The Effects of Action Video Game Experience on Perceptual Decision Making

by

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The author was born in Biloxi, Mississippi on July 19, 1980. His family moved near Rochester, NY in 1989 and he later attended LeRoy High School in LeRoy, NY. He attended Genesee Community College in Batavia, NY concurrent with his final two years of high school and received his A.S. degree in Math and Science in May 1998, just prior to receiving his high school degree in June 1998. He attended the University of Rochester from 1999 until 2001 and graduated with a B.A. degree in Brain and Cognitive Sciences in June 2001. After spending two years as a full-time research assistant at the University of Rochester, he began graduate studies in the Department of Brain and Cognitive Sciences in the fall of 2003. He received an M.A. degree in Brain and Cognitive Sciences in 2006.
Abstract

Action video game players (VGPs) have been shown to outperform their non-game playing (NVGPs) peers on a number of sensory/cognitive measures. In tasks that require accurate responses to quickly presented visual stimuli, VGPs typically exhibit higher levels of accuracy than NVGPs. In particular, VGPs have demonstrated enhancements in a number of tasks thought to tap reasonably independent aspects of visual attention (spatial distribution and resolution, temporal characteristics, capacity, etc). In tasks that require speeded responses, the VGP enhancement is observed as a large decrease in reaction time (RT) in VGPs compared to NVGPs (accuracy is typically equivalent in the two groups). Here we put forward the hypothesis that a single mechanistic explanation, an increase in the rate of sensory integration in VGPs, can account for the entirety of the data, thus bridging the gap between the accuracy and RT literatures. To test this hypothesis, two sensory integration tasks were employed - a standard motion coherence paradigm and a novel auditory localization task which, in combination with a model developed by Palmer et al (2005), allow for a more explicit test of the relative contribution of sensory integration rate, criteria, and motor execution in generating the differences observed between VGPs and NVGPs. In both the motion and auditory tasks, VGPs demonstrated a large reduction in RT compared to NVGPs with equivalent accuracy. This pattern was well captured by the model with an increase in the rate of information accrual and a concurrent decrease in criteria in the VGPs. Several follow-up experiments provide further support for the hypothesis that VGPs acquire sensory information more rapidly than
NVGPs. Importantly, similar effects can be induced in NVGPs through extensive action video game training. Finally, to examine how these changes may be implemented at the neural level, a model by Ma and colleagues (2007) was utilized, with the primary difference between VGPs and NVGPs being an increase in the strength of feed-forward projections between sensory and integration areas in the VGP group.
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CHAPTER 1: Introduction*

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The Atari video game platform was released in the late 1970s. Nintendo was born in the early 1980s. Since then, the percentage of Americans who play video games has grown at an astronomical pace; in fact it has been estimated that 90% of school-aged individuals currently play video games. However, despite the common view of video games being “for kids,” the average age of a video game player is presently 33 years old with 70% of the heads of households playing video games (Entertainment Software Association, 2007). This explosion has been spurred on by advancements in both hardware technology and software development that allow a more intense and realistic gaming experience. In addition to the improvements in graphical capability, advances in online gaming now allow users to play with sometimes hundreds of others, a fact that is slowly changing the perception of video game play from a solitary to a social activity. Unsurprisingly, both popular and scientific interest in the potential consequences of game play has been driven by this dramatic surge in video game use. While the majority of research (and media attention) has focused on the potential for video game play to negatively affect temperament and social behavior, or on the potential to harness video games to help
children learn, a subset of cognitive scientists have investigated the more fundamental question of how video games may alter the way in which people see the world.

In most of the biological sciences, the question of “nature versus nurture” is often debated. Researchers constantly strive to determine whether a certain skill arises from nature (is genetically based), nurture (is completely determined by experience), or as is usually the case, if the skill reflects a combination of nature and nurture. In cognitive science the relationship is often quite complex, with the relative roles of nature and nurture interacting through development with one playing a larger role in some developmental stages and vice versa. For example, humans require “normal” visual experience in infancy and throughout childhood to enjoy normal vision in adulthood. When infants are deprived of normal experience (by cataracts for instance), massive and reasonably permanent deficits may result (Birch & Stager, 1996; Lewis & Maurer, 2005). However, the same cataracts experienced later in life may lead to no enduring deficits once removed. Thus, the effect of experience in this case is greatest in younger humans and grows progressively weaker through adulthood.

While there are myriad similar cases in which “less than normal” experience leads to deficits in perception and cognition, researchers that investigate the effects of video game play on perception and cognition ask a slightly different question – what is the effect of “more than normal” experience? To what extent are our perceptual systems constrained by genetics? One could argue that evolution is notoriously cost-effective and thus there is little impetus for our visual system to possess capabilities beyond
those needed in our typical environment. On the other hand, in order for a species to be successful over an extended time span, members must be capable of adapting to changes in their environment. One might further note that the skills needed in today’s civilized world are likely far different than those that were required to survive as the human species evolved, and thus we may retain some additional capacity that unless tapped, simply goes unused. A particular subset of video games, which we dub action video games, offers an interesting “natural experiment” into the effect of “more than normal” experience. We define action video games as those games that have many quickly moving objects, that require effective peripheral processing as items in the periphery must constantly be localized and identified, and where the number of independent items that need to be kept track of far exceeds the circumstances experienced in normal life. In short, an action video game is one that places extraordinary demands on the visual and visuo-motor systems. Games from a variety of genres are included as action games, but most typically include first-person shooters (FPS), third-person shooters (TPS) and some car racing games. Many young adults are immersed in these environments for more than 20 hours per week. The question is therefore not whether humans can learn to adapt to these environments (the very fact that these individuals spend such exorbitant amounts of time playing the games suggests that they can), but instead the question is how does the system change to handle these demands? What systems or processing stages are affected and how do these changes manifest themselves?
1.1. Observed differences between VGPs and NVGPs

The literature on the effects of video game experience on perceptual, perceptuo-motor, and cognitive skills can be roughly divided into two complementary branches. The first branch is comprised of tasks wherein accuracy is the primary dependent measure. These tasks generally require subjects to make perceptual judgments about quickly flashed stimulus displays. Subjects are instructed to be as accurate as possible, and reaction time is typically not measured. In these paradigms, enhancement in the video game player (VGP) population is manifested as an increase in accuracy as compared to non-video game players (NVGPs). The second branch of the literature consists of tasks wherein reaction time is the primary dependent measure. Although accuracy is also recorded in these tasks, it is typically near ceiling, thus making reaction time the only truly informative measure. In these paradigms enhancement in the VGP population is manifested as a decrease in reaction time as compared to NVGPs.

1.1.1. Increased accuracy observed in VGPs

VGPs have demonstrated superior accuracy in a number of tasks designed to tap reasonably distinct aspects of visual attention including the spatial distribution of attention, the spatial resolution of attention, the temporal characteristics of visual attention, and the capacity of visual attention. The following four published papers explain the tasks and the aspects of visual attention they are thought to evaluate in detail.
1.1.1.1. The spatial distribution of visual attention


- Version below is the final draft version and thus may differ from the final published version in terms of formatting, precise wording, etc.

**Effect of action video games on the spatial distribution of visuo-spatial attention**

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Abstract

This paper investigates the effect of action gaming on the spatial distribution of attention. The flanker compatibility effect was used to separately assess center and peripheral attentional resources in gamers versus non-gamers. Gamers exhibited an enhancement in attentional resources compared to non-gamers not only in the periphery, but also in central vision. A target localization task was then used to unambiguously establish that gaming enhances the spatial distribution of visual attention over a wide field of view. Gamers were more accurate than non-gamers at all eccentricities tested and the advantage held even when a concurrent center task was added, ruling out a trade-off between central and peripheral attention. By establishing the causal role of gaming through training studies, this work demonstrates that action gaming enhances visuo-spatial attention throughout the visual field.
1. Introduction

Visual acuity, or the ability to discriminate small changes in shape in central vision, is a key determinant of vision. Ask someone how good their vision is, and they will typically comment on their ability to read a sign, to recognize faces from afar, or to score 20/20 on an optometrist’s eye chart. However, many of the visual tasks we complete on a day-to-day basis often bear little relation to our ability to read the bottom line on an eye chart. For instance, driving does not require perfect acuity (many states in the USA require that vision be only 20/40 to receive a driver’s license). Instead, the most common visual demands present while driving involve focusing attention on relevant stimuli such as pedestrians, animals, and other cars, while ignoring the many irrelevant distractors that clutter the visual environment. The dichotomy between visual acuity and visual attention has been exemplified by many studies (Ball, Beard, Roenker, Miller, & Griggs, 1988; Ball & Owsley, 1991; Ball, Owsley, & Beard, 1990; Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Intriligator & Cavanagh, 2001; Owsley & Ball, 1993; Owsley, Ball, & Keeton, 1995; Sekuler & Ball, 1986), with the general finding being that simple tests of visual acuity and perimetry are poor predictors of performance on tasks that demand effective visuo-spatial attention.

A number of paradigms have been developed with the goal of quantitatively measuring visual selective attention (Carrasco & Yeshurun, 1998; Eckstein, Pham, & Shimozaki, 2004; Eriksen & Eriksen, 1974; Lavie & Cox, 1997; Treisman & Gelade,
In many of these paradigms, targets are presented simultaneously with distracting objects and the influence of the distracting information on target processing is measured. Groups thought to have diminished attentional abilities such as the elderly (Ball et al., 1988; Madden & Langley, 2003; Maylor & Lavie, 1998; Plude & Hoyer, 1986; Scialfa, Esau, & Joffe, 1998) or young children (Akhtar & Enns, 1989; Enns & Cameron, 1987; Enns & Gurgus, 1985; Plude, Enns, & Brodeur, 1994; Rueda et al., 2004) typically demonstrate larger effects of distracting information on attentional tasks than normal adult controls, indicating an effect of age on the determinants of visual selective attention. Similarly, a host of data indicates that the control of visual selective attention decreases in most pathological populations, including frontal patients (Husain & Kennard, 1997), Alzheimer’s patients (Levinoff, Li, Murtha, & Chertkow, 2004; Tales, Haworth, Nelson, Snowden, & Wilcock, 2005; Tales, Muir, Jones, Bayer, & Snowden, 2004), children with ADHD (Shalev & Tsal, 2003) and neglect patients (Russell, Malhotra, & Husain, 2004; Sprenger, Kompf, & Heide, 2002; Vivas, G.W., & Fuentes, 2003). While most of the studies describing changes in visual selective attention document a decrease in performance as compared to normal healthy young adults, of interest to us was the possibility that this type of selective attention may be enhanced (rather than reduced) from the level typically observed in young adults.

Several researchers have noted enhancements in various aspects of visual attention as a result of video game play (Castel, Pratt, & Drummond, 2005; Gopher, 1992; Gopher, Weil, & Bareket, 1994; Green & Bavelier, 2003; Greenfield, DeWinstanley,
Kilpatrick, & Kaye, 1994; Trick, Jaspers-Fayer, & Sethi, 2005). Many of today’s action video games are remarkably visually challenging. They regularly have rather unnaturally stringent attentional requirements, much more so than any everyday situation to which one may be exposed. For instance, in many video games, multiple items must often be processed simultaneously, a task that would be benefited by additional attentional resources across space. Additionally, many games also require the efficient rejection of irrelevant objects, a process that would be benefited by a more proficient selection process. The penalty for either failing to process a target or allowing non-essential information to interfere with the processing of potential targets is often great in video games; therefore, those who play should be especially motivated to develop both capabilities. It is the goal of this paper to assess whether action video game experience enhances visuo-spatial attention and its allocation over space. Our previous work led to the hypothesis that action video game play results in an increase in the amount of available attentional resources as well as an increase in the selectivity of spatial processing (Green & Bavelier, 2003). It has remained unclear however whether the improvements noted were specific to the visual periphery, possibly occurring at the cost of central vision. The present study reports on two types of paradigms that test the distribution of attention over space and that contrast central and peripheral processing. The first, the perceptual load paradigm of Lavie and colleagues (Lavie, 1995; Lavie & Cox, 1997), offers a measure of the attentional resources available to both video game players (VGPs) and non-gamers (NVGPs), and was adapted to compare central and peripheral resources across
populations. The second, the Useful Field of View (UFOV) paradigm developed by Ball and colleagues (Ball et al., 1988; Ball & Owsley, 1992), allows for a measure of the distribution and selectivity of visual attention across a wide field of view, while controlling for different levels of central load. Portions of Experiments 1 and 2 were presented in Green and Bavelier (2003).

2. Experiment 1 – the perceptual load paradigm

In order to gain a general understanding of the amount of attentional resources available to distribute across space in gamers and non-gamers, the perceptual load paradigm was employed (Lavie & Cox, 1997; Proksch & Bavelier, 2002). In this paradigm, the effect of task irrelevant distractors on primary task performance is measured and used as an index of the degree to which these irrelevant distractors are processed. By contrasting central and peripheral distractors, this paradigm allows us to compare attentional resources across space in VGPs and NVGPs.

The effect of the distractors is measured using the compatibility effect, wherein the presence of distractors that lead to the same response as the target (response compatible) results in faster reaction times than distractors that lead to a different response as the target (response incompatible) (Eriksen & Eriksen, 1974). Work by Lavie and colleagues (Lavie, 1995; Lavie & Cox, 1997; Lavie, Hirst, Viding, & de Fockert, 2004) has shown that the effect of extraneous distractors on reaction time is largely a function of the perceptual load of the target task display.
(perceptual load in this case roughly corresponds to the number of items in the visual search array). When the perceptual load is low (for instance, the visual search array contains only the target), the effect of an extraneous distractor on performance is great. However, when the perceptual load is high (the visual search array contains the target as well as several additional items), the effect of an extraneous distractor on performance is minimal.

This finding is incorporated in the load theory of selective attention and cognitive control (Lavie, 2005; Lavie et al., 2004). Relatively easy perceptual tasks do not require “all” of one’s attentional resources to reach adequate behavioral performance. In this case, the resources left over from the task are not simply turned off, but are instead distributed to adjacent locations/items leading to a sizable compatibility effect. Conversely, challenging perceptual tasks demand a larger percentage of the available attentional resources, thereby leaving little to spread to non-task locations/items and resulting in little or no compatibility effect (Lavie, 1995; Lavie & Cox, 1997). Although the load theory posits that the distribution of attention is automatic, it is not the case that the exact distribution of attention is identical in all humans. Proksch and Bavelier (2002) have demonstrated that hearing individuals do typically allocate more attention to the area around fixation (central vision), but in contrast deaf individuals appear to allocate more attention to the periphery. If action video game play primarily affects peripheral visual attention, then VGPs may also exhibit a proportionally larger compatibility effect for peripheral distractors as noted in deaf individuals. Conversely, if action video game play similarly affects both
central and peripheral vision, then the distribution should be similar to what is observed in normal hearing subjects, that is greater allocation around fixation than peripherally (Beck and Lavie, 2005; Proksch & Bavelier, 2002). In Experiment 1, the compatibility effects induced by peripheral versus central distractors were compared in VGPs and in NVGPs to gain a measure of the amount of available attentional resources as a function of eccentricity in each population.

2.1. Method

2.1.1. Participants

Sixteen males with normal or corrected vision were placed into one of two groups, video or non-video game player, based upon their responses to a questionnaire given prior to the experiment. Because of the relative difficulty in the acquisition of females with sufficient video game experience, only males underwent testing.

The criterion to be considered a video game player (VGP) was a minimum of 3-4 days a week of action video game usage for the previous six months. Eight right-handed males with a mean age of 20.9 years fell into this category. Seven of the eight reported daily video game usage for at least the previous six months, while the eighth reported playing several times a week for the same time span. It is important to note that only action video game players were included in this and all subsequent experiments. Action video games are those that have fast motion, require vigilant
monitoring of the visual periphery, and often require the simultaneous tracking of multiple targets. The following is a representative sample of the games reported as played which qualify as action games based on our criteria: Grand Theft Auto, Half-Life, Counter-Strike, Marvel vs. Capcom, Rogue Speare, and Super Mario Kart.

The criterion to be considered a non-video game player (NVGP) was little, although preferably no, action video game usage in the past six months. Eight males (six right- and two left-handed) with a mean age of 21.6 years fell into this category. Seven members reported no video game experience whatsoever in the past year, while the eighth reported a maximum of five instances of non-action video game play over the same time frame.

All participants were paid for their participation and provided informed consent in accordance with the guidelines set by the University of Rochester.

2.1.2. Stimuli

All stimuli/procedures were identical to Proksch & Bavelier (2002). Stimuli were presented on a 21” Mitsubishi monitor from a standard PC equipped with a Matrox Millennium video card using OpenGL routines. Each participant viewed the display at a test distance of 60 cm in a darkened room.

The stimuli consisted of three categories of items (target, filler, and distractor) presented in light gray on a black background (Figure 1). The target set consisted of a square and a diamond. The filler set was composed of a house-like shape, an
upside-down house shape, a sideways trapezoid, a triangle pointing up, and a triangle pointing down. Both the target and the filler shapes subtended an average of .6° vertically and .4° horizontally, and were always presented inside circular frames.

Throughout the experiment, the six circular frames were presented in the same location, arranged around the central fixation point at a distance of 2.1°. The distance between the centers of adjacent circular frames was also 2.1°. One, and only one, member of the target set (square or diamond) always appeared in one of the six circular frames. Random members of the filler set could occupy zero, one, three, or five of the remaining circular frames. The frames in which target and fillers appeared were randomly selected across trials. For all analyses and for the purposes of subsequent discussion, the two lowest levels of perceptual load (zero fillers or one filler) were grouped into a single “low load” condition, while the two highest levels of perceptual load (three or five fillers) were grouped into a single “high load” condition.

The distractor set consisted of a square, a diamond, and an elongated circle. One member of the distractor set was presented during each trial in one of four locations. The distractor could appear either centrally (.5° to the right or left of fixation – which falls within the ring of circular frames) or peripherally (4.2° to the right or left of fixation – outside the ring of circular frames).

