A resource model suggests that individuals with low VSTM capacity spread their limited resources too thinly over many items and therefore maintain less precise representations in

VSTM, which results in poorer recall performance (Bays & Husain, 2008; but also see, Zhang & Luck, 2008; Zhang & Luck, 2011).

Another alternative is the information-load model proposed by Alvarez and Cavanaugh (2004), which extends the slots model and suggests that both the number of objects and the total amount of visual information per object limits VSTM capacity (i.e., more capacity must be allocated to more complex stimuli). Alvarez and Cavanaugh (2004) found that as the amount of information per item approached zero, the capacity grew only to a maximum of four or five items, which is consistent with the capacity estimates found by Luck and colleagues (1997; 2008). Information-load theory is also supported by neuroimaging evidence that suggests a dissociation between areas of the posterior parietal cortex with regard to VSTM capacity. Specifically, activation in the inferior intraparietal sulcus (IPS) is correlated with maintaining spatial attention over a fixed number of objects, whereas activation in the superior IPS and lateral occipital complex (LOC) seems to encode and maintain a variable subset of attended objects, depending on their complexity (Todd & Marois, 2004, 2005; Xu, 2007; Xu & Chun, 2006). This converging evidence suggests that VSTM capacity contains a fixed number of slots, but each slot is filled based on the amount of visual information contained in each to-be-remembered object (Alvarez & Cavanaugh, 2004; Awh, Brian, & Vogel, 2007; Zhang & Luck, 2008, 2011). In others words, as Zhang and Luck (2008) stated, VSTM capacity is limited by a small set of discrete slots, but slots themselves are a type of resource.

Therefore both the quantity and the quality of visual representations stored in VSTM may vary among individuals and may have the potential to be improved through training.

VSTM and Attention

One topic that pervades the literature on individual differences in VSTM capacity is the link between visual attention and VSTM. The links between attention and VSTM provide a guide for what type of training may most effectively enhance VSTM. Before turning to training, a brief overview of the literature on attention and VSTM will be discussed.

Visual attention is a mechanism that selects a location/feature or a set of locations/features containing relevant perceptual information within a visual scene. Visual attention and VSTM have been characterized as overlapping and interactive processes and there is an extensive body of literature documenting a relationship between individual variability in VSTM capacity and visual attention. As discussed above, both the quality and the quantity of information stored in VSTM can vary among individuals. This distinction between quality and quantity extends into the visual attention literature because it has been established that individual differences in separate attentional networks are predictive of the quantity and the quality of stored representations. First, there is a strong link between one’s ability to orient attention toward to-be-remembered objects and the quality with which information is encoded and maintained in VSTM (e.g., Machizawa & Driver, 2011). Second, selective attention, the ability to attend to task-relevant information while filtering out task-irrelevant information, appears to be very closely related to the quantity of information stored in VSTM (e.g., Vogel, et al., 2005). These distinct effects of attention on the quantity and quality of VSTM representations are discussed in more detail in the following paragraphs.

Evidence that orienting attention influences VSTM comes from two main lines of research. First, several studies have shown that focusing or orienting attention on a spatial location increases the probability that the information at the oriented location or a spatially nearby location will be encoded into VSTM (Jiang, Olson, & Chun, 2000; Linke, Vincente-Grabovetsy, Mitchell, & Cusack, 2011; Schmidt, Vogel, Woodman, & Luck, 2002; Woodman, Vecera, & Luck, 2003). Particularly relevant to training is that high VSTM capacity individuals orient their attention more efficiently than their low capacity counterparts by spatially orienting to groups of objects or locations to be encoded into VSTM (Jiang, Chun, & Olson, 2004; Linke, et al., 2011). Second, orienting attention to items being maintained in VSTM appears to be crucial in protecting and preserving the integrity of information being currently stored in VSTM once external input is removed (Griffin & Nobre, 2003; Matsukura, Luck, & Vecera, 2007; Murray, Nobre, Clark, Cravo, & Stokes, 2013). Further, several functional neuroimaging studies have supported the claim that orienting attention to internal memory representations serves to protect or enhance the stored items by activating or maintaining the original neural trace that corresponds to that information (Berryhill, Chein, & Olson, 2011; Kuo, Yeh, Chen, & D'Esposito, 2011; Lepsien & Nobre, 2007; Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012). Therefore, individual differences in one's ability to orient attention to internal representations likely influences the degree to which someone can protect the quality of memory items from decay or interference during a maintenance period.

Selective attention is thought to act as a gate that dictates which information is chosen for further processing. Selective attention influences the encoding and maintenance of information in VSTM by filtering out task-irrelevant information, thereby reducing the load on an extremely capacity-limited system (Kuo, Stokes, & Nobre, 2012). Specifically, high VSTM capacity individuals are more efficient at representing only the relevant items in a task than are low capacity individuals, who inefficiently encode and maintain information about irrelevant items present in a memory display (Rutman, Clapp, Chadick, & Gazzaley, 2010; Vogel, et al., 2005). Further evidence for the role of selective attention in individual differences in VSTM capacity comes from studies using large, supra-capacity set sizes, which require a greater degree of selectively during encoding since all items cannot be held in VSTM (Cusack, et al., 2009). Therefore, an efficient selective attention network determines the quantity of task-relevant information that is able to be stored in VSTM by filtering out task-irrelevant information and/or additional items that will not “fit” into VSTM in the case of supra-capacity set sizes.

Evidence from studies of individual differences in VSTM capacity has provided extensive information about how orienting and selective attention influence the quantity and the quality of information stored in VSTM. Specifically, one's ability to orient or focus attention on spatial locations or objects appears to enhance the quality with which visual information is encoded and maintained in

VSTM. The orienting attention network likely works in concert with selective attention in order to select task-relevant information for storage in VSTM. Variation in the selectivity of task-relevant information is a crucial factor in VSTM capacity because it allows individuals to control access to the limited number of slots available to them. Because both orienting and selective attention impact VSTM capacity, these attentional networks provide specific targets for training VSTM.

Training VSTM

Given the individual differences literature discussed above, it seems plausible that either (or both) the quantity and quality of information stored in VSTM may be malleable, and therefore could potentially be trained. The assumptions that VSTM capacity is limited by the number of slots one has, and that each slot also represents a resource affected by the degree of representational complexity or precision (Alvarez & Cavanaugh, 2004; Awh, et al., 2007; Luck & Vogel, 1997; Zhang & Luck, 2008, 2011) also suggests that specific protocols used to train VSTM may take several forms.

Category-Specific VSTM Enhancement

Previous work has shown that category-specific enhancement of VSTM is possible with extensive experience. Specifically, Curby and Gauthier (2007) found a VSTM advantage for faces compared to other objects. This VSTM advantage is attributed to individuals’ expertise with faces. A second study further bolstered the influence of perceptual expertise on this advantage by using non-face objects of expertise and finding a similar VSTM advantage (Curby, Glazek, & Gauthier, 2009). By comparing VSTM capacities for car stimuli in both car experts and car novices, the authors demonstrated that car experts had a greater VSTM capacity for cars as compared to car novices. Moreover, this VSTM advantage was correlated with an individual's level of expertise; the greater one's perceptual expertise with cars, the greater the VSTM advantage for cars. Curby and colleagues (2007; 2009) suggested that the mechanism underlying this expert VSTM advantage likely involves holistic processing, which is common to the processing of faces and other non-face objects of expertise (e.g., Gauthier & Tarr, 2002). An additional study found that perceptual expertise enhances the resolution, but not the number of representations held in VSTM (Scolari, Vogel, & Awh, 2008). Therefore, holistic processing may allow for more robust representations to be maintained in VSTM, which reduces the amount of error that occurs when retrieval of the information is needed. Especially considering the inherent visual complexity of faces, holistic processing may allow individuals to decrease the information-load of each to-be-remembered item and thus better utilize each available VSTM slot.

Despite the documented category-specific VSTM advantage for objects of expertise, other studies have failed to find training effects for VSTM. Notably, one study has found that VSTM for shapes and locations is not improved by training (Olson & Jiang, 2004). In this study, training was done by repeatedly presenting a subset of memory displays, thereby creating long-term memory representations for the displays. However, the results demonstrated that individuals did not perform better on repeated displays as compared to new displays. This failure to find an effect of training may have resulted from the brief nature of the training used. It is possible that more extensive training, akin to the extensive practice used in the perceptual expertise literature (e.g., Gauthier & Tarr, 1997), may produce a training effect on VSTM. The use of extensive training may also aid in answering the open question of whether VSTM can be enhanced in a more generalizable manner, i.e., not specifically linked to one type of information or stimulus category.

Action Video Game Experience

The complex visual environments inherent in action video games provide one documented example of extensive experience affording generalized visual cognitive enhancements. There are several studies that support the notion that prolonged experience playing action video games (e.g., first-person shooter games) may enhance various facets of visual cognition (Bavelier, Achtman, Mani, & Focker, 2012; Chisholm, Hickey, Theeuwes, & Kingstone, 2010; Chisholm & Kingstone, 2012; Clark, Fleck, & Mitroff, 2011; Colzato, van den Wildenberg, Zmigrod, & Hommel, 2012; Dye, Green, & Bavelier, 2009a, 2009b; Feng, Spence, & Pratt, 2007; Green & Bavelier, 2003, 2006a, 2006b, 2007; Green, Pouget, & Bavelier, 2010; Karle, Watter, & Shedden, 2010; Li, Polat, Makous, & Bavelier, 2009; Mishra, Zinni, Bavelier, & Hillyard, 2011; Oei & Patterson, 2013; Spence & Feng, 2010; Strobach, Frensch, & Schubert, 2012; Sungur & Boduroglu, 2012; West, Stevens, Pun, & Pratt, 2008; Wilms, Petersen, & Vangkilde, 2013; Wu et al., 2012). For example, previous studies have demonstrated that action video game play results in enhanced allocation of visual attention across space (Green & Bavelier, 2003, 2006a), greater temporal resolution of visual attention (Green & Bavelier, 2003), reduced attentional capture (Chisholm, et al., 2010; Chisholm & Kingstone, 2012), increased speed of visual processing (Dye, et al., 2009b), more efficient task switching abilities (Green, Sugarman, Medford, Klobusicky, & Bavelier, 2012), overall greater attentional capacity (Green & Bavelier, 2003), and more efficient selective attention (Bavelier, et al., 2012). Notably, training studies have also provided evidence consistent with a causal link between action video game play and these benefits to visual attention (Bavelier, et al., 2012; Dye, et al., 2009b; Green & Bavelier, 2003, 2006a, 2007, 2012; Green, et al., 2010).