Although 4.2° from fixation is better described as parafoveal rather than peripheral, this location was chosen to ensure that peripheral and central distractors were presented at comparable distances from the target ring. This point is important
if differences in effects between central and peripheral distractors are to be interpreted in terms of eccentricity (central versus peripheral) rather than absolute distance (Miller, 1991). The size of the distractors was corrected for the known cortical magnification factor (Rovamo & Virsu, 1979). Accordingly, central distractors subtended .3° vertically and .2° horizontally, while peripheral distractors subtended .9° vertically and .5° horizontally.

The design was fully intermixed with all combinations of target (square or diamond), perceptual load (0, 1, 3, or 5 fillers), distractor compatibility (compatible, incompatible, or neutral), and distractor eccentricity (central or peripheral) being equally represented and presented in pseudorandom order.
The participants’ task was to determine as quickly and accurately as possible which of two possible target shapes (square or diamond) appeared in one of the six circular frames. Task difficulty was manipulated by the addition of other shapes in the circular frames. Low loads correspond to displays with the target alone or with one other shape in the circular frame, while high loads correspond to displays with three or five shapes in addition to the target. The ‘distractor shape’ is the shape that does not appear in one of the six circular frames. Subjects were explicitly told to ignore the distractor shape which could be either ‘compatible’ (led to the same response as the target) or ‘incompatible’ (led to the opposite response as the target). The distractors shapes could be presented either centrally, that is appearing within the ring of circular frames, or peripherally, appearing outside of the ring.

2.1.3. Procedure

Each trial began with a one second fixation point followed by a 100 ms presentation of the trial shapes. The relative brevity of the presentation time was chosen to preclude eye movements as a potential source of differences.
The task of the participant was to identify which of the two potential target shapes (square or diamond) appeared in one of the six circular frames as quickly and accurately as possible. Subjects were reminded to ignore any stimuli that did not appear in the circular frames (i.e. the distractor). Participants responded to the target by pressing the key labeled with the corresponding target shape. Feedback was given after each trial by a change in the color of the fixation point. Trials were grouped into two halves of 576 trials. Following each block of 48 trials, participants were given a resting screen that informed them of their performance over the previous block (reaction time and percent correct). Subjects were instructed to respond as quickly as possible and to aim for 90% correct.

Before testing began, participants were given two blocks of practice during which time responses were monitored by the investigator to ensure comprehension of the task. Following successful training, the participants were left to complete the first half, followed by a short intermission, and the second half. The entire experiment lasted approximately one and a half hours.

2.2. Results

As in our past studies, all analyses focused on trials with incompatible or compatible distractors (Green & Bavelier, 2003; Proksch & Bavelier, 2002).

2.2.1 – Reaction Time
For the reaction time analysis, incorrect trials were first removed (VGP: 12.1% +/- 1.5, NVGP: 13.0% +/- 1.6) and as well as any trial with reaction times greater than 1800 ms or less than 300 ms (less than 2% of trials in both VGPs and NVGPs). Trials were then separated based upon distractor eccentricity (central, peripheral). For each subject a mean and standard deviation was computed for each of the two eccentricities; any trial in which the reaction time was more than two standard deviations away from the mean was excluded (approximately 2% of trials for both VGPs and NVGPs). This filtered RT data was then analyzed in a 2x2x2x2 omnibus ANOVA with video game experience (VGP/NVGP), perceptual load (low/high), distractor eccentricity (central/peripheral), and distractor compatibility (compatible/incompatible) as factors.

The standard main effects of perceptual load (low load: 629.2 ms +/- 9.5, high load: 712.4 ms +/- 11.2; F(1,14) = 119.4, p < .001), reflecting an increase in task difficulty with increasing perceptual load, and distractor compatibility (compatible distractors: 664.1 ms +/- 11.5, incompatible distractors: 677.5 ms +/- 11.6; F(1,14) = 63.0, p < .001), demonstrating the effect of distractor compatibility on RT, were observed. Also, as has been consistently reported, an interaction between load and compatibility was observed (F(1,14) = 7.0, p = .02) with the RT difference between incompatible and compatible distractors decreasing with increasing perceptual load (Table 1).

Table 1
Table 1: Reaction times and (SE) for each of the conditions of Experiment 1

NVGPs show a clear decrease in the size of the compatibility effect with increasing load for both central and peripheral distractors, while VGPs show a decrease in the size of the compatibility effect with increasing perceptual load only for the peripheral distractors. The opposite effect, an increase in the size of the compatibility effect with increasing perceptual load, is observed in the VGP population for the center distractor condition.

In accord with our previous report (Green & Bavelier, 2003), a video game experience x perceptual load x distractor compatibility interaction (F(1,14) = 7.4, p = .02) was also observed, with NVGPs showing a larger decrement in the size of the compatibility effect with increasing load than the VGPs (Table 1). VGPs instead demonstrate a consistently high compatibility effect across perceptual load conditions. This indicates that the VGPs continued to process the extraneous distractor even at the highest loads, suggesting an increase in available attentional resources. Importantly, this effect did not further interact with eccentricity (F(1,14) = 1.15, p > .3) signifying the effect of video game experience was similar for both central and peripheral distractors (see also Figure 2). Finally, consistent with previous reports demonstrating greater attentional resources in central vision, a
perceptual load x distractor compatibility x distractor eccentricity interaction (F(1,14) = 8.1, p = .01) was observed with the decrease in the size of the compatibility effect with increasing load being more pronounced for peripheral than central distractors. Because differences in baseline RTs between groups may produce interactions with within-subjects measures that reflect only the magnitude of the baseline RT differences, it is important to note that although the mean VGP reaction time was approximately 37 ms faster than the mean NVGP reaction time, the main effect of gaming did not approach significance (VGP: 652.4 ms +/- 13.5, NVGP: 689.2 ms +/- 8.8; F(1,14) = .8, p > .3) indicating relatively comparable overall reaction times in VGPs and NVGPs.

To better assess the spatial distribution of attentional resources in VGPs and NVGPs, the two groups were separated and the size of the compatibility effect (incompatible – compatible RTs) for each group was examined in 2x2 ANOVAs with perceptual load (low/high) and eccentricity (central/peripheral) as factors. In the NVGP group, only a main effect of load was found with compatibility effects being larger for the low load than the high load condition (low: 21.6 ms +/-4.3, high: -0.5 ms +/-4.4; F(1,7) = 28.4, p = .001). As previously reported (Proksch & Bavelier, 2003), the compatibility effect was approximately double for central distractors as compared to peripheral distractors (central: 14.4 ms +/-4.4, peripheral: 7.0 ms +/-5.7); however, in this study the main effect was not statistically significant (F(1,7) = .63, p > .4).
In the VGP group no effect of load was found (low: 15.2 ms +/-4.3, high: 15.5 ms +/-4.7; F(1,7) = .001, p > .9). However, an eccentricity by load interaction was observed (F(1,7) = 8.1, p = .03) with compatibility effects being greater for low load in the periphery and for high load in the center. This indicates that in the VGP population, the allocation of attention shifts from a more peripherally biased distribution under conditions of low load to a more centrally biased distribution under conditions of high load.

2.2.2 – Accuracy

**Figure 2: Experiment 1 – Results**

Size of compatibility effect (RT incompatible – RT compatible) as a function of eccentricity: As in previous work, there is a trend for greater compatibility effects to be present for center distractors. Importantly, VGPs show compatibility effects for both center and peripheral distractors, suggesting that the changes in the VGP population are not specific to the visual periphery.
Error rates were analyzed in a 2x2x2x2 omnibus ANOVA with video game experience (VGP/NVGP), perceptual load (low/high), distractor eccentricity (central/peripheral), and distractor compatibility (compatible/incompatible) as factors. This analysis revealed only a main effect of perceptual load (low load: 94.3% +/- 1.0, high load: 80.6% +/- 1.3; F(1,4) = 221.5, p < .001). No other main effects or interactions were significant including the main effect of video game experience (F(1,14) = .09, p > .7). The increase in error rate with higher levels of perceptual load highlights the increase in task difficulty with increasing perceptual load. However, the lack of a main effect of or interactions with video game experience suggests that the task was equally difficult for the VGP and the NVGP populations.

2.3. Discussion

Experiment 1 establishes that VGPs continue to be affected by distracting items at much higher perceptual loads than NVGPs. As previously discussed, the perceptual load at which compatibility effects disappear provides an estimate of the amount of available attentional resources. The higher the perceptual load of the task when this occurs, the greater the attentional resources available. VGPs demonstrate a clear compatibility effect even under conditions of high load, while NVGPs cease to show an effect of the distractors at these loads. This indicates an increase in the attentional resources available in the VGP population.
Other potential alternative explanations for this result are not wholly consistent with the data. One may surmise for instance, that the discrimination task is less perceptually demanding for the VGPs than the NVGPs. It would then follow that the perceptual difficulty of, for instance, a load of four for a NVGP is equivalent to a load of eight for a VGP. However, although the VGPs do show a slight advantage in both percent correct (VGPs approximately 1% more accurate) and in simple reaction time (VGPs 37 ms faster) neither is significant, nor are there video game experience by perceptual load interactions for either dependent variable. Thus, behaviorally one must assume the tasks are similarly difficult for the two groups. Another possible explanation is that non-target objects simply more easily distract VGPs than NVGPs. While it is unintuitive that the “advantage” in attentional resources manifests itself through a greater effect of distractors (which would suggest poorer control of visual selective attention), it should be noted that at a load of one, which elicits the maximum compatibility effect from NVGPs, the VGP compatibility effect is if anything smaller than that of the NVGPs (p = .1). This issue will be addressed more thoroughly in Experiments 2 and 3, but in all, the hypothesis most consistent with the data is that VGPs have an enhancement in attentional resources compared to NVGPs.

Importantly for the question at hand, the spatial distribution of attention found in VGPs was similar to that seen in NVGPs. In accord with the previous literature (Beck & Lavie, 2005; Proksch & Bavelier, 2002), a bias was seen for central vision, with the size of the compatibility effect decreased more sharply with increasing load for peripheral than for central distractors reflecting greater attentional resources in
central than peripheral locations (Figure 2). It is also significant that the interaction between video game experience, perceptual load, and distractor compatibility did not interact further with distractor eccentricity. This suggests that even as load increased, the VGPs continued to process both central and peripheral distractors to a greater degree than the NVGPs. Thus, enhanced attentional capacities in VGPs are not exclusive to the visual periphery, but instead are present in both central and peripheral vision.

To more conclusively answer the question of whether VGPs can make the most of this attentional enhancement, a different type of paradigm was employed. After all, in the perceptual load task distractors are processed, despite the fact that doing so could be detrimental to the successful completion of the primary task. The question then arises, are VGPs actually better at filtering out irrelevant items, which is really the hallmark of visual selective attention? To answer this question we turned to the Useful Field of View paradigm, which allowed us to measure the effect of distracting information and changes in central task load on peripheral target localization.

3. Experiment 2 – the Useful Field of View paradigm

The Useful Field of View (UFOV) task (Ball et al., 1988; Ball & Owsley, 1992; Goode et al., 1998; Mazer, Sofer, Korner-Bitensky, & Gelinas, 2001; Myers, Ball, Kalina, Roth, & Goode, 2000; Sekuler, Bennett, & Mamelak, 2000) measures the
ability to locate a target as a function of the eccentricity of the target, the amount of distracting elements in the display, and the presence of an added center task.

Performance on the UFOV is poorly correlated with so-called “perceptual” visual attributes (contrast sensitivity, acuity, perimetry, etc) and is instead thought to provide an index of the distribution of visual attention across the visual scene (Ball et al., 1990; Owsley et al., 1995). Previous results indicate that the ability to localize a peripheral target decreases with eccentricity, with distraction and as a center task is made more difficult (Ball et al., 1988).

Three different target eccentricities (10°, 20°, and 30°) were used allowing the distribution of visual attention to be mapped as a function of eccentricity. Because the peripheral stimulus in Experiment 1 was within the range of normal video game playing, we were unable to assess the generality of the learning across space. In the UFOV paradigm, we can test the effect of action video game experience within, at the border of, and beyond, the eccentricity games are typically played at (our players generally reported a viewing angle of 7.5-10° from the center of the screen). If the effect of action video game play is specific for trained parts of the visual field, there should be little to no effect of experience at 30°, whereas if action video game play alters processing throughout the visual field, differences should be observed at all three eccentricities.

To better understand the effect of video game playing on the allocation of attention over the visual field, the paradigm we used included one condition without a center task and one with a center task. By contrasting performance with or without a
concurrent center task, the UFOV allowed us to test whether enhanced peripheral localization performance in VGPs may be occurring at the cost of central performance. If VGPs indeed have greater attentional resources both centrally and peripherally as suggested in Experiment 1, the detrimental effect of the center task on peripheral localization should be lesser in the VGPs than NVGPs (while maintaining equal accuracy on the central task). Alternatively, if enhanced peripheral performance in the VGPs is at the cost of central attention, we may observe a larger tradeoff between central and peripheral tasks in VGPs than NVGPs.

Finally, the paradigm we used included displays with and without distractors. Participants were first asked to perform the task without distractors and then with distractors. Performance in the distractor condition is thought to reflect the same processes as in typical visual search; however, because block order was fixed, this design does not allow us to address the issue of whether there is a discriminative effect of distractor load. Thus, our paradigm is not suited to address the role of gaming on the rate of visual search.

3.1. Method

3.1.1. Participants

16 right-handed males with normal or corrected vision, none of whom had participated in Experiment 1, were again classified as either VGPs or NVGPs according to the same requirements as those used in Experiment 1. Eight males were
classified as VGPs (mean age 19.5, all right handed). The remaining 8 participants fell into the NVGP category (mean age 20.1, 7 right-handed).

3.1.2. Apparatus

The apparatus consisted of a MacIntosh G3 computer running a program to present stimuli and collect the data using the Matlab computer language (The Math Works Inc., Natick, MA) and the Psychophysical Toolbox routines (Brainard, 1997; Pelli, 1997) (http://psychtoolbox.org). The stimuli were displayed on a 24” Sony GDM-FW900 driven at 160Hz, 800x600 resolution by a MP 850 video card (Village Tronic Computer, Sarstedt, Germany).

3.1.3. Stimuli/Procedure:

Each observer viewed the display binocularly with his head positioned in a chin rest at a test distance of 22 cm. Each trial consisted of four successive displays presented on a large monitor. The displays were similar to those used by Ball et al. (Ball et al., 1988), but stimulus size and presentation time were both decreased to account for the increased ability of comparatively younger subjects.

The initial display consisted of a square outline (4° x 4°) that directed fixation to the center of the screen. One second later the target stimulus, a filled triangle within a circle outline (subtending 3° x 3°), appeared along with the central fixation box. The target stimulus could appear randomly at one of twenty-four locations on the
screen. Each location was positioned on one of eight radial spokes and at one of three possible eccentricities - 10°, 20°, or 30°. Rapid presentation of the stimulus ensured that no purposeful change in fixation could be completed during the presentation. Localization difficulty was roughly equated at all eccentricities by manipulating the exact stimulus presentation duration to allow a fair comparison of the effects of gaming across eccentricities. Based on the results from a few pilot VGPs (none of whom took part in the subsequent experiments), the duration of the stimulus presentation was chosen to lead to about 80% correct performance in VGPs at all three eccentricities tested. To achieve this goal, a shorter display presentation was used at 10° (6.7 ms) than for 20° and 30° (13.4 ms). By preventing ceiling effects in the VGP group, this manipulation enabled us to assess the true size of the group effects at each eccentricity. After the test stimulus, a mask screen appeared for 750 ms. The mask screen, designed to eliminate afterimages as a possible source of information, consisted of randomly spaced vertical and horizontal lines of variable thickness and luminance, circles and squares of random sizes, and thick lines (luminance equal to that of the stimulus) that completely covered each possible stimulus location. The location, size, and contrast of the mask items was randomized every trial to avoid the creation of potentially confounding consistent local elements. Finally, a response screen consisting of a radial pattern (eight evenly spaced spokes - four cardinal directions as well as four diagonals) appeared to direct the response. Each spoke was labeled in a one to one stimulus-response mapping with the keyboard
number pad (i.e. the number 8 spoke was straight up from center, the number 4 spoke was straight left) to best facilitate subject response.

Subjects were allowed to respond at any time after the presentation of the stimulus by pressing the number on the keyboard number pad corresponding to the radial spoke they believed the stimulus had appeared on. Pilot data from Ball et al. (Ball et al., 1988) indicated that when subjects could accurately determine the radial location of the stimulus, they also knew the target’s eccentricity more than 90% of the time. Therefore, subjects were not required to indicate the eccentricity of the target. While most subjects responded during the mask presentation time, if the subject had not yet responded, the spoke pattern remained visible until the subject made a selection. Subjects were made aware that accuracy rather than speed of response was critical and no penalty was assessed for slow responses. After subject response, feedback was given and the subject pressed the middle key on the number pad (the number 5, which was not associated with a spoke) to initiate a new trial.

Two main levels of distraction were tested. Under the no distractor condition (0-distractor block), the stimulus appeared alone on the screen. In the distractors present condition, two sub-levels of distraction were tested. In one (23-distractor block), distractors were present in the twenty-three potential target positions not occupied by the target (on the eight spokes and at all three possible eccentricities). The distractors consisted of open squares of the same luminance as the stimulus and subtending 4° x 4°. In the other (47-distractor block), the distractors occupied all of the same locations as in the half-distraction condition as well as the areas between,
thus filling a 60° diameter circle with distractors. Each subject underwent 120 trials (eight spokes x three eccentricities x five repetitions of each) for each of the three distraction blocks (0, 23 and 47). The blocks were always tested in a fixed order with 0-distractors, followed by 23-distractors, and then 47-distractors. It should be noted again that for the purposes of statistics and discussion, because performance differences have not been observed between the 23- and 47-distractors block either by our own lab or others (Ball et al., 1988), the data from the 23- and 47-distractor block were collapsed into the distractors present group. This resulted in twice as many trials in the distractors present group than the no distractors group. Coupled with the fact that distractor order was not counterbalanced, separate analyses were performed for no distractors and distractors present conditions.

In a different set of blocks, one for each block of distractors (0, 23 and 47), subjects performed the same peripheral localization task, but also performed a center shape discrimination task as well. The central stimulus was either an isosceles triangle or a diamond. In these blocks, subjects were asked to determine which of the two shapes (triangle or diamond) was presented centrally (within the center fixation box) by pressing the correspondingly labeled key on the keyboard. Subjects then indicated the spoke upon which the peripheral target fell on the keypad (in the same manner as previously described).

The experiment therefore consisted of 6 blocks, 0, 23-, 47- distractor blocks each with and without a simultaneous central task. The level of center task was counter-balanced as to which was given first, but again, the distractor conditions were
always run in the order: 0 distractor first, followed by 23-distractors, and then 47-distractors.

To summarize, four main factors were manipulated: the amount of video game experience of each subject (2 levels – VGP/NVGP), the eccentricity of the target (3 levels - 10°, 20°, 30°), the amount of distraction (2 levels – no distractors, distractors present), and the center task (2 levels – no center task, center task present).

3.2. Results

Because the design of the experiment did not counterbalance between distractor blocks (and thus distractor condition is confounded with task experience), peripheral localization accuracy was analyzed in two separate 2x3x2 ANOVAs, one for the no distractors condition and one for the distractors present condition with video game experience (VGP/NVGP), eccentricity (10°, 20°, 30°) and center task (no center task/center task present) as factors. The peripheral localization data for the center task present conditions was filtered prior to analysis by removing any trials in which the center shape was incorrectly identified.

It should be noted that because several of the cell means for the NVGPs approached floor (and thus may have deviated from normality), we also performed the same ANOVAs on arcsin transformed data. In no cases did a significant p-value in the untransformed analyses become non-significant using the arcsin transform or
vice versa, and thus for ease of interpretation, only the analyses on untransformed accuracy are presented.

3.2.1. Peripheral Localization Accuracy - No Distractors Condition

First, although we tried to match performance across eccentricities, a main effect of eccentricity ($F(2,28) = 4.7, p < .05$) was still observed. Unlike previous UFOV studies however, where the main effect of eccentricity represented decreasing accuracy with increasing eccentricity, the main effect of eccentricity here represents a failure to equalize the difficulty of each eccentricity by altering the presentation times. By using different presentation times (7 ms for $10^\circ$ and 13 ms for $20^\circ$ and $30^\circ$) we had hoped to achieve relatively stable performance across eccentricities. However, while $10^\circ$ and $30^\circ$ did have similar performance with these timings, performance at $20^\circ$ was slightly better than both. Second, a main effect of center task ($F(1,14) = 5.2, p < .05$) was observed with subjects making more peripheral localization errors when the center task was present. Finally, as predicted by our hypothesis, a main effect of video game experience was observed (VGP: 84.3% +/- 2.5, NVGP: 31.8% +/- 3.6; $F(1,14) = 44.4, p < .001$) (Figure 3A) as the VGP group outperformed the NVGPs by a large margin. No other effects reached significance.

3.2.2. Peripheral Localization Accuracy - Distractors Present Condition

As in the no distractors condition, a main effect of eccentricity ($F(2,28) = 6.5, p < .01$) was observed. The main effect of center task did not reach significance
(F(1,14) = 3.8, p = .07), but was in the same general direction as in the previous analysis. Again, as predicted, a large main effect of video game experience was observed (VGP: 73.6%+/−3.0, NVGP: 30.0%+/−3.1; F(1,14) = 37.5, p < .001, Figure 3B) indicating superior localization performance by the VGPs. Finally, a video game experience x eccentricity x center task interaction (F(2,28) = 4.5, p = .02) was observed and appears to be rooted in the fact that the VGPs performed disproportionately well in the center task condition at 10° of eccentricity (fastest presentation time).

Figure 3: Experiment 2 – Accuracy of target localization as a function of eccentricity for gamers and non-gamers

VGPs localize a peripheral target far more accurately than NVGPs at each eccentricity (X-axis), both without (A) and with (B) distractors present.

3.2.3. Center Identification Task Performance
The previous analyses only included trials in which the center shape identification was correct. However, to conclusively demonstrate that any differences observed in peripheral localization accuracy were not related to allocation of attention to the periphery at the expense of the center task, center shape identification was analyzed in a 2 (video game experience: VGP/NVGP) x 3 (eccentricity: 10°, 20°, 30°) ANOVA collapsed across all distractor conditions.

VGPs exhibited greater accuracy than NVGPs at the center discrimination task itself (VGP: 97.2% +/- .8, NVGP: 90.1% +/- 1.1; F(1,14) = 25.4, p < .001). A main effect of eccentricity (F(2,28) = 15.0, p < .001) highlights the differences in presentation time. When the peripheral stimulus was presented at 10° of eccentricity, the presentation time was one screen refresh fewer than when the peripheral stimulus was at 20° or 30°. Thus, the presentation time of the center stimulus was also decreased by this amount at 10°. VGPs were able to achieve the same level of center identification performance for each eccentricity/presentation time (10°: 98.6% +/- .41; 20°: 97.9% +/- .6; 30°: 95.2% +/- 1.5) whereas NVGPs suffered a cost at the quicker presentation time (10°: 81.1% +/- 2.5; 20°: 95.2% +/- 1.0; 30°: 96.0% +/- .8) resulting in a video game experience x eccentricity interaction (F(2,28) = 6.3, p = .006).

3.2.4. Overall effect of center task on peripheral localization

Because the results of Experiment 1 made the specific prediction that NVGPs would be more strongly affected by the addition of a concurrent center task than VGPs, the two groups were separated and the effect of center task on peripheral
localization accuracy was analyzed collapsed across eccentricities and distractor levels. As predicted, only the NVGP group showed a significant decrease in performance when the center task was added (No Center Task: 33.8%±7.1, Center Task Present: 25.3%±5.8, F(1,7) = 7.0, p = .03) while the VGPs showed no such decrement (No Center Task: 77.9±5.6, Center Task Present: 76.3%±3.6; F(1,7) = .2, p = .65). This pattern of results supports the conclusion that VGPs have more attentional resources available than NVGPs.

3.3. Discussion

VGPs display enhanced target localization abilities under all conditions tested. VGP performance is superior to NVGPs at all eccentricities, with and without the addition of distractors and with or without a concurrent center task. Together, these findings support the results of Experiment 1 and demonstrate an enhancement in spatial attention in VGPs not only at peripheral but also at central locations.

VGPs more accurately localize the target at all three eccentricities (10°, 20°, and 30°), demonstrating that video game experience enhances visual processing across a large portion of the visual field. In particular, the superior performance of VGPs at 30° suggests that the effects of video game play generalize to untrained locations, as this eccentricity is beyond the eccentricity at which most gamers play.

VGPs also show a clear advantage in localization with or without the presence of distracting objects. The superior performance in the no distractors condition indicates an enhancement at localizing abrupt onsets in the visual periphery. The very
brief amount of time the stimulus is displayed (<15 ms) appears sufficient to create a
detectable change in the visual field that is more easily localized by the VGP
population than the NVGP population. While this condition requires the subject to
locate abrupt onsets and so may draw on exogenous attention, it is also possible that
improvement on this condition could be due to more perceptual factors. The
advantage in the distractors present blocks indicates that video game experience
increases the ability to select targets amongst distractors. Therefore, although the
results of Experiment 1 could have been attributed to an increase in distractibility in
VGPs, the findings of Experiment 2 conclusively demonstrate that not only are more
resources available to VGPs, but this enhanced attention can act to increase target
selection. This is consistent with previous reports which have found a positive
relationship between increased attention and enhanced visual selection (Carrasco &
Yeshurun, 1998; Eckstein, Shimozaki, & Abbey, 2002; Palmer, 1994).

Finally, when the center task was added, VGPs continue to substantially
outperform the NVGPs. VGPs perform both tasks easily and in fact, their localization
performance shows no effect of the added center task. Conversely, NVGPs show a
small decrease in task performance with the addition of a center task. The size of the
falloff is consistent with previous work on the UFOV paradigm, namely relatively
modest decreases in peripheral localization performance with the addition of a center
discrimination task in younger observers, with substantially larger effects being seen
in the elderly (Ball et al., 1988).
Importantly, VGPs outperform NVGPs on the center task itself suggesting that no trade-off of attentional distribution is involved (although we note that it could be the case that the central task was simply easier for the VGPs). Essentially, VGPs can perform both tasks with near perfect accuracy; this suggests that the load of these two tasks combined is below their capacity limit for dual-task performance, whereas NVGPs show lessened performance at both tasks, suggesting their capacity limit is substantially lower. This mirrors the predictions given by the results of Experiment 1 in which NVGPs were seen to have fewer attentional resources than VGPs both peripherally and centrally.

While our hypothesis predicts that extensive video game playing leads to these enhanced skills, it could also be the case that VGPs have inherently better visual skills and/or were somehow genetically endowed with greater attentional abilities. To demonstrate a causative role of action video game play in these effects, a group of NVGPs were trained on an action video game in Experiment 3. If the effects are due to action video game experience, similar enhancements in localization performance should be observed following training.

4. Experiment 3 – Training Study

NVGPs were divided into two training groups. Half underwent video game training using an action video game, whereas the others played a game that made heavy demands on visuo-motor coordination but unlike action video games did not require the subject to process multiple objects at once at a fast pace. This control
group was added to check for another possible explanation for the difference between VGPs and NVGPs whereby what is learned during video game play is not necessarily visual in nature, but is instead visuo-motor. Although the use of percent correct, and not reaction time, should minimize the effect of visuo-motor coordination in our measures, it is possible that by alleviating the demands of the motor response, video game playing allows VGPs to have more “left-over” resources available to process the stimulus. If the differences observed in Experiment 2 are due to an attentional enhancement and not due to lightened visuo-motor control or genetically endowed traits, a notable improvement in UFOV performance should be observed following training in the action game trainees, but not in the control game trainees. Unlike Experiments 1 and 2 that only included males, Experiment 3 included half males and half females, allowing us to test the generality of our findings to both sexes.

Based on the results of Experiment 2 as well as pilot training data, several modifications were made to the design of the paradigm. Among these were to remove feedback in order to minimize the amount of task-related learning that occurred during testing. Also, a more difficult center discrimination task was employed to avoid potential ceiling effects, as performance on the center identification task of Experiment 2 was quite high.

4.1. Method

4.1.1. Participants
The study enrolled 32 NVGPs, none of whom had taken part in Experiments 1 or 2, who were equally and randomly divided between the experimental and the control group. The criteria for NVGP remained the same as in all previous experiments. All subjects underwent training as described below. In all 8 females and 8 males (mean age = 21.3, all right-handed) made up the final experimental group, while the final control group consisted of 9 females and 7 males (mean age = 21.0, 15 right handed).

4.1.2. Pre-Test

Subjects underwent a slightly modified version of the previous tasks. First, only four blocks were run - two no center task blocks and two center task present blocks each with a no distractors and a distractors present condition. Second, a fine orientation discrimination task was selected for the center task. The difficulty of the center task was manipulated based on pilot data to lead to around 70% correct performance making it a far more difficult center task than that used in Experiment 2. Third, because the by-eccentricity timing manipulations had failed to yield equal performance across eccentricities in Experiment 2, each eccentricity was tested with a 13 ms stimulus presentation duration. Fourth, a white noise mask was chosen, as participants found the pattern mask used in the previous experiments especially disrupting, and there were concerns that this difficult pattern mask may have been disproportionately disruptive to NVGPs as compared to VGPs. Finally, to minimize the effect of test-retest improvements, no feedback was given. Because no effect of
center task order was found in Experiment 2, and because of the presence of several other tasks unrelated to the task at hand, subjects were always tested on the no center task condition first, then the center task condition (making the run order: no center task/no distractors, no center task/distractors present, center task present/no distractors, center task present/distractors present). Finally, to minimize any test-retest effects each subject underwent only 72 trials (eight spokes x three eccentricities x three repetitions of each) for each condition.

4.1.3. Apparatus

4.1.3.1. Testing

The apparatus was identical to that described in Experiment 2 except the monitor was a ViewSonic P817 21-in monitor (ViewSonic, Walnut, CA).

4.1.3.2. Training:

Both groups played on 20” monitors.

4.1.4. Training Stimuli/Procedure

For both groups, training consisted of playing the pre-determined video game for 30 total hours (maximum of 2 hours per day, minimum of 5 hours per week, maximum of 8 hours per week). The sixteen members of the experimental group played the game Unreal Tournament 2004 (henceforth referred to as the action video
game). This game was chosen to be similar to those played by our VGPs. It has a relatively simple interface, uses first-person point of view and requires effective monitoring of the entire visual field (extent from fixation about 13°-height x 16°-width). Each hour session was divided into three 20 minute blocks. The difficulty of each block was adjusted based upon the kill/death ratio. If in a block the player scored twice as many kills as they had deaths, the difficulty level was increased one level. Players were re-tested on lower difficulty levels on the final two days of training to quantitatively assess improvement.

The sixteen members of the control group played the game Tetris, which was displayed to cover the entire extent of the screen. The FOV of the Tetris game was actually slightly larger than that of the action game - the effective game area extended 18°-height x 13°-width from fixation. This game was selected to control for the effect of improved visuo-motor coordination, while putting little demands on the processing of multiple objects at once. Accordingly, the version of Tetris on which subjects were trained had the preview block option turned off. In a manner analogous to the action-trained group, improvement was quantitatively measured by comparing performance on day 1 versus that on day 30.

4.1.5. Post-Test

After video game training, subjects were re-tested on the same experiment as in the pre-test, as well as the other aforementioned unrelated tasks.
4.2. Results

4.2.1. Game Play:

In order to assess game improvement, several measures were used with a percent change score being calculated for each. For the action game, the two measures used were kills and death. For each of five levels of game difficulty (level five being the highest level that all players attained) the measure taken on their first playing of the level (which, because of the way in which difficulty was progressed was not necessarily on the first day of training) was compared with their final playing of the level on Days 29-30. A substantial increase in number of kills, decrease in number of deaths, and increase in the ratio of kills/deaths was seen at each difficulty level (Level 1: 226% increase in kills, 64% decrease in deaths; Level 2: 147% increase in kills, 38% decrease in deaths; Level 3: 160% increase in kills, 27% decrease in deaths; Level 4: 80% increase in kills, 33% decrease in deaths; Level 5: 52% increase in kills, 32% decrease in deaths).

For the control game, the mean and median scores from Day 1 were compared with the same values on Day 30. As in the action game, the control players showed substantial improvements after training, the mean score improving by 323% and the median score by 359%.

These results demonstrate that both groups were engaged in their training and showed improvement on the training task.
4.2.2. UFOV Task

Accuracy was analyzed in four 2x2x3 ANOVAs, blocked by distractor level and center task condition, with game trained (action/control), test (pretest/posttest), and eccentricity (10°, 20°, 30°) as factors. As in Experiment 2, center task present trials were first filtered to include only those trials wherein the center task was correct.

As in Experiment 2, the observation of near-ceiling performance in some cells led to an analysis with arcsin transformed data. In only one case did a non-significant p-value in the untransformed analyses become significant in the arcsin transform analyses (noted in section 4.2.2.1) and in no cases did a significant p-value in the untransformed analyses become non-significant in the arcsin transformed analyses. As in Experiment 2, only the untransformed analyses are presented.

4.2.2.1. Peripheral Localization Accuracy - No Distractors, No Center Task

A main effect of eccentricity was observed \( (F(2,60) = 3.9, p < .05) \) with accuracy decreasing with increasing eccentricity. A main effect of test was observed \( (F(1,30) = 4.5, p < .05) \) with accuracy improving from pre- to post-test. However, although the interaction between game trained and test did not reach significance \( (F(1,30) = 3.8, p = .06, \text{Figure 4A}) \), it was in the direction predicted by our hypothesis, with the action group improving more than the control group. The ability to see a clear difference between groups was likely hindered by the near ceiling performance in this condition. It is also worth noting that this effect would be
statistically significant assuming a one-tailed test, which would be justified given our specific prediction of greater improvements in the action trained group, and also that this effect was significant (F(1,30) = 4.6, p < .05) in the arcsin transformed analysis.

4.2.2.2. Peripheral Localization Accuracy - No Distractors, Center Task Present

Main effects of eccentricity (F(2,60) = 37.2, p < .001) with accuracy decreasing with increasing eccentricity and of test (F(1,30) = 10.5, p < .01) with accuracy increasing on the post-test relative to the pre-test were observed. Also observed was a game trained by test interaction (F(1,30) = 6.8, p < .05) caused by a greater improvement in the action game than the control game (Figure 4B).

4.2.2.3. Peripheral Localization Accuracy - Distractors Present, No Center Task

A main effect of eccentricity (F(2,60) = 72.4, p < .001) was observed. Main effects of game trained (F(1,30) = 4.9, p < .05) and of test (F(1,30) = 25.4, p < .001) were observed with the action group being more accurate than the control group, and subjects performing better on the post-test than the pre-test. A significant interaction between game trained and test (F(1,30) = 12.8, p = .001) indicates that the action group improved significantly more than the control group, which is likely the root of the main effect of game trained. Finally, a significant interaction between trained game, test, and eccentricity (F(2,60) = 4.8, p < .05) was caused by the action group’s performance falling off less steeply with eccentricity following training (Figure 4C).
4.2.2.4. Peripheral Localization Accuracy - Distractors Present, Center Task Present

Only a main effect of eccentricity ($F(2,60) = 70.3$, $p < .001$) and a game trained by test interaction ($F(1,30) = 5.1$, $p < .05$) were observed with again, accuracy decreasing with increasing eccentricity, and the action group improving by a larger margin than the control group (Figure 4D).
Figure 4: Experiment 3 - Accuracy of target localization as a function of eccentricity, training group, and test

The action trained group showed a significantly greater improvement in localization accuracy than the control group following training at each eccentricity for all of the conditions other than the no distractors/no center task condition where the result was nearly significant (p = .06).

4.2.2.5. Center Identification Task Performance

First, although the center task performance was knocked far from ceiling, there was no general increase in center discrimination task accuracy following
training, and this held true for both groups (action trained: pretest: 61.3% +/- 3.0, posttest: 66.6% +/- 4.3, control trained: pretest: 66.6% +/- 3.1, posttest: 67.5% +/- 3.7; main effect of test p > .05; interaction between test and game trained, p > .5). A main effect of distractor level (F(1,30) = 7.6, p = .01) indicates that central task performance was affected by the demands of the localization task with worse central task performance for the distractors present than the no distractors condition.