Specifically relevant to VSTM, three studies provide evidence that suggests that action video game players (AVGPs) display greater top-down control of selective attention and enhanced orienting attention. First, using an attentional capture paradigm, it was demonstrated that AVGPs displayed less capture (i.e., less interference in the presence of an attention capturing distractor), which suggests greater top-down attentional control (Chisholm, et al., 2010). Moreover, one study suggests that AVGPs flexibly allocate selective attention more automatically than non-video game players (NVGPs), which results in greater distractor filtering during an attention-demanding task (Bavelier, et al., 2012). Finally, it has been shown that AVGPs (of all ages) display better orienting attention, as measured by the attentional network test (Dye, et al., 2009a; Fan, McCandliss, Sommer, Raz, & Posner, 2002). In this study, AVGPs more efficiently utilized a spatially valid cue, which indicated where a stimulus would appear, compared to NVGPs. Therefore, evidence that AVGPs have superior orienting attention and greater control of selective attention suggests that action video game play may provide a unique platform for training VSTM.

Given the inherent link between attention and VSTM, and previous work suggesting enhanced attentional abilities in AVGPs, it is possible that action video game play may also enhance VSTM. Consistent with this possibility, two studies have shown that AVGPs have a VSTM advantage over NVGPs (Blacker & Curby, under review; Boot, Kramer, Simons, Fabiani, & Gratton, 2008). Based on the evidence that AVGPs outperformed NVGPs regardless of whether they were given limited or ample time to encode an initial memory display, Blacker and Curby concluded that a general increase in visual speed of processing could not account for AVGPs' VSTM advantage (but also see, Wilms, et al., 2013). However, both previous studies illustrated that AVGPs' VSTM advantage was most prominent in the context of large, supra-capacity set sizes (Blacker & Curby, under review; Boot, et al., 2008), which may suggest that enhanced selective attention underlies AVGPs' advantage (Cusack, et al., 2009; Herrero, Nikolaev, Raffone, & van Leeuwen, 2009; Linke, et al., 2011). If AVGPs possess enhanced selective attention (Bavelier, et al., 2012), it may afford them more efficient selection when presented with supra-capacity set sizes. Thus, these results suggest that the enhanced selective attention in AVGPs may underlie this generalized benefit to VSTM.

Action Video Game Training

Group differences in VSTM capacity between AVGPs and NVGPs suggest the possibility that action video games serve to enhance VSTM performance through its documented effects on attentional abilities. However, one alternate explanation of these previous findings is the presence of a selection bias (i.e., high VSTM capacity individuals may be more likely to start playing video games initially). While this explanation seems unlikely due to evidence from video game training studies that have established a causal link between gaming and other visual cognitive enhancements (Feng, et al., 2007; Green & Bavelier, 2003, 2006a, 2007; Green, et al., 2010; Green, et al., 2012; Strobach, et al., 2012; but also see Boot et al., 2008), a training study is needed to test this issue within the context of AVGPs' VSTM advantage.

Importantly, Boot and colleagues (2008) did not find significant transfer to a measure of VSTM after 21.5 hours of action video game training. However, one very recent study has shown evidence that action video game training does improve VSTM (Oei & Patterson, 2013). Oei and Patterson (2013) found that a group who trained on an action game for 20 hours significantly improved on a change detection task from pre- to post-training; however, they used multiple other game training groups and did not specifically report a comparison of the action group to a control group(s), which makes it unclear whether their action group improved above and beyond that of their other game training groups. Further, Oei and Patterson (2013) had participants play their respective games on 3.5” iPhone/iPod Touch screens, which is strikingly different from other video game training studies, which typically use much larger computer or television monitors for training. The contradictory results and inconsistent methodologies of Oei and Patterson (2013) and Boot et al. (2008) make the topic of whether action video game training improves VSTM a contentious one, which requires further investigation. Therefore, the current study sought to further investigate whether action video game training improves either (or both) the quantity and quality of representations stored in VSTM.

Although previous studies suggest that enhanced selective attention may underlie AVGPs' VSTM advantage, there may be additional factors at work that have not yet been explored. One possibility is that AVGPs also benefit from encoding items into VSTM with greater precision or resolution, which bolsters performance. One recent study has demonstrated a VSTM precision advantage for AVGPs using a cross-sectional design (Sungur & Boduroglu, 2012), but the causal link has yet to be established. Additional evidence for this possibility comes from Dye and colleagues' (2009a) study demonstrating that AVGPs of all ages show greater orienting attention and studies that show that orienting attention to objects impacts the precision with which those objects are encoded and/or maintained in VSTM (Griffin & Nobre, 2003; Hollingworth, 2003; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009; Machizawa & Driver, 2011; Matsukura, et al., 2007; Schmidt, et al., 2002; Woodman, et al., 2003). Thus, the current study examined whether action video game training could enhance the quality or the precision with which items are stored in VSTM using the color wheel task (Bays, Catalao, & Husain, 2009; Zhang & Luck, 2008).

Previous studies examining the effects of action video game play on visual cognition have supported the notion that the enhancements that result from habitual video game play are relatively generalized (i.e., not linked to one specific stimulus category). Thus, an interesting question is whether AVGPs' VSTM advantage extends to tasks that utilize visual working memory (VWM)[1], which requires additional processing and/or manipulation of the to-be-remembered visual information. The current study examined the possibility of AVGPs' VSTM advantage extending to improvements on a complex span VWM task. While these VWM tasks have some overlap with VSTM tasks, complex span tasks have some unique processes at work as well (Chein, Moore, & Conway, 2011; Unsworth & Engle, 2006, 2007). Complex span tasks differ from traditional short-term memory tasks in that they require the participant to shift attention away from each successive to-be-remembered stimulus in order to perform some other task (Chein, et al., 2011; Daneman & Carpenter, 1980; Turner & Engle, 1989). These tasks are thought to be a realistic reflection of WM in everyday cognition because they require maintenance of information in the face of concurrent processing. Furthermore, performance on complex span tasks has been shown to predict higher order cognition, above and beyond that of simple span tasks, which do not contain a concurrent processing task (Engle, Tuholski, Laughlin, & Conway, 1999). Consequently, much research has been dedicated to examining the possibility of improving working memory capacity through training (for a review, see Morrison & Chein, 2011) because of the established relationship between

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[1] Some authors use the term VWM to refer to the process that here I refer to as VSTM (e.g., Luck & Vogel, 1997). Here VSTM refers to maintaining a visual representation over a brief delay, whereas VWM refers to maintenance *and* an additional processing/manipulation stage.

working memory and higher order cognition (e.g., Jaeggi, Buschkuehl, Jonides, & Perrig, 2008). However, video game training constitutes a very different method of training compared to traditional working memory training paradigms. Thus, it is unclear whether action video game training will yield any enhancements to VWM capacity.

Study Objectives

In sum, the current study sought to address the following questions: a) Is there a causal link between action video games and enhanced VSTM capacity? b) Does action video game play influence the resolution/precision with which information is encoded into VSTM? and c) Does action video game play enhance VWM capacity, as measured by a complex span task?

CHAPTER 2

METHOD

Participants

A total of thirty-nine male participants with normal or corrected-to-normal vision enrolled in the study[2]. All participants were undergraduates, recruited through an online participant pool and/or through study advertisements, and were compensated monetarily. All participants were tested for normal color vision prior to enrolling in the study. Five participants dropped out of the study before completion. All five participants who dropped out reported being unable to commit to the necessary time requirements of the study. Two of the five dropped out after the pre-training assessments and completed no training, whereas the other three dropped out after one (n=1) or two (n=2) training sessions. There were no discernible differences between those participants who dropped out and those who completed the study. The remaining 34 participants who completed the study had a mean age of 20.53 years (*SD*=2.57). Participants were randomly assigned to the action or control group. The 17 action group participants had a mean age of 20.41 years (*SD*=3.04) and the control group participants had a mean age of 20.65 years (*SD*=2.09). Participants were unaware of the alternate training condition (i.e., control participants did not know that other participants were playing an action game and vice versa).

Prior to study enrollment, participants completed a video game experience questionnaire. Participants reported the average number of hours per week that

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[2] In addition to the 39 participants who enrolled in the study, another 26 were recruited but either did not meet the video game experience criteria (n=23) or were colorblind (n=3).

they spent playing various genres of video games in the past year. The genres included: action, fighting, strategy, fantasy, sports and others[3]. Following previous studies, participants were enrolled in the study if they reported not having played action games in the past year[4] (Green & Bavelier, 2003, 2006a, 2007; Green, et al., 2010; Li, et al., 2009). Some participants reported experience with other genres of games in the past year; the action group reported a mean of 1.55 hrs/week (*SD*=1.53) of other genres of games and the control group reported a mean of 1.63 hrs/week (*SD*=2.52).

Due to the high correlation between measures of fluid intelligence and visual memory capacities (Cowan, et al., 2005; Cusack, et al., 2009; Fukuda, Vogel, Mayr, & Awh, 2010), two measures were used to ensure equal distribution between the action and control groups. Participants were asked to self-report SAT scores and were tested on the Ravens Progressive Matrices (RPM; Raven, 1990) as part of the pre-training assessments. Only 20 of the 34 participants reported their SAT scores (9 action, 11 control); however, of those who did report SAT scores, the action group reported a mean score of 1230 (out of 1600, *SD*=63) and the control group reported a mean score of 1221 (out of 1600, *SD*=140), which were not statistically different means, *t*(18)=.18, *p*=.86. On a split-half version of RPM, participants in the action group scored similarly (*M*=12.59, *SD*=2.72) to the control group (*M*=11.88, *SD*=3.24) with no significant difference between the groups, *t*(32)=.69, *p*=.50.

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[3] Participants' video game genre classifications were verified to ensure accurate estimates for each genre of game.

[4] Notably, previous studies have enrolled individuals who had not played action games in the past 6 months, whereas the current study used a more stringent criterion of 1 year.

Therefore, the random assignment to the two training groups was effective and each group had a similar distribution of age and fluid intelligence.

Training Methods

The action game training group played Call of Duty®: Modern Warfare® 3 (2011, ActiVision Publishing Inc.) and Call of Duty®: Black Ops® (2010, ActiVision Publishing Inc.). These games were chosen to be similar to those played by our AVGPs in a previous study (Blacker & Curby, under review) and because of the first-person point of view used. Participants played the games in single-player, campaign mode in which the player assumes the role of various characters and attempts to complete different missions. Each mission has a specific set of objectives (e.g., reach a checkpoint, eliminate enemies) and various checkpoints throughout. The game automatically saves the player's progress at these checkpoints, which was used in order to save progress across training sessions. Performance in the game was measured in numerous ways: a) the number of missions completed, b) the number of deaths per session, and c) the amount of time required to pass each mission. In addition participants performed 2 rounds of a "Special Ops" mission, which contains never-ending waves of enemies, in order to assess performance. This Special Ops mission was performed after 1 hour of training (to serve as a baseline) and after 28 hours of training. These missions provided statistics on shooting accuracy, kills, headshots, amount of time survived and a composite score, which takes into account all of these variables. Training gains were quantified by examining the composite score improvement from 1 hour to 28 hours of training.