4.3. Discussion

The results from Experiment 3 establish that the act of playing an action video game improves performance on the UFOV task. Importantly, action trained subjects showed greater training induced improvements than subjects trained on a control game that relies heavily on eye-hand coordination. Thus, improvement after action game training cannot be attributed to a general test-retest advantage or to the fact that video game training facilitates visuo-motor coordination. Instead, action video game play appears to truly modify visuo-spatial attention.

As in Experiment 2, the action video game trained group improved their localization ability at all eccentricities – even at 30°, which is beyond the maximum eccentricity of game training. This result confirms that the effects of action video game play do generalize to untrained locations in the visual field. The action trained group also improved their localization performance both with and without the presence of distractors, confirming that action video game play does enhance the
ability to monitor the peripheral visual field and also to select targets from within a field of distractors.

Finally, a strong effect of training was seen on peripheral localization both without and with the presence of a center task in the action-trained group. The finding that the action-trained group outperforms the control trained group even when a center task is added demonstrates that the enhanced peripheral localization performance of action gamers is not at the cost of central performance. Unlike in Experiment 2, the central task was equally difficult for both groups. As the participants in Experiment 2 have many more hours of training than those of Experiment 3, this pattern of result is consistent with the view that visual performance may be harder to modify in central than in peripheral vision. Finally, the equivalent performance on the center task in the two training groups in Experiment 3 demonstrates that the center task was perceptually as demanding in action-trained and control trained group. It is therefore unlikely that the enhanced performance induced by action game training could be due to perceptual factors. Rather the proposal that action video game training enhances attentional resources over the whole field offers a more parsimonious explanation of the data presented.

5. Relationship between action game improvement and UFOV improvement

The goal of Experiment 3 was to establish a causal link between action video game play and enhanced performance on the UFOV task. By showing that subjects
required to play action video games display greater improvements on a visuo-spatial attention task than subjects required to play a control game, this study establishes a causal link between action game play and attentional capacities. What remains unclear, however, is whether performance on an action video game can be used to predict how good visual selective attention is. On the one hand, it is clear that individuals who play action video games are better at these games than those who do not play. Combined with our finding that action game players outperform non-players on a visual selection task, it would seem natural to hypothesize that performance on action game play does predict attentional resources, at least as tested by the UFOV. On the other hand, action video games are extremely rich, not only visually but also strategically. There are therefore many ways to excel at action video game playing. While visual selective attention skills likely contribute strongly to action game success, other aspects of cognition such as planning, memorizing landmarks and the lay of the land, and understanding the strengths and weaknesses of the various characters, weapons, and positions also play a large role in performance. In addition, the behavioral measures provided by commercially available games are rather coarse. For instance, shooting accuracy is greatly influenced by the type of gun the player uses (a fully automatic weapon requires less accuracy than a semiautomatic weapon to achieve the same ends). Other measures such as kills and deaths are likely much better correlated with high level strategies (which weapon to use, when to hide and when to attack, remembering to replenish health/armor, etc) than low-level perceptual skills. Nevertheless for Experiment 3 we tested whether there was a correlation
between improvement in action game performance and improvement on the UFOV task.

5.1. Correlation Analysis

Percent improvement for each of the individual UFOV conditions in Experiment 3 (No Distractors/No Center Task, No Distractors/Center Task Present, Distractors Present/No Center Task, Distractors Present/Center Task Present) was correlated with percent change in number of kills and in number of deaths for each of the five levels of game difficulty. If those subjects who improved their scores by the greatest margin on a particular condition of the UFOV task also demonstrated the greatest increase in either of these measures, a significant relationship should be observed. Out of the forty correlations (four UFOV conditions by five kill improvement scores and five death improvement scores) there were no significant correlations (using a Bonferoni corrected p-value of .00125)

5.2 Discussion

This analysis indicates a lack of correlation between available measures of game improvements and UFOV improvement. Although the finding of a such positive correlation would have nicely complemented the finding of a causal relationship between number of hours of action game play and UFOV performance, it still remains that the very act of playing action games at a challenging level enhances performance on a visual selection task to a greater extent than playing other, similarly
challenging, control games. It will be for future research to further assess the link between the exact level of game expertise of a player and the quality of its visual selective attention. This may require the development of finer outcome measures for action video games improvement that do not mix perceptual aspects of gaming with various strategic decisions.

6. General Discussion

The results of these three experiments demonstrate the positive effect of action video game play on visuo-spatial attention. First, by measuring the compatibility effect as a function of perceptual load, we were able to gain a measure of the attentional resources available to VGPs and NVGPs (Lavie et al., 2004). VGPs continued to show compatibility effects at greater perceptual loads than NVGPs confirming the proposal that VGPs have enhanced attentional resources. This effect held for both central and peripheral distractors, suggesting an overall enhancement in attentional resources in VGPs rather than some manner of tradeoff.

As seen in several recent studies (Beck & Lavie, 2005; Proksch & Bavelier, 2002), there was less of a decrease in the compatibility effect with increasing load for central distractors than peripheral distractors. It has been suggested that this is due to preferential access to attentional resources around fixation, at least in the hearing population (Beck & Lavie, 2005). Interestingly, the differences seen in VGPs between low and high perceptual load conditions suggest that they may allocate
attention in a more dynamic manner across space. During conditions of low perceptual load, VGPs distributed attention proportionally more to the visual periphery, but as the perceptual load of the primary task was increased, attention was shifted to central vision. One can easily imagine how such a configuration would be useful during action video game play. During “low-load” conditions, such as when the player walks down an empty path, it would be beneficial for attention to be shifted toward the periphery in order to best detect any incoming enemies. However, during “high-load” conditions, such as when the player is being attacked by charging enemies, it would be beneficial for those resources to be shifted to the area around the player (near fixation). In all, these results suggest that while the sizing of the attentional window may be largely automatic, it need not occur with the same spatial distribution in every population or in a static manner across levels of perceptual load.

A more direct measure of the effect of gaming on visuo-spatial attention was obtained by using the UFOV paradigm (Ball et al., 1988) in which subjects were asked to localize a very briefly presented target stimulus at multiple eccentricities, with and without the presence of distracting items, and with and without the presence of a concurrent center task. VGPs showed increased localization abilities both within and outside of their typical game playing field of view, indicating that the effect of action video game play generalizes to untrained locations. VGPs also showed a decided advantage in localization accuracy over NVGs both when distractors were absent and when they were present. The former demonstrates that VGPs display a general enhancement in the ability to detect an abrupt onset target in the visual
periphery. While it is known that this type of task draws on exogenous attention (Yantis & Jonides, 1990), it is also possible that improvement on this condition could also be accounted for by perceptual, rather than purely attentional factors. The VGP advantage in the distractors present condition indicates that VGPs are better able to select targets amongst distractors than NVGPs. The fact that the distractors present condition requires the successful selection of the target from amongst competing alternatives suggests that VGPs do indeed display an enhancement in visual selective attention, which has been shown to increase the spatial resolution of visual processing (Carrasco, Williams, & Yeshurun, 2002; Talgar & Carrasco, 2002; Yeshurun & Carrasco, 1998).

Alternative hypotheses that have purely perceptual factors at the root of the differences observed in the distractors present condition are unlikely for several reasons. First, as mentioned briefly in the introduction, performance on the UFOV is quite poorly correlated with basic perceptual skills (acuity, contrast sensitivity, perimetry) (Ball et al., 1990; Owsley et al., 1995). In fact, the UFOV was initially designed by Ball and colleagues specifically because driving accidents in the elderly were found to be poorly predicted by basic perceptual abilities, and a test was required that better tapped the visual attentional requirements present while driving (peripheral monitoring, target selection, distractor rejection). Of special note is the fact that the relationship between low-level perceptual skills and UFOV performance is particularly weak for the distractors present condition (Owsley, et al., 1995). Second, the type of low-level sensory enhancements that could potentially underlie
increased performance in the no distractors condition, such as signal enhancement, would be of much less use in the distractors present condition in which target selection is of the essence.

Unfortunately, our design does not allow us to address the issue of search efficiency in which the rate of visual selection is measured by systematically varying set size. Although the UFOV task manipulates the number of distractors, our design used steps in distractor number that are too large (0, 23 or 47 distractors) as well as blocked order of distractor presentation, preventing any estimation of the rate of visual search proper. However, a recent study comparing visual search skills in action video game players and non players by Castel et al (2005) speaks to this issue. In the Castel et al (2005) paper, video game players were found to have faster response times for both easy (feature/parallel) and difficult (conjunction/serial) visual search displays - an advantage that held for displays ranging from four to twenty-six items. The difference was quite large, with VGP s performing the difficult search task with a set-size of twenty-six in less time than the NVGPs performed the task with a set-size of eighteen. Importantly, as would be predicted by an increase in search efficiency in VGP s, Castel et al (2005) observed a significant interaction between group (VGP/NVGP) and set-size. The authors state that this “interaction indicates that videogame players are more efficient in searching through displays than the non-videogame players” (Castel et al, 2005, pp. 226). However, because the set-size by group interaction disappeared when only the largest set-sizes were included in the analysis (set-sizes of 10+) the authors concluded that the VGP RT advantage might
be better understood as a change in stimulus-response mappings rather than a change in visual selective attention. Based on the results of the current study, it appears as though the initial interpretation of increased search efficiency in VGPs may have some validity. This proposal does not discount the possibility that some proportion of the difference between VGP and NVGP reaction time in their experiment could be accounted for by stimulus-response mappings or other mechanisms. One might hypothesize that the mechanism(s) leading to enhanced search in VGPs is capacity limited, the effect of which on total reaction time would necessarily be diminished with increasing set size. It will be for future research to tease out the roles of sensitivity, criteria, and residual response time as it pertains to VGPs in visual search.

Finally, the use of the UFOV paradigm also allowed us to study the effect of action game play on dual-task performance. When a concurrent center task was added to the peripheral localization task, NVGPs showed a clear cost of the added center load in the form of decreases in peripheral localization ability, while VGPs showed no such effect suggesting an improvement in the ability to dual-task in VGPs. These results are well predicted by the increased capacity of visual attention in VGPs seen in Experiment 1. In addition, they unambiguously rule out the possibility that VGPs may show increased peripheral performance at the cost of central vision. The attentional resources of VGPs are sufficient to perform both central and peripheral tasks at high accuracy. In contrast, the center task depletes the resources of NVGPs and therefore decreases peripheral localization. Experiment 3 demonstrated that the effects noted in Experiment 2 can be induced by training, establishing a causative
relationship between action video game experience and performance enhancement on the UFOV. Along with the results of Experiment 1, these findings establish that action video game experience improves both central and peripheral visuo-spatial attention by increasing attentional resources and facilitating visual selective attention.
References


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1.1.1.2. The spatial resolution of visual attention


- Version below is the final draft version and thus may differ from the final published version in terms of formatting, precise wording, etc

**Action video game experience alters the spatial resolution of vision**

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Abstract

Action video game play enhances several different aspects of visual processing (Green & Bavelier, 2003); however the mechanisms underlying this improvement remain unclear. Here we show that action video game play can alter fundamental characteristics of the visual system such as the spatial resolution of visual processing across the visual field. To determine the spatial resolution of visual processing we measured the smallest distance a distractor can be from a target without compromising target identification. This approach exploits the fact that visual processing is hindered as distractors are brought nearer to the target, a phenomenon known as crowding. Video game players could tolerate smaller target-distractor distances, establishing an enhancement of the spatial resolution of visual processing in this population. Critically, similar effects were observed in non-video game players that were trained on an action video game, thus verifying a causative relationship between video game play and augmented spatial resolution.
Video game players appear to outperform non-game players on several different visual tasks (Castel, Pratt, & Drummond, 2005; Gopher, Weil, & Bareket, 1994; Green & Bavelier, 2003, 2006, In Press; Greenfield, DeWinstanley, Kilpatrick, & Kaye, 1994; Trick, Jaspers-Fayer, & Sethi, 2005). For example, avid action video game players (VGPs) were found to localize a peripheral target in a field of distracting objects more accurately than NVGPs, to process a visual stream of briefly presented objects more efficiently and to track more objects at once than NVGPs. Non-game players trained on an action video game exhibited similar improvements establishing that the very act of action video game play results in an increased ability to perform such complex visual tasks (Green & Bavelier, 2003, In Press). Although the effect of game play on complex visual tasks is striking, it remains unclear whether the improvements previously described may be mainly due to strategic changes or to changes in more fundamental aspects of visual processing. We show here using a crowding paradigm that video game play alters the spatial resolution of vision - one of the fundamental characteristics of vision.

Crowding refers to the general finding that it is substantially more difficult to identify a target object when other distracting objects are present in its immediate vicinity than when the target object is presented in isolation. This decrement in performance is a function of the number of distractors and the distance between the target and the distractor(s), with performance decreasing as the number of distractors increases, as well as when targets and distractors are moved closer together (Leat, Li, & Epp, 1999; Miller, 1991; Orbach & Wilson, 1999). The region in space around a
target wherein the presence of distracting objects leads to decreased sensitivity for the target is known as the “crowding region” or the “zone of spatial interaction” (Bouma, 1970; Flom, Weymouth et al., 1963; Intriligator & Cavanagh, 2001; Jacobs, 1979; Toet & Levi, 1992), and in our everyday life limits our ability to identify letters or words embedded in text for example.

Several lines of explanation for visual crowding have been advanced. Some have suggested important roles for interactions between the facilitatory and inhibitory regions within neuronal receptive fields in early visual areas or interactions between neurons via long-range horizontal connections (Flom, Heath, & Takahashi, 1963; Polat & Sagi, 1994; Tripathy & Levi, 1994). Others have suggested that crowding, particularly foveal crowding, is a form of spatial frequency masking or contrast masking (Chung, Levi, & Legge, 2001; Levi, Klein, & Hariharan, 2002) or is related to the physical properties of the stimulus (Hess, Dakin, & Kapoor, 2000). Alternatively, it has been proposed that the size of the crowding region offers a measure of the resolution of visual attention (Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002). Importantly for our purpose, whichever interpretation of crowding may prevail all parties agree that crowding reflects a fundamental limitation on the spatial resolution of the visual system.

In this paper we test the hypothesis that action video game play leads to enhanced spatial resolution, by using a crowding paradigm modeled after Toet and Levi (1992). Experiment 1 establishes that avid action game players (VGPs) exhibit smaller crowding regions than non-game players (NVGPs), meaning that VGPs
maintain high performance at target-distractor separations that hinder NVGPs performance. In Experiment 2 we use a training paradigm to demonstrate a causative relationship between action video game experience and performance in a training study.

**Experiment 1**

The proposal of enhanced spatial resolution in VGPs predicts that the size of the crowding region will be smaller in VGPs than NVGPs. The size of the crowding region was measured by testing the ability of participants to discriminate between a right-side up and an upside-down T as a function of the distance between this target object and two flanking distractor T shapes presented above and below the target (Figure 1) (Toet & Levi, 1992). The size of the crowding region was assessed at three different eccentricities (0°, 10°, and 25°) chosen to allow the measurement of potential changes both well within (0° and 10°) and just at the limit of (25°) the field of view of normal game playing (most of our gamers reported playing on screens that subtended an average of +/-15° from the center of the screen). If changes in the size of the crowding region do arise as a result of action video game experience, but the learning is specific for the trained region of space, one would predict greater enhancements for 0° and 10° than for 25°. Conversely, if similar changes were observed across eccentricities, it would be evidence for generalization of the learning beyond the more highly trained regions of space.
Figure 1 - Stimuli

The stimuli consisted of three ‘T’ shapes randomly oriented either right-side up or upside down. The subject’s task was to indicate the orientation of the center T. In separate blocks, three eccentricities were tested: 0°, 10°, and 25°. The size of the Ts was set to be 1.5 times each individual subject’s T-alone threshold at each given eccentricity.

Method

Participants

Twenty right-handed males (all undergraduates at the University of Rochester) with normal or corrected-to-normal vision were placed into one of two groups, VGP or NVGP, based on the outcome of an interview about their video game playing habits (only males were tested in Experiment 1 because of the relative scarcity of female action video game players). Participants were asked about different types of video games in turn (action, sports, fantasy, role playing, other), and for each type, were asked to name all the games they had played in the past 12 months. For each video game the participants reported playing, they were asked how often they played that game in the previous 12 months (daily, weekly, monthly or less), and if applicable, how many hours they spent playing per week (0, 0-1, 1-2, 3-5, 5-10, 10+) and for how long they played it during a typical session.
To be considered a video game player, a subject needed to report a minimum of 5 hours a week of action video game usage for the previous six months (N=10, mean age= 19.7 years). The criterion to be considered a non-video game player was a report of zero hours per week of action games for at least the previous six months (N=10, mean age =20.3 years; note: playing other games was allowed). Subjects provided written informed consent and were paid $8/hour.

**Apparatus**

The apparatus consisted of a MacIntosh G3 computer running a program to present stimuli and collect the data using the Matlab computer language (The Math Works Inc., Natick, MA) and the Psychophysical Toolbox routines (Brainard, 1997; Pelli, 1997- http://psychtoolbox.org). The stimuli were displayed on a 24” Sony GDM-FW900 driven at a resolution of 1920x1440 at 75Hz by a MP850 video card (Village Tronic Computer, Sarstedt, Germany).

**Stimuli**

The stimuli/procedure were modeled after Toet & Levi (1992; Figure 1). The stimuli consisted of three vertically aligned Ts formed by black pixels (3cd/m²) with stroke widths of 2 pixels, which were presented against a uniform white background (70 cd/m²). The Ts were randomly presented either right-side up (T) or upside down. For each eccentricity tested, the size of the Ts was set to 1.5 times each individual subject’s T-alone discrimination threshold. The T-alone discrimination threshold was
derived by averaging the threshold obtained in two blocks prior to the experimental condition where the T was presented in isolation.

**Viewing conditions**

The three eccentricities tested, 0°, 10° and 25°, called for three different viewing distances (300cm, 90cm, 50cm respectively). For the two peripheral conditions, the stimuli were always centered on the horizontal meridian to the right of fixation, and subjects were eye-tracked. The eye-tracking analysis was conducted offline; thus, trials in which an eye movement occurred could not be removed from the final analyses. However, the number of eye movements made was quite few (< 4% of trials) and did not differ between groups (F(1,18) = .7, \( p_{rep} < .58 \)) or among eccentricities (F(1,18) = .98, \( p_{rep} < .65 \)). The order of eccentricity blocks was counterbalanced across subjects. No effect of run-order was found and will not be discussed further.

**Procedure**

Each trial began with a short auditory tone followed by a 150ms ISI. For the 0° stimulus the fixation dot was extinguished during this interval to diminish any possible forward masking. For the two peripheral conditions the fixation dot remained visible throughout the trial. The stimuli were then presented for 100 ms. The subject’s task was to indicate the orientation (up/down) of the center T by pressing the corresponding key on the keyboard. The subject was free to respond at
any time following stimulus presentation. Subjects were told that accuracy rather than speed of response was critical. Following response, auditory feedback was given (low tone – incorrect, high tone – correct).

The critical manipulation was the center-to-center spacing between the two flanking Ts and the target T (initial spacing: 30/400/600 minutes of arc for 0/10/25° conditions respectively), which was controlled by a three up, one down staircase (step-size of 5%). Rather than ending the staircase procedure after a certain number of reversals, in order to ensure that subjects were given equal experience (as three different eccentricities were tested and compared), all subjects underwent 200 trials per condition. The final crowding threshold value was calculated by averaging the center-to-center target/distractor spacing across the final 10 trials.

**Results and Discussion**

The crowding threshold varied from approximately 10 minutes of arc for the 0° condition, to 120 minutes of arc at 10° to more than 300 minutes of arc for the 25° condition. The finding that the crowding region increases dramatically with eccentricity mirrors previous reports in the field (Leat et al., 1999; Toet & Levi, 1992). To be able to compare the effect of video game experience across eccentricities, the distance thresholds were first converted to \( \log_{10} \) values thus allowing a relative equalization of the means/variances across conditions (Leat et al., 1999).
The effect of VGP status (VGP/NVGP) and eccentricity (0°/10°/25°) were analyzed in a 2x3 ANOVA run on log distance thresholds. A main effect of eccentricity was observed (F(2,36)=331.7, p_{rep} > .99, partial eta-squared=.95), with the size of the crowding region increasing with increasing eccentricity as expected. Importantly, a main effect of VGP status was also observed (F(1,18) = 22.4, p_{rep} > .99, partial eta-squared=.55), with VGPs demonstrating smaller crowding regions than NVGPs (Figure 2A). Eccentricity did not interact with VGP status (F(2,36) = .9, p_{rep} < .58) suggesting that the effect of VGP status was consistent across the eccentricities tested.

Although our primary goal was to ascertain the size of the crowding zones in VGPs and NVGPs, another interesting pattern of results was observed in the T-alone condition. Analyses of the T-alone thresholds as a function of VGP status (VGP/NVGP) and eccentricity (0/10/25°) in a 2x3 ANOVA on log_{10} transformed values revealed, as expected, a main effect of eccentricity (F(2,36) = 412.6, p_{rep} > .99, partial eta-squared=.96) with the size of the T at threshold increasing with increasing eccentricity. Unexpectedly though, a main effect of VGP status was also observed (F(1,18) = 15.9, p_{rep} > .99, partial eta-squared=.47) with VGPs being able to discriminate smaller Ts than NVGPs. VGP status did not interact with eccentricity (F(2,36) = 1.2, p_{rep} < .65) suggesting the effect was consistent across the eccentricities tested.

Together these results demonstrate that video game players have both smaller regions of spatial interaction and better visual acuity thresholds. It is worth noting that
the performance improvement seen in gamers is consistent across all eccentricities tested. A difference between groups at 0° is somewhat surprising as it is generally assumed that foveal vision is near optimal, and therefore more difficult to enhance through training than peripheral vision (Neville & Bavelier, 2002). Nonetheless, the present study establishes a central performance enhancement of a comparable magnitude as that observed in the periphery. In addition, the presence of a group difference at 25° of eccentricity suggests that some transfer of learning has occurred, as this eccentricity is not within the well-trained region of space. If this finding were truly due to experience with action video games, it would be in contrast with much of the perceptual learning literature, which has demonstrated exquisite spatial specificity for learning in many training tasks (Fahle, 2004, 2005; Karni & Sagi, 1991).

Before any conclusions can be reached about the effects of action video game experience, self-selection needs to first be ruled out as a potential factor. It is possible that by selecting avid game players we have chosen a population that would have superior visual skills even without the difference in training. It may be, for example that individuals with better visual skills are more likely to excel at game playing and therefore more likely to become avid players.
Figure 2 - Results

A) VGPs demonstrated smaller crowding regions than NVGPs. However, while the size of the crowding region increased with increasing eccentricity, the size of the VGP effect was consistent across eccentricities.

B) A significant decrease in crowding threshold was observed in NVGPs following action video game training.

C) No reliable change in threshold was seen in the control group following training suggesting that the effect seen in the action group was not due to test-retest effects or changes in visuo-motor factors.

# - SEM for all data points was less than the size of the squares denoting the values

## - (*: \( p_{rep} > .92 \), **: \( p_{rep} > .97 \))

Experiment 2

Experiment 2 employed a training paradigm to investigate whether a causative relationship exists between action video game experience and higher spatial resolution. Thirty-two non-gamers were divided into two training groups. One group was then trained on an action game that was similar to those played by the VGPs in Experiment 1 (described below), while the other was trained on a game that was less visually intense, but that did require substantial visuo-motor coordination (also described below). In addition to controlling for any effects of improved visuo-motor
coordination (better hand-eye coordination could conceivably reduce the resources necessary for response execution, leaving more resources free for target identification), the control group also acted as a control for test-retest improvements (improvements due to practice on the tests themselves), and for any Hawthorne-like effects (any improvements due to the fact that the experimenters had “paid attention” to the subjects during the training - Benson, 2001). Crowding threshold were measured pre- and post-training (30 hours of training over a span of 4-6 weeks). If action video game experience is sufficient to cause a decrease in the size of the crowding region, a greater pre-post reduction will be seen in the group trained on the action game than on the control group.

Method

Participants

Thirty-two NVGPs were equally and randomly divided between the experimental and the control group. The criteria for NVGP remained the same as in Experiment 1. All subjects underwent training as described below. In all, 8 females and 8 males (mean age = 21.3; all right-handed) made up the final experimental group, while the final control group consisted of 9 females and 7 males (mean age = 21.0, 15 right handed).
Testing: Apparatus/Stimuli/Procedure

The apparatus/stimuli/procedure were identical to that described in Experiment 1 with three exceptions. First, because subjects underwent several unrelated experiments, the total testing duration was minimized and thus only one T-alone block was completed prior to the experimental block. Also, to decrease running time, the step size of the change in T size was set at 20% until three reversals were observed and then decreased to 5%, allowing stable thresholds to be reached in 120 trials. Finally, because no effect of run order was found in Experiment 1, the three eccentricities were run in the fixed order: 0°, 10°, 25°. Eye movements were again measured for the two peripheral conditions and as in Experiment 1, were quite rare (approximately 3% of trials) and did not differ as a function of test, game, or eccentricity nor were there interactions between any of these variables.

Training: Apparatus/Stimuli/Procedure

For both groups, training consisted of playing the pre-determined video game for a total of 30 hours (maximum of 2 hours per day, minimum of 5 hours per week, maximum of 8 hours per week). The sixteen members of the experimental group played the game Unreal Tournament 2004 (henceforth referred to as the action video game). This game was chosen to be similar to those played by our VGPs; it has a relatively simple interface, uses first-person point of view and requires effective monitoring of the entire visual field (extent from fixation about 13°-height x 16°-width). Each hour session of the action game was divided into three 20-minute
blocks. The difficulty of each block was adjusted based upon the kill/death ratio. If in a block the player scored more than twice as many kills as they had deaths, the difficulty level was increased one level. Also, players were periodically re-tested on lower difficulty levels to quantitatively assess improvement.

The sixteen members of the control group played the game Tetris, which was displayed to cover the entire extent of the screen (18°-height x 13°-width from fixation). As such, the field of view of the Tetris game was actually slightly larger than that of the action game. Tetris was selected to control for the effect of improved visuo-motor coordination, while putting little demands on the processing of multiple objects at once. Accordingly, the version of Tetris on which subjects were trained had the preview block option turned off. In a manner analogous to the action-trained group, improvement was quantitatively measured by comparing performance on Day 1 versus that on Day 30.

Both groups played their respective games on 20” monitors. The action game group played on Dell FlatPanel displays, whereas the control group played on CRT monitors.

**Results and Discussion**

**Game Play**

Game improvement was assessed using several measures. For the action game, the two measures used were kills and death. For each of five levels of game difficulty (level five being the highest level that all players attained) the measure
taken on their first playing of the level (which, because of the way in which difficulty was increased was not necessarily on the first day of training) was compared with their final playing of the level on Days 29-30. A substantial increase in number of kills and decrease in number of deaths was seen at each difficulty level (Level 1: 226% increase in kills, 64% decrease in deaths; Level 2: 147%, 38%; Level 3: 160%, 27%; Level 4: 80%, 33%; Level 5: 52%, 32%).

For the control game, the mean and median scores from Day 1 were compared with the same values on Day 30. As in the action game, the control players showed substantial improvements after training, the mean score improving by 323% and the median score by 359%.

These results demonstrate that both groups were engaged in their training and showed improvement on the training task.

Crowding Thresholds

As in Experiment 1 the crowding thresholds were first converted to log\(_{10}\) values and then analyzed in a 2x2x3 ANOVA with trained game (action/control), test (pre/post), and eccentricity (0°/10°/25°) as factors. A strong main effect of eccentricity was observed (F(2,60) = 2506.5, p\(_{rep}\) > .99, partial eta-squared=.98) with crowding thresholds increasing with increasing eccentricity. A main effect of test was also observed (F(1,30) = 4.8, p\(_{rep}\) = .93, partial eta-squared=.14) with crowding thresholds being lower post-test than pre-test. Importantly, and confirming the results from Experiment 1, an interaction between trained game and test was observed.
(F(1,30) = 11.6, \( p_{rep} = .99 \), partial eta-squared=.28) with the action group showing larger decreases in crowding threshold from pre-test to post-test than the control game (Figure 2B and 2C respectively). This effect did not interact with eccentricity (F(2,60) = .03, \( p_{rep} < .1 \)) suggesting that the effect of training was similar across the eccentricities tested.

Unlike in Experiment 1, where VGPs showed lower thresholds than NVGPs, no effect of trained game or test was detected in the T-alone data in Experiment 2. Only a main effect of eccentricity (F(2,60) = 918.8, \( p_{rep} > .99 \)) was observed, with, as typical, thresholds increasing with increasing eccentricity.

The results of Experiment 2 establish that subjects trained on an action video game have significantly greater decreases in crowding threshold than those subjects trained on the control game. Unlike in Experiment 1, visual acuity (T-alone threshold) was not detectably modified by 30 hours of training. Although it is unclear at this point whether more training could produce a reliable change in visual acuity, Experiment 2 unambiguously demonstrates that visual crowding can be altered through action video game training.

**Discussion and Conclusions**

Action video game experience was shown to lead to an increase in the spatial resolution of vision as measured by crowding. VGPs could tolerate smaller center-to-center spacing between target and distractors than NVGPs. This improvement was noted not only at peripheral locations but also in central vision, indicating that even
the high central resolution can be enhanced with proper training. In addition, improvements in the periphery were seen at locations well within the range of playing as well as at more eccentric locations, indicating transfer of training beyond the highly trained regions of space. NVGPs specifically trained on an action video game for 30 hours showed similar improvement in the size of the visual crowding region establishing a causative relationship between video game experience and a reduction in the size of the crowding region. These results establish that video game play may alter basic properties of the visual system.

This study extends previous findings on the impact of video game and visual skills by showing that video game play can alter visual performance even in a task where the location and time of arrival of the stimulus are fixed and known ahead of time to the subject. In contrast, previous work in gamers focused on complex visual tasks that by design relied on uncertainty, such as in visual search tasks where the target location is uncertain and has to be found. Although the finding that video game play changes performance on such complex visual tasks is interesting, a number of other manipulations are known to also affect performance on such tasks. For example, much previous research documents enhanced visual spatial resolution when exogenous cues are used to reduce spatial and temporal uncertainty (Carrasco, Williams, & Yeshurun, 2002; Yeshurun & Carrasco, 1999), or alternatively poorer performance when a difficult secondary task is added (Zenger, Braun, & Koch, 2000). Here VGPs demonstrated reductions in crowding thresholds even though where and when the stimulus would appear was fixed allowing subjects to focus at their optimal
level. The finding of improved performance under such conditions cannot easily be attributed to strategic factors. Rather, one of the mechanisms by which action video game play may enhance visual processing is by increasing the spatial resolution of visual processing across the visual field.

The present study highlights the potential of action video game training for rehabilitation of visual deficits. Indeed a common feature in visually impaired patients is greater vulnerability to crowding, such as in the cases of amblyopia or normal aging (Ball et al., 1988; Ball & Owsley, 1992; Hariharan, Levi, & Klein, 2005; Levi, Hariharan, & Klein, 2002; Levi & Klein, 1985; Polat, Sagi, & Norcia, 1997). Of course, much work remains to characterize the level(s) of processing at which video game playing may be acting; however, by establishing that a video game training regimen can reduce the detrimental effects of crowding, this research opens new avenues for the development of rehabilitation software.
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References


1.1.1.3. The temporal characteristics of vision

Excerpt from:

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- Version below is the final draft version and thus may differ from the final published version in terms of formatting, precise wording, etc

**Action video game modifies visual selective attention**

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As video-game playing has become a ubiquitous activity in today’s society, it is worth considering its potential consequences on perceptual and motor skills. It is well known that exposing an organism to an altered visual environment often results in modification of the visual system of the organism. The field of perceptual learning provides many examples of training-induced increases in performance. But perceptual learning, when it occurs, tends to be specific to the trained task; that is, generalization to new tasks is rarely found\textsuperscript{1–10}. Here we show, by contrast, that action-video-game playing is capable of altering a range of visual skills. Four experiments establish changes in different aspects of visual attention in habitual video-game players as compared with non-video-game players. In a fifth experiment, non-players trained on an action video game show marked improvement from their pre-training abilities, thereby establishing the role of playing in this effect…

We next examined the temporal characteristics of visual attention and asked whether the pressure to act rapidly on several visual items, which is inherent to most action games, alters the ability to process items over time, particularly the ability to avoid ‘bottlenecks’ of attention that often occur in temporal processing. The experimental paradigm that we used to test the temporal aspects of visual attention is the attentional blink task (refs\textsuperscript{20–22} and Fig. 4a). Attentional blink refers to the phenomena wherein subjects have difficulties reporting a second target when it appears a few hundreds of milliseconds after the onset of a first target. In our case, we used a variant of the attentional blink, in which participants were asked to identify a
first target and then detect a second target. This task includes two distinct attentional bottlenecks. First is the attentional blink per se, which is the difficulty of processing a second target that comes 200–500 ms after the onset of the first one. Second is the cost of switching tasks between the first and second target (from identification to detection); unlike the attentional blink per se, this effect is most pronounced when the two targets are temporally adjacent and then decreases slowly as the time between the two targets increases. This attentional bottleneck is not specific to vision but rather appears amodal. Thus, by using an identification/detection attentional blink task, we could test whether the enhanced capacities after video-game training not only applied to a purely visual bottleneck but also generalized to an amodal one.

VGPs outperformed NVGPs on second-target correct detections from lag 1 to lag 5, indicating less attentional blink (Fig. 4b). The finding of a population difference as early as lag 1 indicates that video-game training enhances task-switching abilities as well as decreasing the attentional blink. Thus, both the visual and amodal bottlenecks identified during temporal processing of visual information are reduced in VGPs. Clearly, these individuals have an increased ability to process information over time; however, whether this is due to faster target processing, such as faster selection and stabilization of information in memory, or to an increased ability to maintain several attentional windows in parallel, cannot be determined from our current data.
Figure 4.

**A.** Measure of attention over time.

**a. Attentional blink task.**

Black letters were rapidly presented at fixation in a standard rapid, serial, visual presentation manner. At a random time in the stream, a white letter was presented (first target). After this first target, an ‘X’ (second target) was presented among the following letters 50% of the time. After the trial, the subject gave the identity of the first target and then indicated whether the ‘X’ was presented. Of interest is the performance of subjects on the ‘X’ detection task, given that they have correctly identified the white letter.

**b. Attentional blink performance.**

At early lags, VGPs performed better (less blink) than NVGPs; as lag increased, the effect of the attentional bottlenecks decreased and, as expected, the two populations became comparable (lag by population $P < 0.02$). Error bars denote s.e.m. Points without error bars indicate that the s.e.m. was smaller than the size of the square (**$P < 0.01$**).

We also carried out a training experiment to alleviate concerns over the source of the VGP and NVGP population differences. By selecting VGPs, we may have
selected individuals with inherently better attentional skills than NVGPs. The consequence of this potential split would be that VGPs, with their greater natural ability, did well at video games and so played often, whereas NVGPs, whose inherent abilities limited their success, avoided playing games as a result. Another possible confound was that, because of relatively superior visuo-motor coordination, VGPs were better able to perform the motor aspect of the tasks and thus had more spare resources to devote to the visually demanding part of the tasks. To rule out these potential confounds, a group of NVGPs underwent action-video-game training, in which they were asked to play Medal of Honor (a game similar to those reported being played by the VGP population) for 1 h per day for 10 consecutive days. A control group was trained, over the same time span, on the game Tetris. This game contains a challenging visuo-motor component but, whereas action games require that attention is distributed and/or switched around the field, Tetris demands focus on one object at a time. Tetris, therefore, would not be expected to change the aspects of visual attention described above and thus affords an excellent control for monitoring improvement due to enhanced visuo-manual expertise and test–retest improvements. Before and after training we tested each group on the enumeration, useful-field-of-view and attentional-blink experiments. The training was successful as all participants improved their scores on the video game on which they were trained. Notably, action-game training led to greater performance improvement than did the control game on all three experimental tasks. Enumeration increased by 1.7 items in individuals trained on action games, whereas the control group showed no improvement.
population by improvement, \( p < 0.05 \)). Training on action video games enhanced the useful field of view and lead to faster recovery from the attentional blink (Fig. 5)…

Figure 5

![Graph showing training and attentional blink](image)

**Figure 5: Training – Attentional Blink**

The group trained on an action video game recovered faster from the attentional blink than did the control group trained on a non-action video game.