The control game group played The Sims™ 3 (2009, Electronic Arts Inc.). The Sims™ 3 is a simulation-style strategy game, wherein the player takes complete control of the life of a character, which involves everything from everyday activities (eating, bathing, etc.) to going to work, managing relationships with other characters, getting married, having and raising children, and eventually growing old and dying. As characters are added to the household, the player takes control of those characters as well. Game performance was measured by tracking: a) number of characters controlled, b) number of relationships maintained, and c) lifetime happiness points, which are acquired throughout the game.

Based on previous training studies (See Table 1), each group trained on their respective game for 30 hours over a maximum duration of 30 days (Green & Bavelier, 2006a, 2007). The groups played their respective games on a 21.5" ViewSonic 1080p HDMI monitor. The action group participants completed the 30 hours of video game training in an average of 27.18 days (*SD*=4.17) and the control group completed the 30 hours of training in an average of 27.76 days (*SD*=4.40).

Table 1. Previous Training Studies. Summary of previous video game training studies' methods. EXP = Experimental group, CTRL = Control group, NO CON = No Contact controls

Authors	**Year**	**N per group**	**Total Training Hrs**	**Total Training Duration**
Green & Bavelier	2003	9 EXP, 8 CTRL	10 Hours	10 Days
Green & Bavelier	2006	16 EXP, 16 CTRL	30 Hours	30 Days
Green & Bavelier	2007	16 EXP, 16 CTRL	30 Hours	30 Days
Feng, Spence, & Pratt	2007	10 EXP, 10 CTRL	10 Hours	4 weeks
Boot et al.	2008	20 EXP, 20 CTRL, 23 NO CON	21.5 Hours	15 Sessions (4-5 weeks)
Li, Polat, Makous, Bavelier	2009	13 EXP, 9 CTRL	50 Hours	Avg 44 days (max 9 Weeks)
Li, Polat, Makous, Bavelier	2009	6 EXP, 7 CTRL	50 Hours	Avg 44 days (max 9 Weeks)
Green, Pouget, & Bavelier	2010	14 EXP, 11 CTRL	50 Hours	Avg 44 days (max 12 weeks)
Green et al.	2012	19 EXP, 17 CTRL	50 Hours	6-14 weeks
Strobach, Frensch, & Schubert	2012	10 EXP, 10 CTRL, 12 NO CON	15 Hours	4 weeks
Oei & Patterson	2013	16 EXP, 16 CTRL,	20 Hours	4 weeks

Assessment Battery Methods

All assessments were conducted pre- and post-training. To avoid order effects for the assessment battery, two different fixed orders were used and each participant was randomly assigned to one of the two orders. The two task orders were evenly distributed between the two groups. All assessment tasks were presented on a 21.5" ViewSonic 1080p HDMI monitor at a viewing distance of 60-cm, with the exception of the color wheel task (details described below).

VSTM Capacity Task: Change Detection

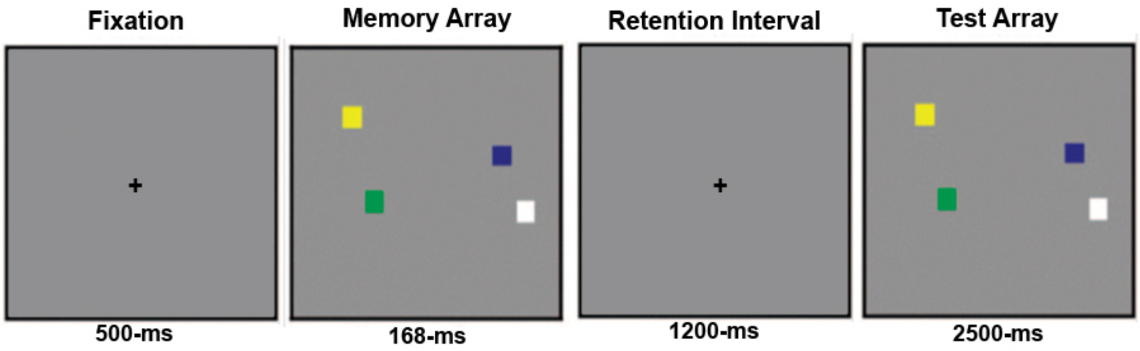
Stimuli

Stimuli consisted of colored squares (1.0°x1.0°), which were displayed on a gray background. The color of each square was chosen randomly without replacement from a set of seven: red, green, yellow, blue, black, white, and purple. Each square was located within an invisible 4x4 grid subtending a visual angle of 8.5°x8.5°.

Procedure

To measure VSTM capacity, a change detection paradigm was used (e.g., Luck & Vogel, 1997). After 500-ms of fixation, each trial consisted of a memory array of 4, 5, or 6 colored squares, displayed for 168-ms, followed by a 1,200-ms blank delay and then a 3,000-ms test array (Figure 1). The memory and test arrays were identical with the exception that on half of the trials, the color of one of the squares was different between the two arrays. During “change” trials, the new color in the test array was selected at random from the other possible colors not shown in the memory array. Participants indicated whether the two arrays were the same or different by a key press. Accuracy was stressed rather than speed and participants received visual feedback after each trial indicating whether their responses were correct or incorrect. Participants performed 32 trials for each set size. The different set sizes were randomly presented in 4 blocks of 24 trials, for a total of 96 trials and a session duration of approximately 10 minutes.

Figure 1. Change Detection Task. Used to assess VSTM capacity. Set sizes 4, 5, and 6 were used.



VSTM Precision Task: Color Wheel

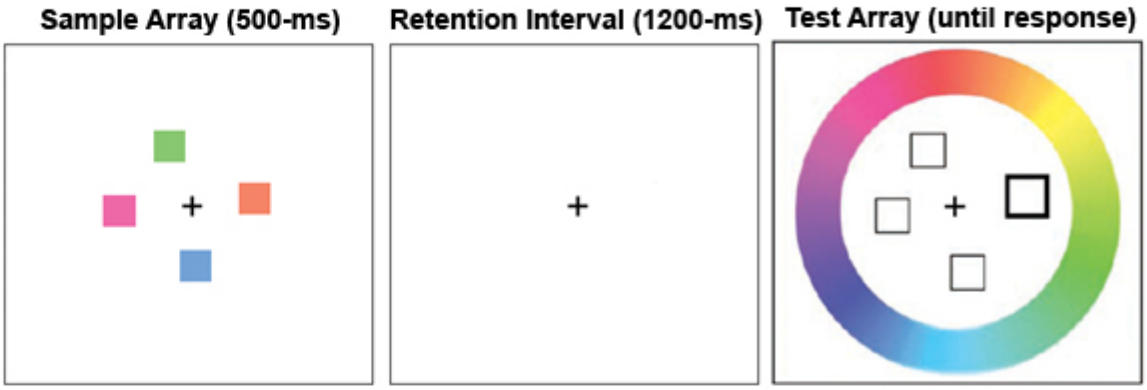
Stimuli

Stimuli were colored squares (2°x2°) presented on a gray background. The colors were selected from a master set of 180 evenly distributed and isoluminant hues on a circle in the perceptually homogenous Commission Internationale de l'Eclairage Lab color space (Bays, et al., 2009; Bays & Husain, 2008; Zhang & Luck, 2008, 2011). Stimuli were presented on a 17" CRT monitor and viewed at a distance of 33-cm.

Procedure

Similarly to Zhang and Luck (2008, 2011), a trial began with a sample array of 1, 4, or 6 colored squares displayed for 500-ms. After a 1,200-ms blank delay period, participants were shown a test array. The test array contained the same number of outlined squares as presented in the sample array and in the same spatial locations. The outline of the probed square was thicker than that of the other squares. Surrounding the test array was a color wheel, which contained all 180 colors (Figure 2). Memory array items were always separated by at least 2 discrete color values. Participants were instructed to use a mouse click to indicate the color of the probed square as precisely as possible. The test array remained on the screen until the participant responded. Participants completed 100 trials for each set size for a total of 300 trials. The different set sizes were randomly presented in 3 blocks of 100 trials with a 2.5-minute break in between blocks, for a total session duration of 20 minutes.

Figure 2. Color Wheel Task. Used to assess VSTM precision. Set sizes 1, 4, and 6 were used.



Data

Recall error was calculated for each trial by determining the difference, in radians, between the location of the response and the true location of the probed color. Precision was calculated separately for each set size as the reciprocal of the standard deviation[5] of the error in participants' responses (zero indicates chance performance). In order to avoid an underestimation of precision, any trials where the participant's response was not within the correct half of the circle as the target (i.e., error $>\pi/2$) were excluded from precision estimates. Furthermore, data were examined based on the probabilistic mixture model proposed by Bays et al. (2009), which accounts for the distribution of errors in this recall task.

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[5] Due to the circular nature of the response area, Fisher's definition of mean and standard deviation for circular data were used for these calculations (Fisher, 1993).

According to this model, the overall response distribution comprises a mixture of three different components: target responses (the observer correctly reports the color value with some variability), non-target responses (the observer mistakenly reports the color value of one of the other, uncued items stored in memory with some variability) and uniform responses (the observer generates a random response unrelated to either cued or uncued items).

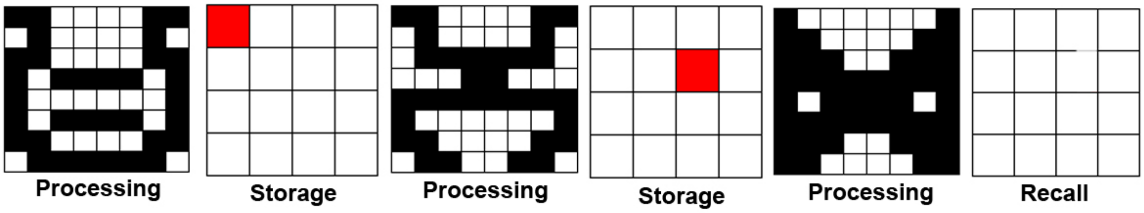
VWM Capacity Task: Symmetry Span

The symmetry span task is a complex span VWM task that has been previously shown to be sensitive to individual differences in capacity estimates (Kane et al., 2004). A complex span task was chosen to dissociate between working memory and short-term memory (Unsworth & Engle, 2007). Complex span tasks differ from traditional short-term memory tasks in that they require the participant to shift attention away from each successive to-be-remembered stimulus in order to perform some other task (Chein, et al., 2011; Daneman & Carpenter, 1980; Turner & Engle, 1989).