Thus, 10 days of training on an action game is sufficient to increase the capacity of visual attention, its spatial distribution and its temporal resolution. By forcing players to simultaneously juggle a number of varied tasks (detect new enemies, track existing enemies and avoid getting hurt, among others), action-video-game playing pushes the limits of three rather different aspects of visual attention. It leads to detectable effects on new tasks and at untrained locations after only 10 days of training. Therefore, although video-game playing may seem to be rather mindless,
it is capable of radically altering visual attentional processing. There are several ways by which video-game training could lead to such enhancements. Changes in known attentional bottlenecks is certainly a possibility; however, speeded perceptual processes and/or better management of several tasks at the central executive level are also likely to contribute. It will be for future studies of the effect of video-game practice to determine the relative contribution of these different factors to skill learning.

Methods

Participants

Subjects were aged between 18 and 23 years. The VGPs had played action video games on at least 4 days per week for a minimum of 1 h per day for the previous 6 months. The games included Grand Theft Auto3, Half-Life, Counter-Strike, Crazy Taxi, Team Fortress Classic, 007, Spider-Man, Halo, Marvel vs Capcom, Roguespeare and Super Mario Cart. The NVGPs had little, and preferably no, video-game usage in the past 6 months. Experiments 1–4 included only males; in experiment 5, both male and female NVGPs underwent training.

For experiment 4—attentional blink (Fig. 4)—the stimuli and procedure described previously were used except that eight lags instead of nine, and eight trials per condition instead of ten, were used. VGPs had almost significantly higher-second-target detection accuracy in the control condition (detecting the X in the absence of a first target, 95.6% to 87.9%, p = 0.061). Conservatively, all analyses were done on
the difference between the variable of interest and the baseline detection condition to eliminate different baseline abilities as a potential confound in interpreting the depth of the attentional blink between populations.

For experiment 5—training (Fig. 5)—all subjects were tested on the useful-field-of-view, attentional-blink and enumeration tasks (in this order) before training; they then underwent training for 1 h per day for 10 days with one of two possible kinds of video game. After training they were retested on the same three tasks (in the same order). The experimental group trained on Medal of Honor: Allied Assault (Electronic Arts, 2002). This game simulates Second World War combat situations and was chosen to be similar to those played by our VGPs. It has a relatively simple interface, uses first-person point of view and requires effective monitoring of the whole visual field. Subjects played the game straight through for the first 8 days. On days 9 and 10, they returned to the beginning of the game to quantitatively measure their improvement (comparing performance over mission 1 during their first and second playings). In all available measures of improvement taken (accuracy and deaths to complete mission), subjects improved their performance after training (accuracy, 17% improvement; deaths to complete, 42% improvement).

For the control group (n = 8), Tetris (Original Tetris, AcademySoft Elorgwhich, 1987; Tengen, 1988) was displayed to cover the entire extent of the screen. This game was selected to control for the effect of improved visuo-motor coordination, while putting few demands on the processing of several objects at once. Accordingly, the version of Tetris on which subjects were trained had the preview block option
turned off. In the two measures of improvement available (high score, maximum level reached), all subjects improved after training (high score, 71% improvement; mean level improvement, 67% improvement).

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References


8. Ahissar, M., Laiwand, R., Kozminsky, G. & Hochstein, S. Learning pop-out
detection: building representations for conflicting target-distractor relationship.


(1988).


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1.1.1.4. The capacity of visual attention


- Version below is the final draft version and thus may differ from the final published version in terms of formatting, precise wording, etc

Enumeration versus multiple object tracking:

The case of action video game players

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Abstract

Here we demonstrate that action video game play enhances subjects' ability in two tasks thought to indicate the number of items that can be apprehended. Using an enumeration task, in which participants have to determine the number of quickly flashed squares, accuracy measures showed a near ceiling performance for low numerosities and a sharp drop in performance once a critical number of squares was reached. Importantly, this critical number was higher by about two items in video game players (VGPs) than in non-video game players (NVGPs). A following control study indicated that this improvement was not due to an enhanced ability to instantly apprehend the numerosity of the display, a process known as subitizing, but rather due to an enhancement in the slower more serial process of counting. To confirm that video game play facilitates the processing of multiple objects at once, we compared VGPs and NVGPs on the multiple object tracking task (MOT), which requires the allocation of attention to several items over time. VGPs were able to successfully track approximately two more items than NVGPs. Furthermore, NVGPs trained on an action video game established the causal effect of game playing in the enhanced performance on the two tasks. Together, these studies confirm the view that playing action video games enhances the number of objects that can be apprehended and suggest that this enhancement is mediated by changes in visual short-term memory skills.

Keywords: Video games; Subitizing; Enumeration; Multiple object tracking
1. Introduction

1.1. Video Games and Visual Skills

Video game play leads to a number of alterations in visual attention, visuomotor coordination, and other perceptual/cognitive processes (Dorval & Pepin, 1986; McClurg & Chaille, 1987; Orosy-Fildes & Allan, 1989; Gopher, 1992; Gopher, Weil, & Bareket, 1994; Greenfield, DeWinstanley, Kilpatrick, & Kaye, 1994; Subrahmanyam & Greenfield, 1994; Yuji, 1996; Green & Bavelier, 2003; Li & Atkins, 2004). For example, several researchers have noted that video game play decreases the reaction time (RT) of subjects asked to respond to visual stimuli (Orosy-Fildes & Allan, 1989; Yuji, 1996). In the case of visual attention, Greenfield and colleagues (Greenfield et al., 1994) demonstrated that in a simple target detection task, expert video game players showed a diminished attentional cost (measured by RT) when presented with low probability targets compared to that observed in non-players, indicating enhancements in the ability to divide attention. Gopher and colleagues, working in collaboration with the Israeli military, demonstrated that cadets trained on a video game performed significantly better than their untrained peers on measures of flight performance (Gopher et al., 1994). Finally, our own work (Green & Bavelier, 2003) has demonstrated that video game players outperform non-players on different aspects of visual attention, in particular in the flexibility and efficiency with which they distribute attention over space and time. Such increases in visual attention in video game players may have real-world practical implications.
The goal of the present study is to assess the claim that, in addition to its effect on the spatial and temporal aspects of visual attention, action video game playing also modifies the number of objects that can be apprehended. In this paper, we compare the performance of video game players (VGPs) and non-video game players (NVGPs) on both an enumeration task and the multiple object tracking (MOT) task. These two particular tasks were chosen because they allow the separate assessment of the number of items that can be enumerated in parallel (also termed immediate apprehension), that can be enumerated serially (also termed counting), and that can be successfully tracked over time. Our results suggest a relationship between the number of items that can be accurately counted and the number of items that can be tracked. In contrast, the number of items that can be immediately apprehended seems to be under the control of distinct constraints. In addition, our results reveal for the first time a dissociation between reaction time measures and accuracy measures during the enumeration task. The consequences of these findings for our understanding of the mechanisms at play in enumeration and MOT studies are considered in the General Discussion.

1.2. The Enumeration Task

The enumeration task has classically been used to study the number of items that can be readily attended. This task requires participants to report the number of briefly flashed items in a display as quickly and as accurately as possible. Participant performance on this task appears best captured by two distinct processes, easily seen
when RT is plotted against the number of items presented. When viewing
enumeration performance in this manner a clear discontinuity, or elbow, is seen,
giving the appearance of a bilinear function. For low numbers of items, usually in the
range of one to four items (Atkinson, Campbell, & Francis, 1976; Oyama, Kikuchi, &
Ichihara, 1981; Trick & Pylyshyn, 1993; Trick & Pylyshyn, 1994), subject
performance is extremely fast. The RT slopes are near zero over this range – also
termed the subitizing range. As numerosity increases above this range, each
additional item has a substantially greater cost in terms of RT. The cost to
performance is evident in the steep slope observed beyond about four items. The
change in reaction time slopes is mirrored by a similar change in accuracy, with
accuracy remaining stable and high within the subitizing range and exhibiting a linear
decrease with increasing numerosity beyond the subitizing range. Although reaction
times and accuracy are typically correlated in enumeration studies, the subitizing
range has been defined in terms of reaction time as the range of numerosities that can
be apprehended without a significant increase in reaction time as numerosity is
increased.

The discontinuity in the enumeration curve has been the subject of much
debate and has been posited to have various explanations. One proposal holds that the
discontinuity marks a fundamental difference in the perceptual quality of the display
when few versus many items are presented. Following this line of thought, some have
proposed that performance when few items are present is exceptionally efficient
because it relies on canonical pattern recognition or configurational effects, which are
not available when many items are present (Mandler & Shebo, 1982; van Oeffelen & Vos, 1982). Along the same line, density differences have also been proposed to lead to the observed discontinuity (Atkinson et al., 1976). A second view holds that the discrepancy can be accounted for by a single cognitive process, counting, measured at different points of a continuum (Gallistel & Gelman, 1992). In this model, the elbow in the curve is thought to reflect a switch from a fast non-verbal mode of counting, to a slower verbal mode of counting (Gallistel & Gelman, 1992). This view is supported by the fact that many studies have demonstrated that the RT curve is not truly flat, even for low numerosity; instead there is often a small slope (between five and ten times shallower than what is seen for greater numbers of items) (Akin & Chase, 1978; Oyama et al., 1981). It has also been speculated that increases in memory load, light for few items but increasingly heavy for many items, may play a role. An alternative view posits that the discontinuity reflects two fundamentally different cognitive processes. From this viewpoint, the nearly flat region has been taken to reflect an automatic, parallel, and immediate process, which has been dubbed ‘subitizing’ (Kaufman, Lord, Reese, & Volkman, 1949). For simplicity, throughout the paper, the region over which performance is immediate will, for ease of exposition, be referred to as the subitizing range. According to this model, the mechanism(s) that underlie the subitizing process are hypothesized to be severely capacity limited (on the order of three to four items). When the number of items to enumerate exceeds the capacity of this automatic system, subjects must use a separate process wherein serial attention is employed to “count” the items from visual short-
term memory. As it is well known that information in STM decays over time, the process is slower and more error-prone. This is clearly reflected in the steep region of the performance graph, which will be referred to as the counting range throughout the remainder of the paper.

While there is much dissent as to whether the subitizing and counting range reflect two separate cognitive processes or a more continuous process with added constraints from short term memory and indexing as the numerosity increases, all parties agree that the subitizing range provides an estimate of the number of items that can be concurrently apprehended. We therefore decided to compare video game players (VGPs) and non-video game players (NVGPs) on the enumeration task.

2. Experiment 1

In Experiment 1, we asked whether playing action video games would alter enumeration ability. Experiment 1 also tests the view that video game play primarily affects peripheral vision. Although our own work (Green & Bavelier, 2003), as well as that of others (Orosy-Fildes & Allan, 1989), has shown improvements occurring in both central and peripheral vision, it is still commonly thought that video game play predominantly modifies peripheral vision. This view partly finds its support in the fact that many video games require subjects to distribute attention peripherally, as “enemies” can appear at any location. To test the effect of video game play on both the central and peripheral visual field, VGPs and NVGPs underwent two different enumeration experiments, one with a field of view restricted around fixation (5°
square; henceforth referred to as the narrow field of view condition) and the other with a much wider field of view (20° square; the wide field of view condition). If video game play disproportionately affects far peripheral vision, any VGP advantage over NVGPs should be magnified in the wide field of view condition. However, if the effects of video game play are consistent across retinal eccentricities, at least for the task under study, then performance should be somewhat equivalent between the two populations at both fields of view.

Using two fields of view also allows us to test the effect of field of view on the two components of the enumeration curve. The subitizing hypothesis suggests that the flat region of the performance graph reflects a preattentive spatially parallel mechanism and therefore predicts a similar subitizing span under both conditions. In contrast, models with canonical patterns or density as the primary causative mechanism predict that performance should be affected by this change in sparseness. In addition, the counting portion of the enumeration task could be adversely affected by the wider field of view as attending to a larger field of view reduces the amount of resources available at any particular location in space and increases the probability that the items will be inaccurately enumerated. The comparison of the two conditions may therefore help in distinguishing between the various accounts of enumeration performance. Experiments 1 and 2 were partially reported in Green and Bavelier (2003).
2.1. Method

2.1.1. Subjects

Twenty-six males with normal or corrected-to-normal vision were placed into one of two groups, VGP or NVGP, based upon their responses to a questionnaire given prior to the experiment. Only males underwent testing because of the relative paucity of females with sufficient video game experience.

The criterion to be considered a VGP was a minimum of 3-4 days a week of action video game usage for the previous six months. Thirteen right-handed males with a mean age of 19.4 years fell into this category. Ten of the thirteen subjects reported daily video game usage for at least the previous six months, while the remaining three reported playing several times a week for the same time span. A highly abridged list of the games reported as played includes: Grand Theft Auto, Half-Life, Counter-Strike, Marvel vs. Capcom, Rogue Speare, and Super Mario Kart.

The criterion to be considered a NVGP was little, although preferably no, video game usage in the past six months. Thirteen males (eleven right- and two left-handed) with a mean age of 19.3 years fell into this category. Eleven of the thirteen members reported no video game experience whatsoever in the past year. The remaining two quantified their video game experience as once per month or less.

Written informed consent was obtained from each subject and each subject was paid $7.50 for each hour of participation.
2.1.2. Stimuli and Procedure

Subjects viewed the display binocularly with their head positioned in a chin rest at a test distance of 60 cm. Each trial began with the presentation of a small white fixation cross in the center of a dark screen. After 500 ms, a stimulus consisting of a random number of white squares was presented for 50 ms (between 1 and 12 squares each subtending .5 x .5 degrees). Subjects were then allowed to respond. This study did not use the typical vocal response of enumeration studies; instead subjects were asked to press the number on the keyboard corresponding to the number of squares they believed were presented. Subjects were instructed to respond by a keyboard press as quickly as possible while maintaining accuracy.

For the response, the numbers 1-12 were placed on the keyboard above their respective keys (10 on the 0, 11 on the -, and 12 on the +). Subjects were instructed to use whatever key pressing strategy was most comfortable. Most used the four fingers of the left hand on 1-4, the four fingers of the right hand for 5-8 and moved the right hand for numbers above 8. However, some subjects used different strategies.

Each subject underwent two experimental blocks of 360 trials each (1-12 items presented, 30 repetitions of each number of items, pseudorandom presentation). The only difference between the two experimental blocks was the extent of the visual field over which the white squares could be presented. In the narrow field of view condition, the white squares were presented in a random location within an invisible boundary square in the center of the screen measuring 5° x 5°. It was also
constrained such that there was at least a .5° separation between adjacent squares. In the wide field of view condition, the squares could be presented over a much wider field of view (20° x 20°). It should be noted that because the squares were kept at the same size in the two field of view conditions, the square density was greater in the narrow than in the wide field of view condition.

The order of the two conditions was counterbalanced. No effect of order was found (p > .7) and thus will not be discussed further.

2.2. Results

Four measures of performance will be discussed for each experiment – accuracy breakpoint, percent correct, average response and RT.

Enumeration studies rely typically on reaction time analyses. In our case, however, the use of a keyboard response, rather than a vocal response, makes the interpretation of RT difficult. Although subjects were trained in advance in typing the key that corresponded to a given number, it is likely that this method of response nevertheless introduced additional variability in the measurement of RTs that may not be consistent across the two groups. Video game players are known to have faster key press RTs (Orosy-Fildes & Allan, 1989) and because there were 12 possible response keys to choose from, issues such as working memory (the ability of a subject to remember which key each finger was resting upon) and strategy (where the fingers were centered, use of both hands versus only one hand, etc.) could have played a role. With these caveats in mind, the RT data will be presented last.
The accuracy breakpoint refers to the point at which the discontinuity in accuracy occurs (the point where the elbow forms in the function). As previously discussed, accuracy performance during enumeration paradigms appears well approximated by a bilinear model. To determine an individual subject’s accuracy breakpoint, their percent correct data was fit to a bilinear model using the least squares method. As our goal was to gain a quantitative measure of the breakpoint, as well as a measure of the slope of the two linear components that intersect at the breakpoint, only the data points for 1-8 items were entered into the model. This range was chosen based on previous evidence that the breakpoint lies approximately in the middle of this span, as well as to minimize the contribution of processes such as guessing, estimation biases, and strategy that may come into play for greater numbers of items. Each subject’s curve was modeled as an intersection between two linear components; the first component was constrained to have a slope very near zero (maximum slope of 3% per item) while the second component was modeled as linearly increasing (as the data is plotted in terms of error rate, not percent correct) with the slope allowed full room to vary in order to best fit the data. The output of the model was therefore the slope of the two lines as well as the accuracy breakpoint – the point at which the two lines intersected. Although the accuracy breakpoint has classically been well mirrored by the subitizing span, or the shallow near zero slope of the reaction time data curve, the use of the term subitizing will be reserved for RT analyses in this paper, as Experiment 3 will reveal for the first time a dissociation between accuracy and RT measures of breakpoints.
The dependent variable percent correct is self-explanatory.

The last dependent variable is average response, as previous models have hypothesized a prominent role of estimation ability in enumeration performance (Krueger, 1982). Average response refers to the average response the subject made when presented with a given number of squares. Perfect performance corresponds to a line starting at the origin with a slope of one. Overestimation leads to a deviation above the perfect line, whereas underestimation leads to a digression below the perfect line.

Accuracy breakpoint was analyzed in a 2(VGP status: VGP/NVGP) x 2(field of view: narrow/wide) ANOVA while percent correct, RT, and average response were each initially analyzed in a 2(VGP status: VGP/NVGP) x 2(field of view: narrow/wide) x 12 (number of squares) ANOVA.