Procedure

Participants recalled sequences of red-square locations within a matrix against a background symmetry judgment task (Figure 3). In the symmetry judgment task, an 8x8 matrix (7°x7°) was presented, with some squares filled in black, and participants had to decide whether the black-square design was symmetrical along its vertical axis; it was symmetrical about half the time. Participants responded via a button press. Following the participant’s response to the symmetry display, a 500-ms delay was followed by a 4x4 matrix with a filled red square presented for 650-ms. Immediately following the to-be remembered matrix, either another symmetry display or the recall cue was presented. When presented with the recall cue, participants were asked to recall the sequence of red-square locations in the preceding displays; in the order they appeared using the mouse to click the sequence in a blank 4x4 grid. Sets of 2, 3, 4, or 5 symmetry–memory matrices were presented per trial. Participants completed 3 trials per set size for a total of 12 trials. In comparison to the VSTM measures, this VWM measure has much fewer trials, but previous work has demonstrated that the task has high test-retest reliability (Cronbach's alpha = .77; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). Further, previous work has provided a normative sample of over 6,000 young adults on the automated version of the symmetry span task used here (Redick et al., 2012).

Figure 3. Symmetry Span Task. Used to assess VWM capacity. Set sizes 2, 3, 4, and 5 were used.



Data

Two scores were calculated separately: an “Absolute Score” and a “Partial Score”. The Absolute Score is the sum of all trials in which all red squares were recalled in the correct location and serial order. The Partial Score is the sum of red squares recalled in the correct location and serial order, regardless of whether the entire trial was recalled correctly. For example, in a set size 3 trial, if two of the three squares were correctly recalled, then two is added to the Partial Score, but nothing would be added to the Absolute Score because all 3 items were not correctly recalled. Therefore, the Absolute Score must always be less than or equal to the Partial Score.

Immediate Free Recall Task

Participants also completed a verbal memory task, which was utilized as a divergent measure that was *not* expected to show differential improvements between the action and control groups. Specifically, an immediate free recall task was used in which participants saw a list of 14 words, presented one at a time, and displayed for 1 sec each (Craik, 1970). After each list of 14 words ended, participants were instructed to recall as many words as possible, regardless of order.

Motivation and Engagement Measures

Prior to each of the assessment tasks, participants were asked to complete a self-report measure about how motivated they were to perform each task using a 0 to 9 scale (0 = not motivated at all, 9 = extremely motivated). After each assessment task, participants were then asked to complete a self-report question about how engaged they had been in the task using a 0 to 9 scale (0 = not engaged at all, 9 = extremely engaged). The same motivation and engagement scales were completed before and after each training session, respectively. These scales were added to ensure that results did not emerge due to differential motivation/engagement levels in training or on the assessment tasks between the two groups.

Exit Survey

Participants completed an exit survey upon completion of the study, which was aimed to evaluate their experience in the study and to determine what their expectations of the purpose and outcome of the study were. Participants were asked about their previous knowledge of research regarding video game playing, both negative and positive. Participants were asked how much they enjoyed the game that they trained on using a likert scale ranging from 1 = "I disliked the game very much" to 5 = "I enjoyed the game very much." Finally, for each assessment task participants were asked to rate how they thought their 30 hours of video game training influenced their performance on each task. They used a likert scale: 1=major decrease, 2=minor decrease, 3=no change, 4=minor increase, 5=major increase. These data were collected in an effort to address an ongoing concern in the literature that differential expectations arise from playing different video games in training studies and these differences in expectations may account for performance gains after training (Boot, Blakely, & Simons, 2011; Boot & Simons, 2012).

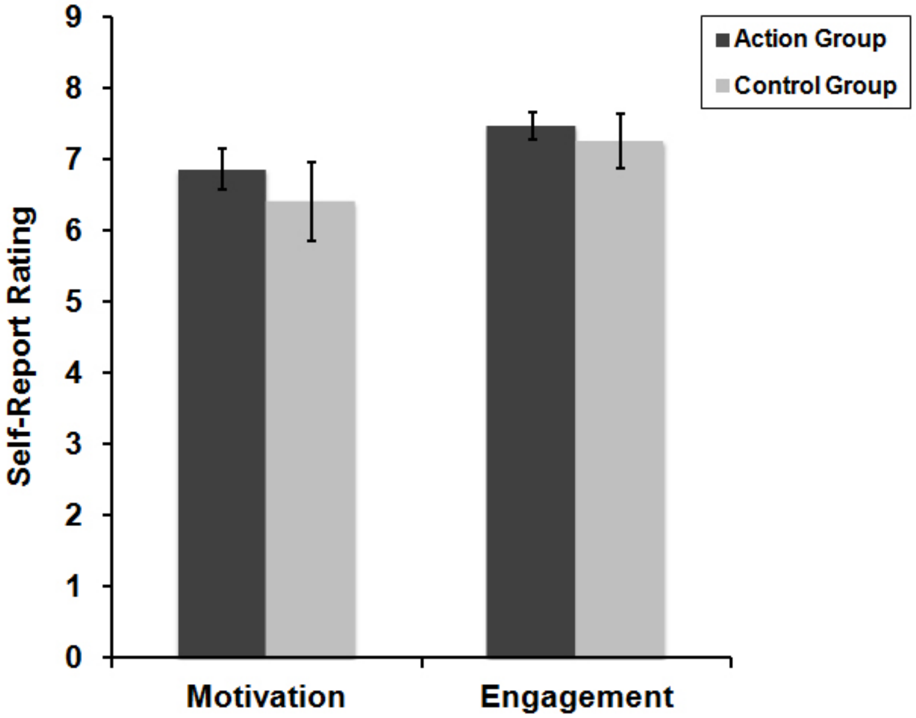
CHAPTER 3

RESULTS

Motivation and Engagement

In order to examine whether motivation and engagement levels differed between the two groups during their respective video game training, independent samples t-tests were used on average motivation and engagement scores. No significant differences in motivation, *t*(32)=.73, *p*=.47, or engagement, *t*(32)=.49, *p*=.63, emerged between the action and control groups (Figure 4).

Figure 4. Motivation and Engagement Data for Training. Average self-report ratings by training group. Error bars represent standard error of the mean.



In order to assess any potential differences in motivation or engagement between groups for the assessment tasks, 2 (time: pre-, post-training) x 2 (group: action, control) repeated-measures analysis of variances (ANOVAs) were tested on motivation and engagement scores for each task separately. For all assessments, no significant main effects or interactions emerged, change detection: all *p*s≥.28, color wheel: all *p*s≥.16, symmetry span: all *p*s≥.16, free recall: all *p*s≥.21 (See Figures 5 and 6). These results suggest that individuals were not more or less motivated or engaged in the assessment tasks before or after training (i.e., no main effects of time), neither group was more or less motivated or engaged with regard to the assessment tasks (i.e., no main effects of group), nor were there any interactions of time and group, which suggests that any performance enhancements after training cannot be readily explained by differential task motivation or task engagement.

Figure 5. Motivation Data for Assessment Tasks. Average self-report ratings by training group, assessment task, and time point. Error bars represent standard error of the mean.

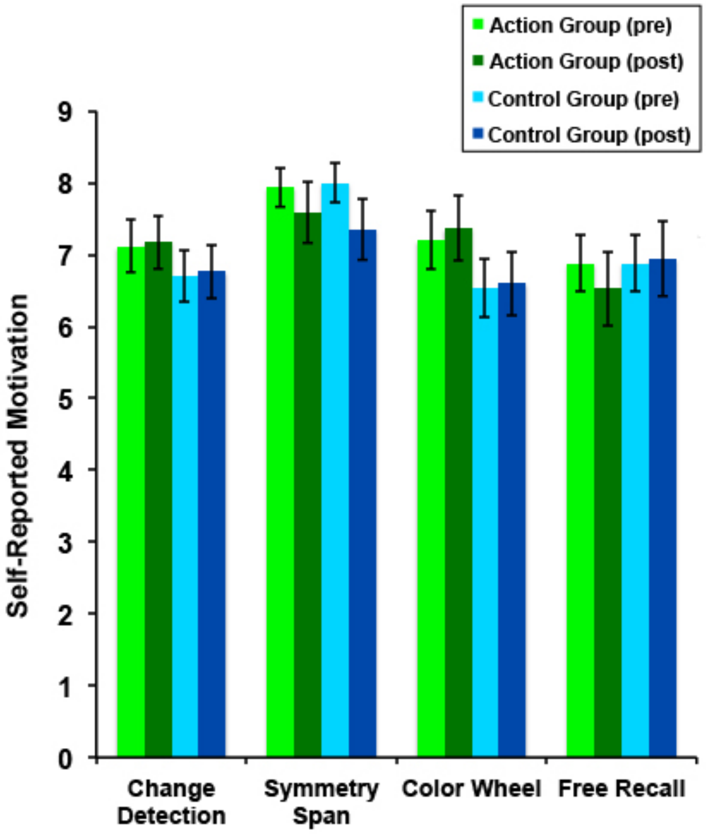
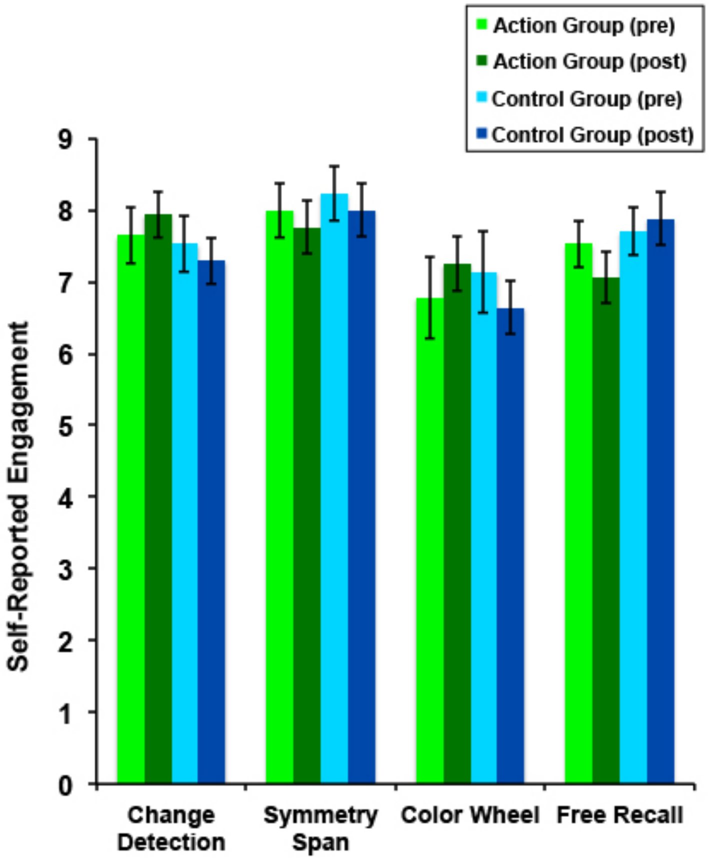


Figure 6. Engagement Data for Assessment Tasks. Average self-report ratings by training group, assessment task, and time point. Error bars represent standard error of the mean.



Training

For Call of Duty, participants performed a training assessment in the Special Ops portion of the game both after 1 hour of training and after 28 hours of training to measure skill improvement. The composite score for the Special Ops mission was used as a measure of training improvement and was shown to be reliable across all attempts (Cronbach's α = .72). Fifteen of the seventeen action participants showed improvement from hour 1 of training to hour 28 of training on this Special Ops training assessment. However, two participants did not improve and showed below average advancement through the game on all measures, including large negative composite scores from hours 1 to 28 of training, and were therefore not included in any further analyses. In addition these participants also demonstrated poor pre- to post-test assessment performance, as evidenced by being in the bottom quartile of the action group for gain scores on all assessment measures. These two participants were also in the bottom quartile of the group for self-reported motivation scores during both training and assessments.

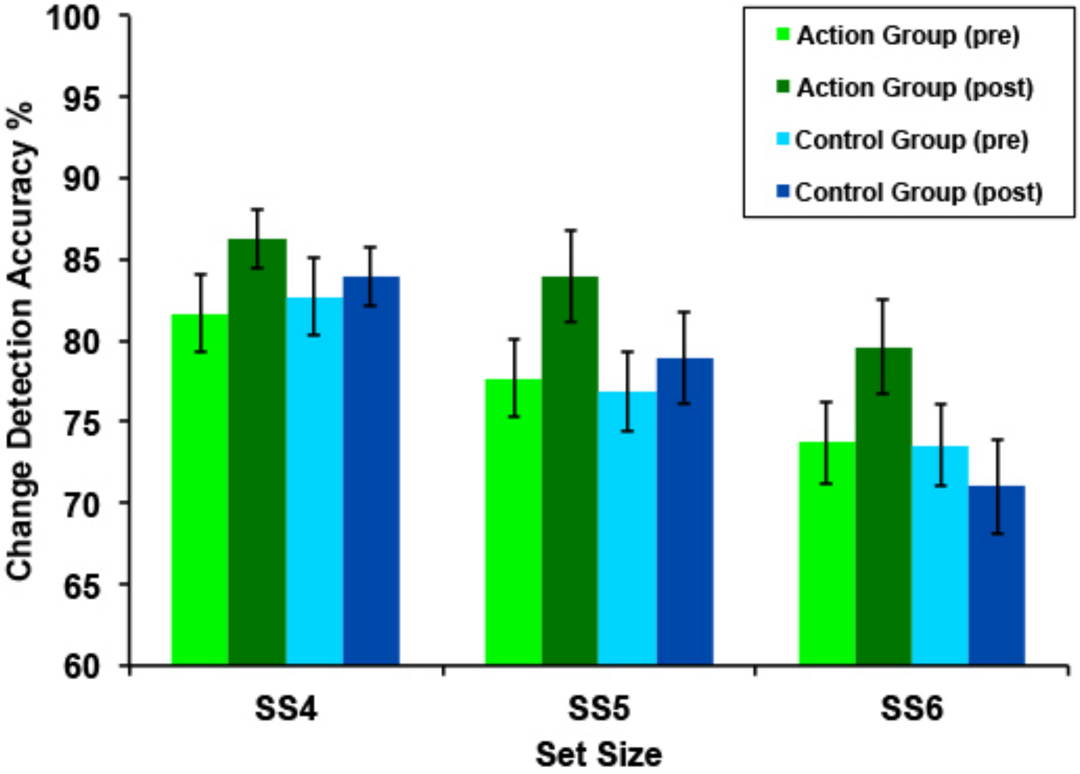
For The Sims, the primary measure of performance was the "Lifetime Happiness" points that are acquired throughout the game. Participants accumulated an average of 293,045 lifetime happiness points (*SD*=168,427). Participants controlled an average of 3 characters and maintained an average of 61 relationships throughout the 30 hours of training. Based on these training measures, there were no statistical outliers and therefore all participants were included in the following analyses, unless otherwise specified below.

Change Detection

Analysis for the change detection task targeted differences in training gains in VSTM accuracy for the action and control groups. A 3 (set size: 4, 5, 6) x 2 (group: action, control) x 2 (time: pre-, post-training) repeated-measures ANOVA was tested on accuracy values. Two control participants were excluded from the analysis due to chance performance (i.e., 50%) on the post-training assessment task. Significant main effects of set size, $F(2,27)=28.48$, $p<.001$, and time, $F(1,28)=6.31$, $p<.05$, emerged with greater accuracy at smaller set sizes and at the post-training assessment time point, respectively. Importantly, the time x group interaction reached significance, $F(1,28)=5.17$, $p<.05$, with the action group demonstrating a greater increase in accuracy after training compared to the control group (Figure 7). The main effect of group and the remaining interactions did not approach significance, *F*s≤1.1, *p*s≥.33.

In order to compare the size of these training effects with reference to capacity estimates, Pashler's K (set size*[(hit rate – false alarm rate)/(1 – false alarm rate)]) was also calculated (Pashler, 1988; Rouder, Morey, Morey, & Cowan, 2011). Because all presented set sizes were at or above normal capacity limits, maximum K-value, K_{max}, across all set sizes is considered here. Prior to training the action group stored an average of 4.0 items (*SD*=.93), whereas after training they stored an average of 4.6 items (*SD*=.75), which represents a significant training gain, $t(14)=3.44$, $p<.01$. In comparison, the control group stored an average of 3.98 items (*SD*=.71) before training and an average of 4.14 items (*SD*=.95) after training, which is not a significant gain, $t(14)=.73$, $p=.48$. In sum, the action group showed significantly more post-training improvement on the change detection task compared to the control group, which suggests that experience playing action video games enhanced VSTM capacity.

Figure 7. Change Detection Data. Accuracy data for the change detection task demonstrating a significant training gain for the action group compared to the control group. Error bars represent standard error of the mean.

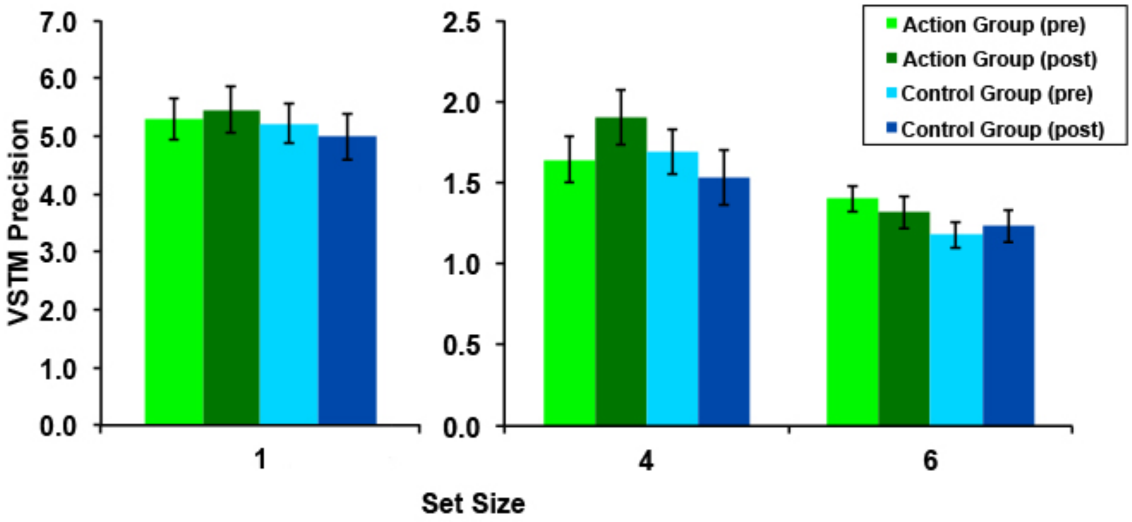


Color Wheel

Analyses for the color wheel task targeted precision values and the probabilistic mixture model described above and whether training influenced these factors for each of the groups. Trials were excluded if reaction time (RT) was greater than 2*SD*s above the entire groups' mean (>3.35 seconds). As a result of this RT filter, two participants lost >25% of their trials and were excluded from any additional analyses. Specifically for precision analyses, an additional 4 participants (2 action, 2 control) were excluded due to extremely negative difference scores (i.e., precision was >20% lower at post-test compared to pre-test). For the remaining 13 action and 13 control participants, a 3 (set size: 1, 4, 6) x 2 (time: pre-, post-training) x 2 (group: action, control) repeated-measures ANOVA was conducted on precision values. A main effect of set size emerged, *F*(2,23)=189.21, *p*<.001, with precision decreasing as set size increased. No other main effects or two-way interactions approached significance, *p*s≥.31. However, the three-way group x time x set size interaction was significant, *F*(2,23)=3.89, *p*<.05 (Figure 8).

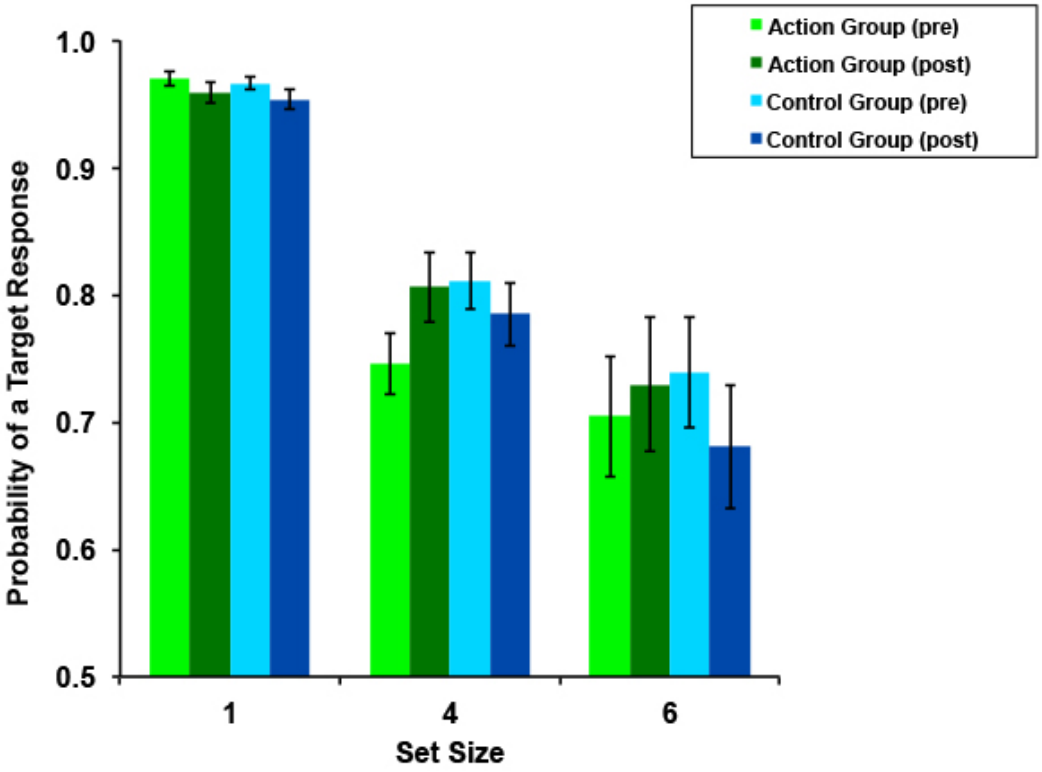
To explore this three-way interaction further, separate 2 (time) x 2 (group) repeated-measures ANOVAs were tested on each set size separately. For set size 1, neither main effect of group or time, nor the interaction approached significance, *p*s≥.52. For set size 4, neither main effect of group or time was significant, *p*s≥.42; but importantly, the time x group interaction did reach significance, *F*(1,24)=5.74, *p*<.05, with the action group showing greater precision after training compared to before training, above and beyond that of the control group. Finally for set size 6, neither main effect of group or time, nor the interaction reached significance, *p*s≥.16. These results suggest the action group showed significant gains in precision only at set size 4. The emergence of this interaction specifically at set size 4 is informative because the load at this set size represents the best approximation of participants' functional capacity limit, even after training.