2.2.1. Overall Analyses

2.2.1.1. Accuracy Breakpoint

The analysis of accuracy breakpoint revealed a clear main effect of VGP status with VGPs switching about 2 items beyond the accuracy breakpoint of NVGPs, VGP: 5.0 +/- .2 squares, NVGP: 3.0 +/- .3 squares, F(1,24) = 27.7, p < .001 (Figure 1A). No interactions with field of view were observed. Separate analysis of the slope of each component yielded no main effect of VGP status, in particular, the lack of effect for the second slope indicates that both groups fall-off at a similar rate beyond
their inflection point in both field of view conditions. While there was no effect of field of view in the analysis of the slope of the first component, a main effect of field of view was observed in the analysis of the second component, with the wide field of view having a significantly greater slope than the narrow field of view, wide: 13.7 +/- 0.7%, narrow: 11.1 +/- 0.7%, \( F(1,24) = 7.3, p = .013 \). Since the accuracy breakpoint was equivalent in the two field of view conditions, it appears that the ability to apprehend low numerosity is unperturbed by the size and density of the display, whereas the greater slope of the second component in the wide field of view condition suggests that the ability to count higher numbers of squares falls off more quickly in the wide field of view condition.

2.2.1.2. Percent Correct

The expected strong main effect of number of squares was observed, with performance decreasing with increasing numerosity, \( F(11,264) = 202.8, p < .001 \). Importantly, a main effect of VGP status was observed with VGPs outperforming NVGPs, VGP: 75.5% +/- 1.4% correct, NVGP: 62.4% +/- 1.8% correct, \( F(1,24) = 9.1, p = .006 \) (Figure 1A). Furthermore, the predicted VGP status x number of squares interaction was also found with both groups performing similarly well for low numbers (1-3), but VGPs outperforming NVGPs as the number of squares exceeded 3, \( F(11,264) = 3.3, p < .001 \).

Also, performance was better in the narrow field of view condition than in the wide field of view condition, narrow: 71.5 +/- 1.5% correct, wide: 66.4 +/- 1.8%
This main effect can largely be attributed to differences in performance for the very large numbers (10-12) between the two fields of view which was further reflected in the observed interaction of field of view and number of squares, F(11,264) = 2.5, p = .005.

Finally, a VGP status x field of view x number of squares interaction, F(11,264) = 2.02, p = .03 will be further explored in analyses separated by field of view, but appeared to be rooted in disproportionately poor performance by NVGPs on even relatively low numbers of squares during the wide field of view condition.

### 2.2.1.3 Average Response

The expected main effect of number of squares, with average response increasing with increasing numerosity was observed, F(11,264) = 1398.3, p < .001.

VGP status and number of squares interacted with both groups having similar average responses for low number of items, but NVGPs beginning to consistently underestimate the number of items before VGPs did, F(11,264) = 7.1, p < .001 (Figure 1B). Field of view also interacted with number of squares, as subjects began to consistently underestimate the number of items earlier in the wide field of view (around 8 items) than in the narrow field of view (around 10 items) F(11,264) = 5.3, p < .001. Finally, a VGP status x field of view x number of squares interaction prompted analyses separated by field of view discussed subsequently, F(11,264) = 2.4, p = .007.
Despite the previously mentioned potential pitfalls with the RT data, the statistics were in harmony with the percent correct data. A main effect of number of squares was observed with subjects taking longer for greater numbers of squares, $F(11,264) = 101.8$, $p < .001$. The main effect of VGP status on RT was non-significant ($p > .05$). However, a VGP status x number of squares interaction was observed, rooted in the fact that VGPs were faster than NVGPs for low number of items (1-2) but then became much slower for greater number of items, $F(11,264) = 3.3$, $p < .001$ (Figure 1C).

A main effect of field of view was also observed with subjects taking longer in the narrow field of view condition than the wide field of view condition, narrow: $1.91+/- .05$ s, wide: $1.7 +/-.05$ s, $F(1,24) = 14.7$, $p = .001$. The effect of field of view further interacted with number of squares, as RTs were relatively equivalent for low numbers of squares, but much longer for larger numbers of squares in the narrow field of view condition, $F(11,264) = 6.2$, $p < .001$. Finally, a VGP status x field of view x number of squares interaction $F(11,264) = 1.9$, $p < .05$, was caused by VGPs taking a disproportionately long time to respond in the narrow field of view condition when many squares were presented.

Because of the observed interactions outlined above, the two field of view conditions were further analyzed separately by field of view along the three components revealing field of view by video game status interactions (percent correct, average response, RT).
Figure 1 - Results

A. **Enumeration accuracy - % correct and breakpoint:** VGPs clearly outperform NVGPs on the enumeration task. The VGP breakpoint (the elbow in the regression line) is approximately 2 items beyond that seen in the NVGPs. Furthermore, the VGP advantage continues to hold even for high numerosity.

B. **Average response:** NVGPs begin to underestimate the true number of items (bar above zero) about 2 items before VGPs. The relative inaccuracy of the NVGPs compared to VGPs can also be seen for all numbers of squares as the VGP bar does not begin to deviate from zero (on average perfectly correct) until around 10 items.

C. **RTs:** NVGPs and VGPs have very similar RTs for low numerosity, VGPs being slightly faster, but as the number of items to enumerate increases, the VGP RT becomes much greater than NVGPs. This is unlikely to represent a speed/accuracy trade-off in the conventional sense, in that longer RTs allow for more information to decay from visual memory. Instead, these results may indicate a more stable visual memory representation in the VGP population.

**Note:** (in all figures: error bars denote SEM, * = p < .05, ** = p < .001)

2.2.2 Narrow Field of View Analyses

2.2.2.1. Percent Correct

Main effects of number of squares and VGP status were again seen, number of squares: F(11,264) = 148.7, p < .001; VGP status: F(1,24) = 11.9, p = .002, with
accuracy decreasing with increasing numerosity and VGPs again outperforming NVGs by a large margin, VGP: 78.2+/−1.9% correct, NVGP: 64.8+/−2.3% correct. A VGP status x number of squares interaction, F(11, 264) = 2.6, p = .004, outlined identical effects as seen in the main ANOVA and is captured by the difference in accuracy breakpoint, with both groups performing similarly well for low numbers of items (1-3 items p > .07) but VGPs significantly (p < .05) outperforming NVGs for all subsequent numbers of items except for 10 squares (p = .055).

2.2.2.2. Average Response

A main effect of number of squares was again observed, F(11, 264) = 1358.2, p < .001. A VGP status x number interaction closely followed the main ANOVA with both groups giving very similar average responses for low numbers of items, but with VGPs making better estimates for higher numbers, F(11,264) = 4.2, p < .001.

2.2.2.3. RT

A main effect of number of squares was observed F(11,264) = 86.9, p < .001. A VGP status x number interaction with VGPs responding faster for small numbers of squares, but becoming slower than NVGs when greater numbers of squares were presented, F(11, 264) = 2.8, p < .001.
2.2.3 Wide Field of View Analyses

2.2.3.1. Percent Correct

A main effect of number of squares was observed with performance as always decreasing with increasing numbers of squares, $F(11,264) = 135.3$, $p < .001$. A main effect of VGP status was again observed, VGP: $72.9+/2.1\%$ correct, NVGP: $60.0+/2.7\%$ correct, $F(1,24) = 5.9$, $p = .02$. And a VGP status x number of squares interaction again highlights the differences seen in accuracy breakpoint with the VGP advantage in accuracy only becoming evident for items above 3, $F(11,264) = 3.3$, $p < .001$.

2.2.3.2. Average Response

Main effects of number of squares, $F(11,264) = 1069.4$, $p < .001$ and a VGP status x number of squares, $F(11,264) = 8.3$, $p < .001$ were observed.

2.2.3.3. RT

A main effect of number of squares was observed, $F(11,264) = 76.8$, $p < .001$. Also, as in the narrow field of view analysis, a VGP status x number of squares interaction, $F(11,264) = 3.4$, $p < .001$, reflected the fact that VGPs were faster than NVGPs for low numbers, but slower for higher numbers.
2.3. **Discussion**

The main finding of Experiment 1 is that VGPs enumerate more accurately than NVGPs. VGPs are able to enumerate with high accuracy about two items more than NVGPs, as exemplified by the reliable difference in accuracy breakpoint between the two populations. Beyond the accuracy breakpoint, the estimate of the number of objects presented remained more accurate in VGPs than for NVGPs. Both groups underestimated the true value at high numerosities, an expected result since subjects were limited in their response to up to 12 items (although see Mandler and Shebo, 1982, who also report systematic underestimation of numerosity beginning at set size of 9 when the maximum number of items was 20). However, the results reveal an additional pattern of underestimation that differs between the two groups. At high numerosities (9 and above), NVGPs systematically underestimated the number of squares presented to a greater extent than VGPs, and were consistently faster than VGPs. While this result takes the form of a simple speed/accuracy trade-off, there are other possible mechanistic explanations for it, such as faster loss of information in memory in NVGPs than in VGPs. If the ability to count accurately from short term memory decays faster in NVGPs than in VGPs, NVGPs’ responses would show greater underestimation of numerosity as well as faster RTs as the number of items they could enumerate is smaller. This point will be discussed further in the General Discussion.

Experiment 1 also reveals a systematic effect of the size of the field of view on performance at high numerosity. The wide field of view condition led to more
errors, systematic underestimation and faster RTs than the narrow field of view condition suggesting an important role for the spread of attention in the enumeration of high numerosities. Importantly, display size did not affect performance at low numerosity, as exemplified by the comparable accuracy breakpoints found in the two field of view conditions. The different sensitivity of low and high numerosity displays to the field of view condition is further documented by the interactions between field of view and number of squares observed in percent correct, average response, and RT analyses. This finding lends support to the view that two distinct sets of constraints are underlying performance for low and high numerosity displays in the enumeration task. In this paradigm, field of view co-varies with density, with the wide field of view condition corresponding to lower density displays than the narrow field of view condition. The data pattern, however, runs counter to that predicted by models that suppose that canonical patterns or density may be at the source of the low/high numerosities split. Indeed, such models predict better performance for low density than high density displays, a prediction which runs contrary to the finding of greater error in the wide condition and equal accuracy breakpoint across conditions.

Accuracy breakpoints and RTs for low numerosities were similar for VGPs and NVGPs across fields of view, indicating that the advantage conferred by video game playing applies equally to narrow and wide displays. Thus, the effects of game playing are not narrow to peripheral locations, but are also visible more centrally. This is consistent with the fact that video game play, in addition to necessitating constant peripheral monitoring, also commonly requires the subject to actively attend
to the center of the visual field, which normally contains the primary object of interest.

Experiment 1 demonstrates that expert video game players outperform non-players in the enumeration task by having both an extended accuracy breakpoint and greater accuracy in the counting range. It is unclear, however, whether the very act of playing is a causative factor in the improved enumeration performance of VGPs or whether selecting for video game players inherently biased us in selecting individuals with better visual skills. After all, individuals with good visual abilities probably have an advantage when it comes to playing video games, and thus may be more prone to become video game players than individuals with poor visual skills. This issue is addressed in Experiment 2.

3. Experiment 2

Results from Experiment 1 indicate enhanced enumeration performance in VGPs. While our hypothesis predicts that extensive video game playing leads to this enhanced skill, it could also be the case that VGPs have inherently better perceptual skills and/or were somehow genetically endowed with greater attentional abilities. Another explanation is that what is learned during video game play is not necessarily perceptual in nature, but is instead a perceptual-motor skill. Although the use of percent correct as our primary dependent measure in Experiment 1 was chosen to minimize the effect of visuo-motor facilitation in our measures, it is possible that by
alleviating the demands of the motor response, video game playing allows VGPs to have more “left-over” resources available to process the sensory stimulus.

To control for these two possibilities, NVGPs underwent video game training in Experiment 2. Some underwent video game training using an action video game, whereas others played a game that placed heavy demands on visuo-motor coordination but did not tap aspects of visual attention of interest in Experiment 1. If the differences observed in Experiment 1 are due to the demands of action video game playing and not due to better visuo-motor control or genetically endowed traits, a notable improvement in the enumeration task should be observed following training in the action game trainees, but not in the control game trainees.

Finally, while Experiment 1 employed only males as subjects, by using an equal number of males and females in Experiment 2, we can test whether the effects of video game play are similar across gender.

3.1. Method

3.1.1. Subjects

The study initially enrolled 20 NVGPs that were equally and randomly divided between the experimental and the control group (5 males/5 females in each group). The criteria for NVGP remained the same as in Experiment 1. All subjects underwent training as described below. One male from the experimental group and one male and one female from the control group did not finish training. Thus 5 females and 4 males (mean age = 20.4, 8 right-handed) made up the final
experimental group, while the final control group consisted of 4 females and 4 males (mean age = 19.7, all right handed).

3.1.2. Pre-Test

As differences between the two fields of view were minimal with respect to the effect of video game play, and because of two additional experimental tasks, not relevant to this paper, subjects completed only the narrow field of view condition.

3.1.3. Apparatus

**Testing:**

The apparatus was identical to that described in Experiment 1.

**Training:**

The control group played on the same experimental setup (computer, monitor, refresh, and resolution) the experiment itself was conducted on. The action group played on one of two Dell computers each equipped with 20” flat-panel LCD monitors.

3.1.4. Training Stimuli and Procedure

For both groups, training consisted of playing the pre-determined video game for one hour per day for ten out of fifteen days. The nine members of the experimental group played the game Medal of Honor: Allied Assault (henceforth referred to as the action video game). This game was chosen to be similar to those
played by our VGPs from Experiment 1. It has a relatively simple interface, uses first-person point of view and requires effective monitoring of the entire monitor display (extent from fixation about 13°-height x 16°-width). Subjects played the game straight through for the first eight days, beginning each day at the point where they had finished the previous day. On days nine and ten they returned to the beginning of the game in order to quantitatively measure their improvement by comparing performance over mission 1 during their first (days 1-2) and last (days 9-10) playing.

The eight members of the control group played the game Tetris, which was displayed to cover the entire extent of the screen. However, because Tetris adds graphics on the side of the screen, the effective game area extended 13°-height x 9°-width from fixation. This game was selected to control for the effect of improved visuo-motor coordination, while placing little demand on the simultaneous processing of multiple items. Accordingly, the version of Tetris on which subjects were trained had the preview block option turned off. Furthermore, this group serves as a control for any possible effects due to familiarity with the task (test-retest). In a manner analogous to the action-trained group, improvement was quantitatively measured by comparing performance on day 1 versus that on day 10.

3.1.5. Post-Test

After video game training, subjects were re-tested on the same experiment as in the pre-test, as well as the other two aforementioned unrelated tasks (Green & Bavelier, 2003).
3.2. Results

3.2.1. Game Play

In order to assess game improvement, two different measures were taken for each group during the first and last playing. Improvement measures were determined by computing the difference between post-training performance and pre-training performance divided by pre-training performance.

For the action game, the two measures were shooting accuracy (number of targets hit/total number of shots fired) and the number of deaths before completing the first mission. In both measures, subjects showed improved performance following training. For shooting accuracy a 68% improvement was seen. In terms of the number of deaths to complete mission one, a 42% improvement was observed.

For the control game, the two measures were high score (highest score achieved in one level) and highest level reached. Again, all subjects improved following training (high score = 71% improvement, highest level reached = 67% improvement).

These results establish that both groups were engaged in their training and showed improvement on the training task.
3.2.2 Enumeration Results

Similar analyses as in Experiment 1 were carried out. In the case of percent correct, average response, and RT each of the factors was initially analyzed in a 2(trained game: action/control) x 2 (test: pre/post) x 12 (number of squares) ANOVA and in the case of accuracy breakpoint 2 (trained game: action/control) x 2 (test: pre/post) ANOVA. Gender was not included as a factor, as a preliminary analysis indicated there was no main effect of gender, nor were there any interactions with gender in any of the effects observed.

3.2.2.1. Accuracy Breakpoint

A main effect of test was observed indicating a slight increase in accuracy breakpoint at post-test, pre:3.0+/-.15 squares, post:3.8+/-.31 squares, F(1,15) = 6.4, p = .02. Importantly for our hypothesis, a trained game x test interaction was also observed, caused by a greater post-test improvement in the action game than in the control game, F(1,15) = 6.1, p = .03. In analyses separated by trained game, a main effect of test was observed in only the action group, F(1,8) = 10.6, p = .01, not in the control group (p > .9), indicating that training had a significant effect on accuracy breakpoint in the action game alone. No effect was observed on the slope of either component (all p’s > .2) (Figures 2A and 2B).
Figure 2

A. Enumeration accuracy - % correct and breakpoint – Action game: The action group demonstrates a clear increase both in breakpoint (by around 1.5 squares) and in overall accuracy.

B. Enumeration accuracy - % correct and breakpoint – Control game: The control group showed no sign of improvement after training, thus ruling out test-retest improvements or improvements in visuo-motor control as possible hypotheses to explain the improvement in the action group.

3.2.2.2. Percent Correct

A main effect of number of squares was observed as expected, F(11,165) = 111.6, p < .001. A main effect of test was also observed with subjects being more accurate post-test than pre-test, pre: 66.9+/−2.1% correct, post: 72.2+/−1.9% correct, F(1,15) = 23.0, p < .001. Importantly, an interaction was observed between trained game and test caused by the action group showing greater improvement than the
control group, $F(1,15) = 15.4$, $p < .001$. Furthermore, significant interactions between test and number of squares, $F(11,165) = 2.1$, $p = .02$, and between trained game, test and number of squares, $F(11,165) = 2.4$, $p = .008$ reveal a similar pattern as in Experiment 1 (Figures 2A and 2B). Following training, the action group was as accurate as the control group for low numbers of squares, but outperformed the control group on higher numbers.

3.2.2.3. Average Response

A main effect of number of squares was observed, $F(11,165) = 5473.0$, $p < .001$, as well as the expected interaction between test and number of squares, $F(11,165) = 4.2$, $p < .001$, indicating more accurate average responses following training. Importantly, a trained game x test x number of squares, $F(11,165) = 2.4$, $p = .008$ revealed that the bulk of the changes in accuracy were in the action group. As was seen with the VGPs in Experiment 1, the trained group became better estimators of large numbers of items following training.