Figure 8. Color Wheel Precision Data. Precision results shown separately for each set size. Error bars represent standard error of the mean.



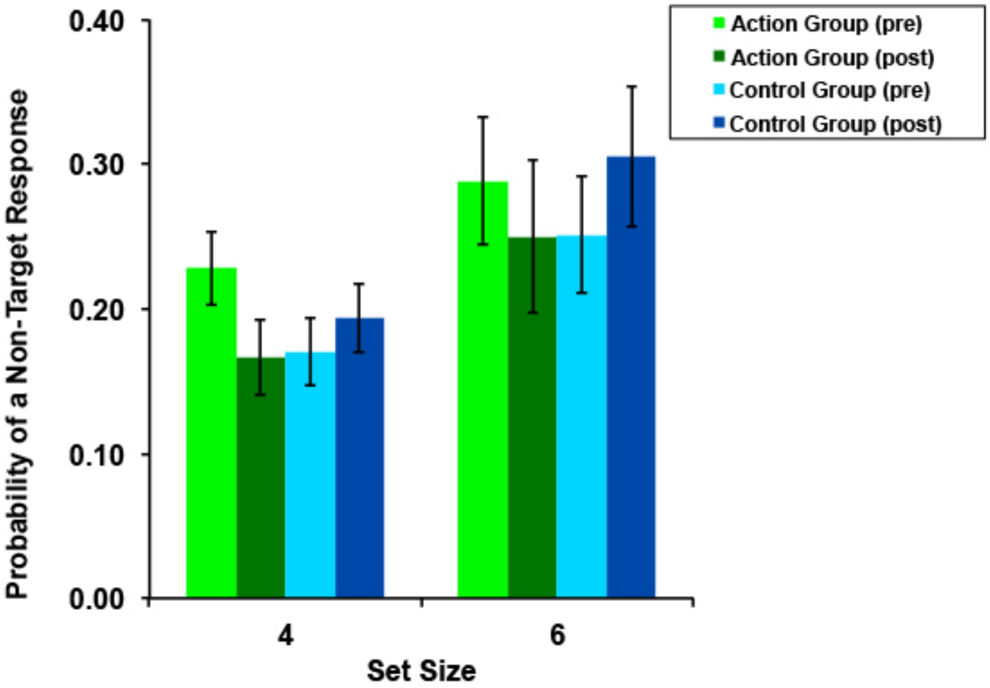
The probabilistic mixture model results add to these precision findings. Separate repeated-measures ANOVAs were run for target responses, non-target responses, and uniform responses. Six participants' (4 action, 2 control) data were excluded from the mixture model analyses because of extremely negative difference scores (i.e., performed ≥20% worse on post-test compared to pre-test). For target responses, a 3 (set size: 1, 4, 6) x 2 (time: pre-, post-training) x 2 (group: action, control) repeated-measures ANOVA was tested. A significant main effect of set size emerged, *F*(2,21)=73.82, *p*<.001, with the probability of having the target in memory decreasing as set size increased. Importantly, the time x group interaction reached significance, *F*(1,22)=4.18, *p*=.05, with the action group demonstrating a greater increase in target responses after training compared to the control group. No other main effects or interactions approached significance, *p*s≥.15. As can be seen in Figure 9, this time x group interaction was again driven primarily by the data at set size 4. To further explore this facet of the data, separate 2 (time) x 2 (group) repeated-measures ANOVAs were tested for each set size. Set size 1 and 6 yielded no significant main effects or interactions, *p*s≥.29, with the exception of the main effect for time in set size 1, which approached significance, *F*(1,22)=3.35, *p*<.08, with performance being lower at post-test compared to pre-test for both groups. At set size 4, a significant time x group interaction emerged, *F*(1,22)=5.40, *p*<.05, with the action group showing a greater increase in target responses after training compared to the control group. Neither main effect for set size 4 approached significance, *p*s≥.38. These set size specific analyses illustrate that the effect of enhanced target response probability for the action group is most evident at set size 4.

Figure 9. Color Wheel Target Responses. Probability of making a target response, shown separately for each set size. Error bars represent standard error of the mean.



For non-target responses, a 2 (set size: 4, 6) x 2 (time: pre-, post-training) x 2 (group: action, control) repeated-measures ANOVA was tested[6]. A significant main effect of set size emerged, *F*(1,22)=10.66, *p*<.01, with probability of making a non-target response increasing as set size increased. Notably, the time x group interaction was again significant, *F*(1,22)=4.77, *p*<.05, with the action group demonstrating a greater decrease in non-target responses after training compared to the control group. No other main effects or interactions reached significance, *p*s≥.51. As with precision and target responses, this effect is driven by performance at set size 4, as evidenced by a significant time x group interaction for set size 4, *F*(1,22)=5.33, *p*<.05, but not for set size 6, *p*=.21 (Figure 10).

Figure 10. Color Wheel Non-Target Responses. Probability of making a non-target response, shown separately for each set size. Error bars represent standard error of the mean.



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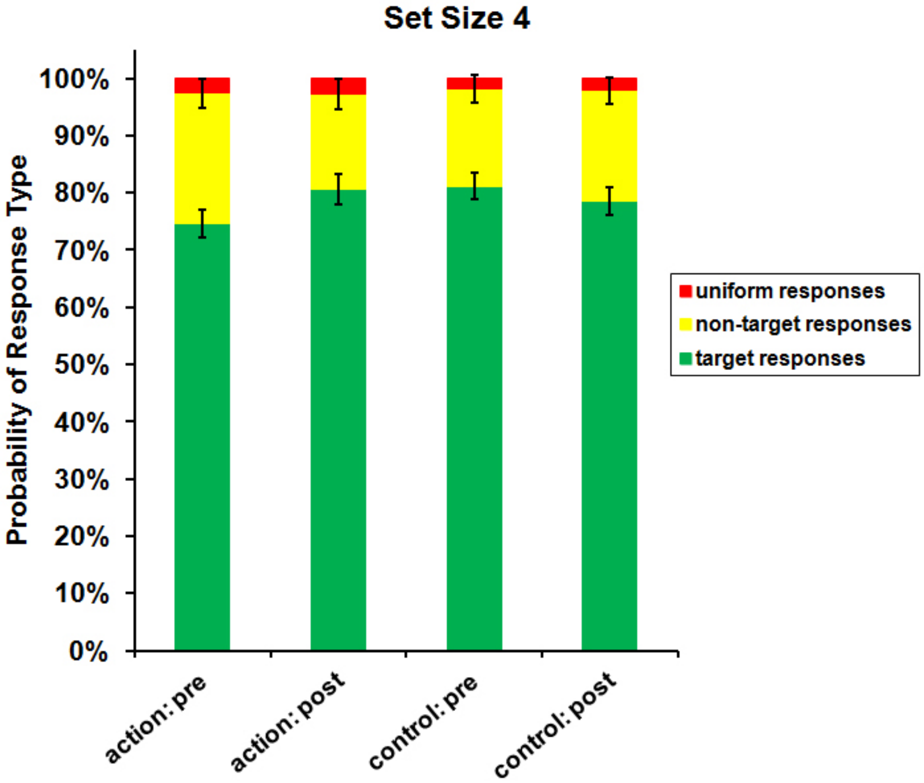
[6] Set size 1 does not contain non-target response probabilities due to only one, target item being presented.

Finally, a 3 (set size: 1, 4, 6) x 2 (time: pre-, post-training) x 2 (group: action, control) repeated-measures ANOVA was tested on uniform response probabilities. A significant main effect of set size emerged, $F(2,21)=11.27$, $p<.001$, with a greater proportion of random responses at lower set sizes. No other main effects or interactions approached significance, $p \geq .15$, which demonstrates that the two groups did not differ in their instances of random guessing before or after training.

These results tentatively suggest that there was a significant training effect for the action group on the color wheel task; tentative because the interactions at times involved numerically decreased performance in the control group post-training, and post-training performance in the action group that was comparable to that exhibited by the pre-training control group. Still, the patterns are intriguing in that the significant findings seem to emerge only at set size 4 both for precision and the mixture model results. Set size 4 is particularly important here because it is the closest approximation of the capacity estimates seen for both groups. The action group showed a significant gain in capacity after training (as measured by the change detection task). Thus, at set size 4 the action group was more likely to have the target color in memory as compared to the control group, likely due to their increased capacity after training (Figure 11). In addition, the action group showed a simultaneous decrease in non-target responses after training suggesting they were less likely to mistakenly report the incorrect color feature from a non-target item. Further implications of these results will be elaborated on in the discussion section below.

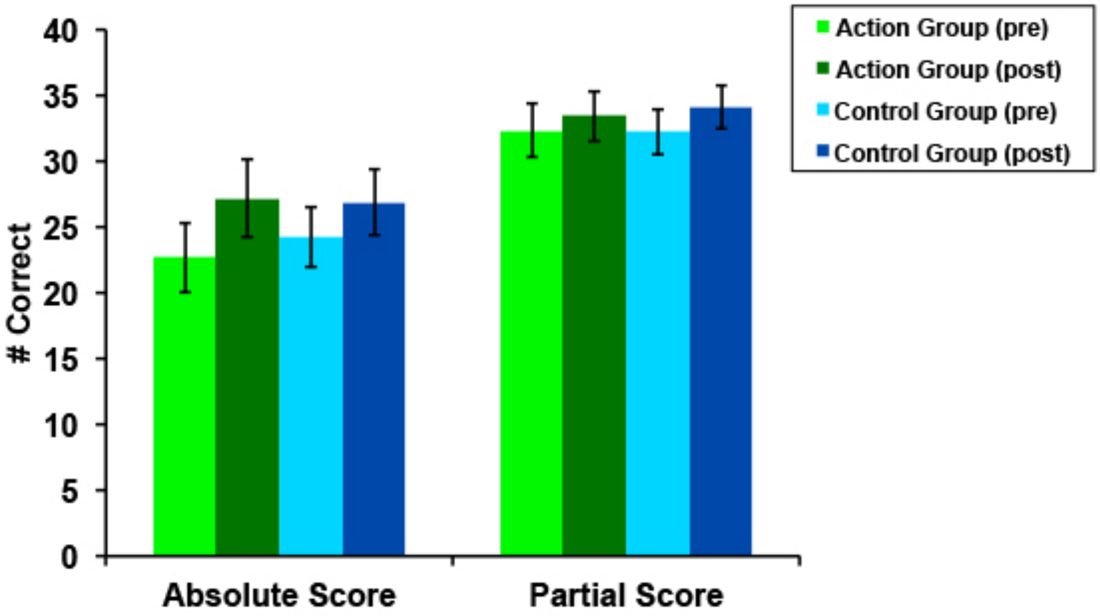
Figure 11. Probabilistic Mixture Model Results: Set Size 4. Probability of each response type for set size 4 for each group and assessment point separately. Error bars represent standard error of the mean.



Symmetry Span

Analysis for the symmetry span task targeted differences in training gains in VWM capacity for the action and control groups. Participants who scored below 80% accuracy on the processing task (i.e., symmetry judgment) were excluded from any analyses (n=4). To examine potential training differences between the two groups, 2 (group: action, control) x 2 (time: pre-, post-training) repeated-measures ANOVAs were conducted on Absolute and Partial Scores separately. For Absolute Score, a significant main effect of time emerged, *F*(1,26)=4.61, *p*<.05, with performance being greater post-training. Neither the main effect of group, *F*(1,26)=.04, *p*=.85, nor the time x group interaction, *F*(1,26)=.29, *p*=.59, approached significance. For Partial Score, the main effects of time, *F*(1,26)=2.32, *p*=.14, and group, *F*(1,26)=.01, *p*=.90, did not reach significance, nor did the time x group interaction, *F*(1,26)=.17, *p*=.69. As can be seen in Figure 12, training does not appear to have differentially improved VWM performance in the complex span task.

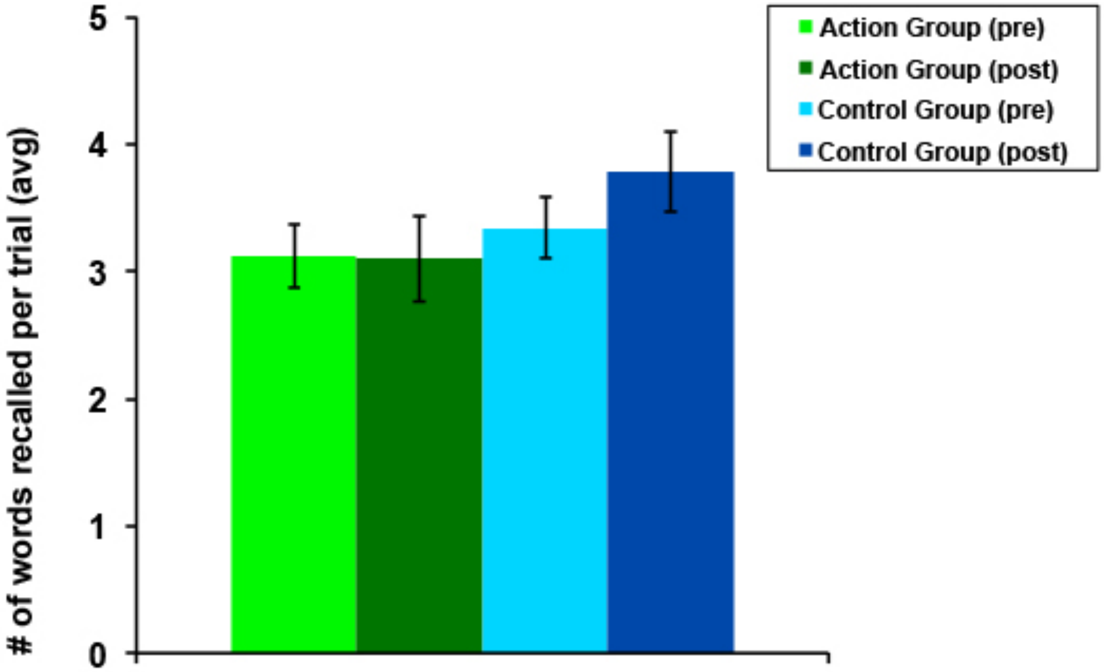
Figure 12. Symmetry Span Data. Absolute and Partial scores shown separately. Error bars represent standard error of the mean.



Immediate Free Recall

A 2 (time: pre-, post-training) x 2 (group: action, control) repeated-measures ANOVA was tested on average number of words recalled. The main effect of time approached significance, *F*(1,30)=3.41, *p*=.07, with performance being slightly greater at post-test. As expected, neither the main effect of group, *F*(1,30)=1.18, *p*=.29, nor the time x group interaction, *F*(1,30)=1.27, *p*=.27, reached significance. These results shown in Figure 13 demonstrate that there were no training-specific increases to verbal memory recall.

Figure 13. Free Recall Data. Results from the immediate recall task. Error bars represent standard error of the mean.



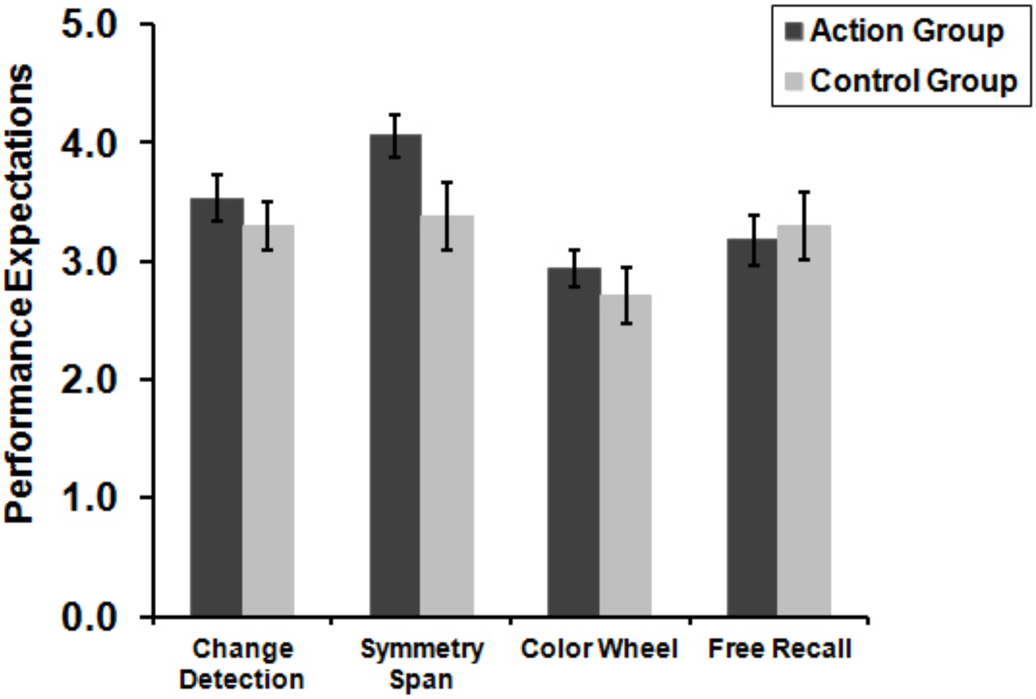
Exit Survey

To assess previous knowledge of video game research and expectations of performance changes, the exit survey data was assessed for each training group. Of the 34 participants who completed the study, 7 (2 action, 5 control) reported being aware of research about the negative effects of video games prior to enrolling in the study (e.g., violent video games and aggression, physical health decrements). Nine participants (5 action, 4 control) reported being aware of research about the positive effects of video games prior to enrolling in the study (e.g., enhanced motor skills in surgeons, faster reaction times, better spatial awareness).

In line with the motivation and engagement results, there seemed to be no significant difference in the degree to which participants enjoyed playing their respective game. The action group reported a mean enjoyment of 4.29 (*SD*=.99), which is similar to the control groups mean enjoyment score of 3.82 (*SD*=1.42), *t*(32)=1.12, *p*=.27.

Most importantly, participants reported whether they expected an increase or decrease in their task performance after training for each assessment task using a 1-5 likert scale (Figure 14). For change detection, *t*(32)=.83, *p*=.41, color wheel, *t*(32)=.82, *p*=.42, and free recall, *t*(32)=-.33, *p*=.74, there was no significant difference between performance expectations between the two groups. However, on the symmetry span task, there was a marginally significant difference in expectations with the action group expecting a greater improvement after training, *t*(32)=1.98, *p*=.056. These results have two major implications: 1) differential expectations are not sufficient to induce significant performance differences, as evidenced by the fact that the action group expected to do better than the control group on symmetry span, but did not show a significant improvement and 2) differential expectations between the two training groups cannot account for the training improvements in VSTM capacity or precision described above.

Figure 14. Performance Expectations. Participant's self-reported performance gains expectations for each assessment task, rated on a 1-5 likert scale. Error bars represent the standard error of the mean.



CHAPTER 4

DISCUSSION

Visual short-term memory is a ubiquitous process that allows us to maintain a stable representation of the visual world in the service of many visual tasks. Despite the constant utility of VSTM in our everyday lives, there is a severe capacity limitation to this system. Excitingly, the results presented here suggest the potential malleability of VSTM through training. Building on the existing literature on action video games enhancing various aspects of visual attention and perception, the current study examined whether action video game training could enhance VSTM capacity, VSTM precision, and/or VWM capacity. Individuals who trained on an action game demonstrated significant improvement on a measure of VSTM capacity compared to those who trained on a control game. In addition, the action group showed significant improvement on a measure of VSTM precision at a specific, crucial set size. However, the VSTM advantages yielded from action video game training did not extend to VWM capacity, or to a measure of verbal memory. These results suggest that action video games enhance the fundamental process of holding visual information in mind over a brief delay, which has broad implications for research on cognitive training and the basic nature of VSTM.

Using a change detection paradigm, the action group demonstrated a significant training-related gain in VSTM capacity, above and beyond that of the control group. This finding is consistent with previous cross-sectional studies, demonstrating a VSTM advantage for avid AVGPs (Blacker & Curby, under review; Boot, et al., 2008). Although Boot et al. (2008) did not find a training effect for VSTM capacity; the current study used one-third more training, which may account for the significant training-related change detection improvements. The current results are consistent with those recently reported by Oei and Patterson (2013). While Oei and Patterson (2013) did not report a comparison of their action groups' training gains to the other groups in their study, here it is demonstrated that action video game training improved change detection accuracy above and beyond that of the control group. The current results demonstrate the reliability of Oei and Patterson's (2013) results using a more conventional training display monitor (i.e., a 21.5" computer monitor). Further, these results fit with previous cross-sectional and training studies demonstrating enhanced selective attention resulting from experience with action video games (Bavelier, et al., 2012; Chisholm, et al., 2010; Chisholm & Kingstone, 2012). Taken together, these two lines of evidence suggesting that action games enhance VSTM and selective attention further add to the existing literature on the link between VSTM and attention. The current results are consistent with the notion that greater selective attention resulting from action video game experience (Bavelier, et al., 2012) may underlie this VSTM advantage. However, neither the current study nor previous studies, have explicitly tested whether selective attention underlies the VSTM advantage that results from action video game experience and this will be an important future endeavor. Regardless of the underlying mechanism, the current results suggest that this extremely capacity-limited VSTM system is responsive to training. More specifically, the change detection results suggest that the quantity of information stored in VSTM is malleable to some degree, as evidenced by the action group storing more items after training compared to the control group. Further, the results from the color wheel task also support this notion of the action group being able to store more information as a result of training.

Before discussing the color wheel results in detail, there is one potential limitation to these findings that warrants discussion. The positive training effects seen for the action group at set size 4 were captured in the presence of negative effects for the control group (i.e., the control group showed decreased performance after training). There is no theoretically grounded expectation that playing the control game for 30 hours should decrease performance on this task. This lack of test-retest reliability has been acknowledged as a concern in the training literature (Boot, et al., 2011) and limits the conclusions that can be drawn from the current color wheel task data. However, one potential explanation here may be the small sample size used, which was necessitated by a time- and resource-intensive training study. The number of outliers in this task diminished the sample size even further. The small sample size may have resulted in unstable group estimates of precision and response probability, which is supported by moderate to low internal reliability estimates for precision (Cronbach's $\alpha = .57$) and for response probabilities (Cronbach's $\alpha = .36$). With this limitation in mind, these results represent one piece of evidence that should be considered in the context of the existing literature on action video game benefits, but replication using larger sample sizes and additional set size manipulations would be beneficial.

The precision with which items are stored in VSTM may contribute greatly to storage efficiency and overall capacity estimates. The results from the color wheel task have implications for the effect of action video games on both the quality of information stored in VSTM and the quantity, each will be considered in turn. First with regard to the precision or quality of information stored, the action group did demonstrate an advantage, but it was specific to set size 4. Second, the probabilistic mixture model results support the change detection results in suggesting that action video game training enhances the capacity of VSTM, making it more likely that a target was stored in memory. The action group made a greater proportion of target responses after training compared to the control group and likewise was less likely to make non-target response mistakes. This effect was most evident at set size 4, which is particularly crucial when discussing the capacity of VSTM. Both the precision and probabilistic mixture model results are consistent with those previously demonstrated by Sungur and Boduroglu (2012) showing that AVGPs are more precise than NVGPs when tested on a color wheel task using a set size of 3 items. The implications of these set size specific results are best couched in terms of evidence from studies also utilizing the color wheel task.

Zhang and Luck (2008) used a color wheel task to directly test a 'slots + averaging' versus a 'slots + resource' model of VSTM capacity. Zhang and Luck (2008) were able to differentiate between these two models, with evidence supporting the 'slots + averaging' model, due to the use of a condition in which a retro-cue was used. Because no such cue was used in the current study, the results here cannot differentiate between these two models. However, both models tested by Zhang and Luck make similar, specific predictions for precision and target response probability when no retro-cue is presented based on the number of items to-be-remembered and one’s capacity (i.e., number of slots). The predictions of these models are consistent with the set size specific results seen in the current color wheel task after training. Again, both a ‘slots + averaging’ model and a ‘slots + resource’ model make similar predictions for the task used in the current study, but for simplicity the results are only discussed in the context of the ‘slots + averaging’ model.

For example, at set size 1, the 'slots + averaging' model predicts that an individual stores the one object in multiple slots and then averages across those slots when recalling the feature color, which yields high precision. As set size increases, but remains below capacity, precision decreases, but the probability of a target response declines very slowly as set size increases until capacity is reached. Once capacity is surpassed, the probability of having the target in memory sharply declines, but precision is constrained based on whether the target is in memory or not because each slot is a fixed-resolution resource (Zhang & Luck, 2008, 2011). Here, the change detection results demonstrate an increase in capacity after training for the action group. Greater capacity would not change the precision or response probability at set size 1 significantly because all participants would be averaging across all slots, regardless of their number of slots. However, as evidenced by the change detection results, the control groups’ capacity hovered around 4 items before and after training whereas the action group was approximately at 4 items before training and above 4 items after training. Therefore, set size 4 is crucial because after training the action group was above this capacity, on average, while the control group was on average at capacity. These differences in training gains likely explain why the action group showed a significant increase in precision and target responses after training compared to the control group. Finally, set size 6 was well above the capacity estimate for all participants and therefore no significant group differences could emerge because the advantage of having slightly larger capacity was not enough to produce a robust advantage at this supra-capacity set size for the action group.

The current results did not support the notion that the VSTM advantage evidenced from action video game training also extends to a measure of VWM capacity. Although participants appeared to improve on the complex span task from pre- to post-training, there was no evidence of a training-specific effect. Both groups improved to about the same degree, which suggests this effect may have been due to practice effects with the task itself. Although VSTM and VWM are related processes, they involve at least one important distinction: VWM, as measured by a complex span task, requires the individual to not only store memory items and later recall them, but also to direct attention away from those memory items and perform a subsequent processing task during the maintenance period. Although action video game experience appears to enhance the capacity of VSTM, it does not seem to extend to VWM. There may be several reasons why this is the case, but two are specifically discussed here. First, it may simply be the case that 30 hours of video game training is not sufficient to bring about significant changes in VWM capacity. Working memory is often conceptualized as a domain-general process that underlies many other cognitive abilities. Thus, changing the capacity of this crucial mental workspace may require more extensive training and/or more targeted training focused on working memory capacity (for a review, see Morrison & Chein, 2011). Secondly, action video games require constant use of VSTM and visual attention, but it is less clear to what extent working memory abilities, like those tested in a complex span task, are utilized in action games. For example, action games are so fast-paced that there is rarely a need or an opportunity to store a piece of visual information and then manipulate it or direct attention away before utilizing the stored information. More commonly, visual information is stored and quickly needed again before any other events or stimuli intervene. Therefore, it may be that action games do not use VWM to the extent that VSTM is used and therefore no training effects can be illustrated. Perhaps other genres of video games or other types of training, which place higher demands on storing and subsequently manipulating visual information, would yield more productive training effects.

The current results suggest that 30 hours of action video game training is sufficient to improve VSTM capacity in a statistically meaningful way. Recently, concerns have been raised about the utility and validity of video game training studies (Boot, et al., 2011). Specifically, Boot and colleagues (2011) state two important methodological concerns with previous training studies: inadequate baseline for transfer effects and differential placebo effects. The results here for all assessment tasks demonstrated some degree of test-retest reliability (with the exception of the color wheel task, discussed above), as evidenced by significant or marginally significant main effects of time for all assessment measures with performance being greater at post-test compared to pre-test. Boot and colleagues (2011) argue that many training studies that show video game training improvements do so in the context of no test-retest effects for the control group. Here, the control group showed some general level of improvement at post-test on the change detection, symmetry span, and free recall tasks. Secondly, upon the suggestion of Boot and colleagues (2011), the current study employed an exit survey in which participants rated their expectations for improvement on each assessment task based on their training experience. These results showed no differences in expectations between the two groups, except for with regard to the symmetry span task, which did not show a training-specific improvement. This pattern of results suggests that the participants were unable to predict the outcome or expectations of the study in any meaningful way. The symmetry span results demonstrate that expectations alone are not enough to induce a training-specific effect as evidenced by the action group expecting to improve more than the control group, yet failing to do so. Moreover, there were no differences between the two groups either on their self-reported enjoyment of the game they trained on, or on their self-reported motivation and engagement levels during training or during assessments.

Thus, the training-related improvement in the action group seen for VSTM capacity cannot be attributed to inadequate baseline measures or differences in motivation, engagement, or performance expectations.

Both the current change detection and color wheel results appear to be explained via an increased VSTM capacity for the action group after training. This finding does not preclude the evidence that individual differences exist in both the quantity and quality of information stored in VSTM because many studies, including this one, demonstrate considerable variability in VSTM precision even at the most basic set size of 1 object. While the action group did show an increase in precision at set size 4, this finding is likely best accounted for by an increase in capacity. Evidence that slots are fixed-resolution resources (Zhang & Luck, 2008, 2011) suggests that the action groups' superior performance at set size 4 was driven by their increased capacity. If a general increase in precision had occurred, then it would be expected that the action group would have demonstrated a training advantage at all set sizes, which was not the case. Therefore, the results here suggest that the advantage the action group demonstrated is more likely accounted for by their increased capacity, and not in a fundamentally improved ability to represent an item(s) in VSTM. These findings add a crucial piece of evidence to the debate about what constrains VSTM by demonstrating the malleability of this capacity-limited system. An important future direction will be for these competing models to not only account for the limiting factors impinging on VSTM capacity, but to account for changes in capacity as a result of training.

In addition to these theoretical implications for the current VSTM training results, there are a number of broader implications for the remediation of VSTM deficits.

Based on the findings, action video game training may represent a unique and engaging platform in which to train one's capacity-limited VSTM system. Training in this manner may be especially applicable for individuals who have known VSTM deficits. For example, deficits in VSTM are often seen in individuals after traumatic brain injury (e.g., Malojcic, Mubrin, Coric, Susnic, & Spilich, 2008), individuals with developmental coordination disorder (e.g., Alloway & Archibald, 2008), individuals with attention-deficit hyperactivity disorder (e.g., Alloway, et al., 2010; Westerberg, Hirvikoski, Forssberg, & Klingberg, 2004), and individuals who have suffered a stroke (e.g., Westerberg et al., 2007). One practical caveat to the use of action video games as a training method is the violent nature of action games. First-person shooter action games have been specifically shown to produce these visual cognitive enhancements, above and beyond that of other genres of games (Cohen, Green, & Bavelier, 2007; also, see Oei & Patterson, 2013). Therefore, an important next step in this research will be to better understand the mechanisms driving these training-related improvements to one's visual skills. By parsing out what drives these enhancements, training could become tailored to specific visual skills (e.g., VSTM, contrast sensitivity, temporal resolution of attention) or to specific populations (e.g., non-violent games for children with visual cognitive deficits).

Action video games provide the player with a complex and constantly changing visual environment in which accurate visual memory and acute attentional skills often determine the player's success or failure in the game. Exposure to these visual environments over an extensive period of time appears to cause enhanced VSTM capacity. Therefore, action video game training represents a distinctive form of training that may allow individuals to exploit the malleability of this inherently capacity-limited VSTM system.

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