3.2.2.4. RT

The only effect was a main effect of number of squares, $F(11,165) = 48.4$, $p < .001$. This is unsurprising however because of the way we required subjects to respond.
3.3. Discussion

Experiment 2 establishes that even relatively little action video game play (10 hours) is sufficient to alter enumeration performance. In fact, similar changes to those described in Experiment 1, albeit of lesser amplitude, were observed in action game trainees for the main aspects of the task. These include a shift of accuracy breakpoint as well as greater accuracy and better estimation for numerosities above the accuracy breakpoint. This conclusively demonstrates that action video game play is at the source of the improved performance on the enumeration task. Furthermore, the fact that no effect of gender was observed, indicates that the consequences of video game play are not sex dependent.

Taken together, Experiments 1 and 2 indicate that action video game play induces two main changes in performance on the enumeration task. First, measures of accuracy breakpoint show that gamers switch from the shallow to the steep component of the enumeration accuracy curve beyond the point where control subjects switch. Second, beyond the accuracy breakpoint, measures of percent correct and average response indicate greater accuracy in gamers than their controls.

When considering the underlying mechanism for these changes, it is important to recognize that the estimation of the subitizing range in enumeration studies has typically relied on RT measures rather than accuracy. In fact, the number of items that can be apprehended in a fast and parallel manner classically defines the subitizing range. Although accuracy measures have typically resulted in a similar pattern of
results to RT measures in previous studies, we cannot rule out the possibility that the
greater accuracy breakpoint in gamers may be due to more accurate counting rather
than an increase in the number of objects that can be immediately apprehended.
Whether gaming does modify the ability to apprehend more objects at once remains
an open question that will be addressed in Experiment 3.

4. Experiment 3

A few caveats in the interpretation of Experiment 1 were addressed in
Experiment 3. First, subjects gave vocal responses thus allowing precise
measurement of RT. Second, afterimages may have played a role in the effects of
gaming reported in Experiments 1 and 2, as the stimuli display was not masked.
Although Simon and Vaishnavi (1996) reported no substantial increase in the
subitizing range when the items were presented as afterimages (thus allowing up to
60 seconds of viewing), because their primary dependent measure was accuracy
rather than reaction time, caution dictated that in Experiment 3, a backwards pattern
mask be employed, specifically designed to eliminate afterimages as a viable source
of information that could be used unequally by the two groups.
4.1. Method

4.1.1. Subjects

Twenty-two males (none of which had participated in Experiment 1 or 2) with normal or corrected vision were again placed into one of two groups, VGP or NVGP, based upon their responses to a questionnaire, slightly modified from that used in Experiment 1. The questionnaire and criteria to be considered a VGP were altered slightly to allow a more accurate measure of the amount of time each subject spent playing specific types of video games. The questionnaire asked the number of hours (0, 0-1, 1-2, 3-5, 5-10, 10+) spent playing each of several types of video games (action, sports, fantasy, role playing, other) per week. To be considered a video game player, a subject needed a minimum of 5 hours a week of action video game usage for the previous six months. Eleven right-handed males with a mean age of 19.1 years fell into this category.

The criterion to be considered a non-video game player was zero hours per week of action games. Eleven right-handed males with a mean age of 20.3 years fell into this category.

Written informed consent was obtained from each subject and each subject was paid $7.50 for each hour of participation.
4.1.2. *Stimuli and Procedure*

The stimulus/procedure was identical to that described in the narrow field of view portion of Experiment 1 except for four changes. First, to rule out any role of afterimages, a backwards pattern mask was presented for 500 ms following the presentation of the squares. The mask consisted of a black and white checkerboard pattern of the same contrast/luminance as the stimulus, designed to eliminate afterimages as a potential source of information. The second change was that the presentation time was increased to 100 ms – a change necessitated by the addition of the mask. Third, the task was shortened by including only 1-10 squares. Finally, the most important change was the method of response. The voice onset time was used to measure RT. The trials were recorded and scored for accuracy offline. If the subject hesitated or changed their response (“thre…no…four”), the trial was omitted from RT and accuracy results (this circumstance occurred on less than 1% of all trials).

4.2. *Results*

The results were analyzed using the same four dependent measures (accuracy breakpoint, percent correct, average response, RT) as well as a new component – RT breakpoint, which was computed in the same manner as the accuracy breakpoint.

4.2.1. *Accuracy Breakpoint*

There was a main effect of VGP status on the breakpoint for accuracy with VGPs again having a 2.5 item advantage over NVGPs, VGP: 5.0+/-.3 squares,
NVGP: 2.5+/-.32 squares, F(1,20) = 33.2, p < .001 (Figure 3A). Again, there was no significant difference in the slope of either component of the model (p’s > .08). This result replicates those of Experiments 1 and 2.
4.2.2. Percent Correct

A main effect of increased errors with increasing number of squares was observed, F(9,180) = 119.1, p < .001. More importantly, there was a main effect of VGP status, VGP: 77.4+/−2.5% correct, NVGP: 60.5+/−3.2% correct, F(1,20) = 27.8, p < .001 and a VGP status x number of squares interaction, F(9,180) = 5.0, p < .001 (Figure 3A). As seen in Experiment 1, this is due to the two groups being roughly

Figure 3 - Results

A. Enumeration accuracy - % correct and breakpoint: As was seen in Experiment 1, VGPs show a clear advantage both in breakpoint as well as overall accuracy.

B. RT: Also as was seen in Experiment 1, VGPs and NVGPs have extremely similar RTs for low numbers of items, but VGPs begin to take significantly longer than NVGPs as the number of items to be enumerated increases. The RT breakpoint, which offers an index of the number of items that can be instantaneously apprehended, is similar in both groups.
equivalent at small numbers of squares (p > .05 for 2 and 3 squares), but diverging for larger numbers with VGPs retaining high accuracy for even large numbers of squares (VGPs more accurate than NVGPs, p < .05 for 4-9 squares).

4.2.3. Average Response

There was only a main effect of squares, F(9,180) = 1792.6, p < .001. There was no main effect of VGP status or any interactions with VGP status, indicating that on average the two groups performed quite similarly. This difference with the previous experiments is not surprising as Experiment 3 included up to 10 squares while the significant difference in average response were most marked at very high numerosity (11-12 squares) in the two previous experiments.

4.2.4. RT

An ANOVA on the simple RT scores revealed a main effect of number of squares, F(9,180) = 155.5, p < .001 and a VGP status x number of squares interaction, F(9,180) = 12.0, p < .001 with the VGPs again starting slightly (although not significantly) faster for low numbers of squares but becoming significantly slower (p < .05) than NVGPs for high numbers of squares (8-10) (Figure 3B).

4.2.5. RT Breakpoint

In contrast to the accuracy breakpoint, no main effect of VGP status was found for RT breakpoint, VGPs: 3.4 +/- .1 items, NVGPs: 3.0+/-.2 items, F(1,20) =
2.8, p = .1. Although the trend appears in the same direction as the accuracy breakpoint, the size in terms of number of squares is certainly much smaller than has been observed in accuracy (Figure 3B). No effect of VGP status was seen in the slope of either component (p’s > .5).

4.3. Discussion

The main finding of Experiment 3 is that there is a difference in accuracy breakpoint between gamers and non-gamers despite similar RT breakpoints. Clearly the accuracy breakpoint of the VGP population does not reflect the “true” number of items that can be immediately apprehended. Instead, it is apparent that despite near perfect accuracy for up to five items in the VGP group, the RTs for four and five squares are slower than that for one to three items. This finding provides the first large dissociation of RT and accuracy on an enumeration task. It has generally been taken for granted that when subjects begin to “count,” they begin to lose information (Sperling, 1960). The more items that are presented, the longer subjects need to count, and the less accurate they become. However, VGPs are apparently counting for four and five dots (as demonstrated by the RT data), while their accuracy continues to be nearly perfect.

This enhancement in counting ability is also seen in the large differences in accuracy and RT between VGPs and NVGPs for greater numbers of items. These results suggest that the VGPs continue to successfully “read-off” the items from their visual memory after the NVGPs have made their best attempt. The correlation
between enumeration performance and working memory ability has been previously demonstrated in the literature (Tuholski, Engle, & Baylis, 2001). Subjects that performed poorly on a working memory task also performed poorly on the counting portion of the enumeration paradigm while no differences were observed in the subitizing span. It therefore seems most likely that what is truly being altered by VGP play is at the level of counting, rather than at the level that mediates immediate apprehension of numerosity.

While it is clear that the capacity of the immediate apprehension mechanism (or in other words the subitizing range defined by the RT breakpoint) in the enumeration task is similar in VGPs and NVGPs, what is left open is whether VGPs can simultaneously track more items than NVGPs. While some researchers have suggested that there may be a connection between the number of items that can be automatically enumerated and the number of items that can be tracked, it is not necessary that they be rooted in the same mechanism. To more directly address this question we made use of the multiple object tracking (MOT) paradigm (Pylyshyn, 1989) which requires subjects to dynamically allocate attention to multiple objects and sustain that attention for several seconds.

5. Experiment 4

In our version of the MOT paradigm, subjects view a number of randomly moving circles. At the beginning of the trial, some subset of the circles is
cued. The cues then disappear and subjects are required to keep track of the circles that were cued (now visually indistinguishable from uncued circles) as they continue to move randomly about the screen. After several seconds of tracking, one of the circles is highlighted and the subject must make a yes (was cued)/ no (was not cued) decision. This method of response, rather than the more typical method of asking the subject to indicate each of the initially cued objects, was employed to minimize the role of working memory in the response process, and in doing so gain a cleaner measure of the number of items that can be successfully tracked.

While previous theories have suggested a preattentive link between subitizing and MOT performance (Pylyshyn, 1989), it is generally accepted that there is a large dynamic attentional component to the MOT task as well (Scholl, Pylyshyn, & Feldman, 2001). The task requires active allocation of visual attention in order to successfully track targets embedded in a field of competing, and visually identical, distracting elements. Several studies have demonstrated that attention is actually split between the items during tracking (Sears & Pylyshyn, 2000). Furthermore, neuroimaging has revealed activation in what are thought of as attentional areas – parietal and frontal regions – when subjects perform a MOT task (Culham et al., 1998; Culham, Cavanagh, & Kanwisher, 2001).

While the subitizing span offers a glimpse at the number of items that can be immediately apprehended, the MOT paradigm offers a good measure of the number of items than can be simultaneously tracked, and some have suggested, simultaneously attended, over a period of time. We therefore decided to use the MOT
task to clarify whether VGPs can actually track more items at once as well as examine what, if any, relationship exists between multiple object tracking and enumeration performance.

5.1. Method

5.1.1. Participants

Twenty males (none of whom had participated in previous experiments reported in this paper) with normal or corrected vision were again placed into one of two groups, VGP or NVGP, in a manner identical to that used in Experiment 3. Ten right-handed males with a mean age of 19.4 years were placed into the VGP category, while ten right-handed males with a mean age of 20.6 years were placed into the NVGP category. None of the participants was red/green colorblind.

Written informed consent was obtained from each subject and each subject was paid $7.50 for each hour of participation.

5.1.2. Stimuli and Procedure

Each observer viewed the display binocularly with his head positioned in a chin rest at a test distance of 57 cm. Subjects were instructed to fixate within a center ring (radius = .25 deg). Subjects pressed a key to begin each trial. Each trial began with 16 circles (radius .5 deg) moving randomly on a circular gray background (radius of circular background = 10 deg) at a rate of 5 deg/sec. The circles repelled
one another before contact (.5 deg minimum separation), and were repelled by the outer edges of the background and by the center fixation circle. At the start of the trial, some number (1-7) of these circles were cued (colored red) while the rest were green. During this time the subject was instructed to attend to the red circles, as they would shortly change to green after which time the subject had to track the circles that were previously cued. After 2 seconds the cued circles changed to green, leaving all 16 circles visually indistinguishable. The subject had to track the cued circles for 5 seconds after which one of the 16 circles turned white (probe). The subject had to press either a yes or no key in response to whether the probe circle was one of the originally cued circles. The probe circle was one of the originally cued circles 50% of the time. Each number of cued circles (1-7) was presented 20 times (10 yes, 10 no) for a total of 140 trials. In many other instantiations of this paradigm subjects were not eye-tracked (Pylyshyn, 2004), or eye-movements were found to have few implications (Pylyshyn & Storm, 1988). However, because of the use of more objects than most MOT paradigms (up to 7) and the possibility that the two groups could differ in eye movement strategies, subjects were eye-tracked and trials where they made an eye-movement greater than 1° from center were omitted from later analyses. This happened fairly rarely (around 6% of trials) and did not differ between groups nor did the occurrence of eye-movements appear to affect accuracy or affect accuracy differently between the two groups (p > .4).
5.2. Results

The results were analyzed in a 2(VGP status: VGP/NVGP) x 7 (number of circles to track) ANOVA as earlier analyses had indicated there was no effect (p > .7) of whether the answer was yes or no (i.e. no response bias). As expected, a main effect of number of circles to track was found with accuracy decreasing with increasing number of circles, F(6,108) = 60.6, p < .001. Importantly, a main effect of VGP status, VGP:84.3+/−1.6% correct, NVGP:78.2+/−1.8% correct, F(1,18) = 9.2, p = .007 was observed indicating better performance in VGPs (Figure 4). As VGP status and number of circles to track did not interact, we can assume the VGP advantage was relatively equal across number of circles. Although there was no interaction of VGP status with the number of circles to track, individual analyses separated by number of circles to track were performed for comparison with following analyses and indicated a significant advantage (p < .05) for VGPs only for three to five circles to track and a marginally significant advantage at 6 circles to track (p = .07). At the ends of the spectrum (one circle to track or seven circles to track) the two groups were equivalent (p’s > .1).
Figure 4. Multiple object tracking performance

VGPs demonstrate a substantial increase in the accuracy with which multiple items can be tracked compared to NVGPs. The effect is most pronounced for 3-5 items to track.

5.3. Discussion

The results indicate that VGPs outperform NVGPs when it comes to tracking several objects over time. Unlike for enumeration accuracy and RT, there was no significant interaction between VGP status and number of items on MOT accuracy. However, the results of the two paradigms do appear qualitatively similar, with VGPs and NVGPs having comparable performance with relatively few items, the differences only emerging after some critical threshold in load is exceeded. The data is furthermore quite consistent with the recent findings of Trick and colleagues (Trick, Jaspers-Fayer, & Sethi, 2005) who reported that children (6-19 years old) who played action video games performed significantly better than non-action game playing children on a version of the multiple object tracking task. Before drawing
further conclusions, Experiment 5 investigates causation through a controlled training study.

6. Experiment 5

As in Experiment 2, it is critical to show a causative effect of video game play on MOT performance. In this experiment, a larger sample of NVGPs than in Experiment 2 was trained for 30 hours, three times as long as the training in Experiment 2. The choice of training time was determined by other tasks not reported in this paper.

6.1. Method

6.1.1. Subjects

The study enrolled 32 NVGPs that were equally and randomly divided between the experimental and the control group. The criteria for NVGP remained the same as in Experiment 4. All subjects underwent training as described below. In all 8, females and 8 males (mean age = 21.3, all right-handed) made up the final experimental group, while the final control group consisted of 9 females and 7 males (mean age = 21.0, 15 right-handed).
6.1.2. Apparatus

Testing:

The apparatus was identical to that described in Experiment 4.

Training:

Both groups played their respective games on 20” monitors. The action game group played on Dell FlatPanel displays, whereas the control group played on CRT monitors.

6.1.3. Training Stimuli and Procedure

For both groups, training consisted of playing the pre-determined video game for a total of 30 hours (maximum of 2 hours per day, minimum of 5 hours per week, maximum of 8 hours per week). The sixteen members of the experimental group played the game Unreal Tournament 2004 (henceforth referred to as the action video game), a different action game than previously used. This game was chosen to be similar to those played by our VGPs; it has a relatively simple interface, uses first-person point of view and requires effective monitoring of the entire visual field (extent from fixation about 13°-height x 16°-width). One source of confounding in the previous game used was the fact that players could learn the development of the story and develop efficient “wait and ambush” strategies. Unreal Tournament 2004 was chosen because there is no “script.” Instead, the game is controlled by the action of 32 AI agents rather than linear story development. Each hour session of the action game was divided into three 20-minute blocks. The difficulty of each block was
adjusted based upon the kill/death ratio. If in a block the player scored more than
twice as many kills than they had deaths, the difficulty level was increased one level.
Also, players were periodically re-tested on lower difficulty levels to quantitatively
assess improvement.

The sixteen members of the control group played the game Tetris, which was
displayed to cover the entire extent of the screen. As such, the field of view of the
Tetris game was actually slightly larger than that of the action game (which was the
same as in Experiment 2 - 13°x16°). The effective control game area extended 18°-
height x 13°-width from fixation. This game was selected to control for the effect of
improved visuo-motor coordination, while putting little demands on the processing of
multiple objects at once. Accordingly, the version of Tetris on which subjects were
trained had the preview block option turned off. In a manner analogous to the action-
trained group, improvement was quantitatively measured by comparing performance
on Day 1 versus that on Day 30.

6.1.4. Post-Test

After video game training, subjects were re-tested on the same experiment as
in the pre-test, as well as the other aforementioned unrelated tasks.
6.2. Results

6.2.1. Game Play

In order to assess game improvement, several measures (slightly different than those collected in Experiment 2) were used. However, as in Experiment 2, a percent change score was calculated for each of the measures.

For the action game, the two measures used were kills and deaths. For each of five levels of game difficulty (level five being the highest level that all players attained) the measure taken on their first playing of the level (which because of the way in which difficulty was progressed was not necessarily on the first day of training) was compared with their final playing of the level on Days 29-30. A substantial increase in number of kills, and decrease in number of deaths was seen at each difficulty level (Table 1).

For the control game, the average and median scores from Day 1 were compared with the same values on Day 30. As in the action game, the control players showed substantial improvements after training, the mean score improving by 323% and the median score by 359%.

As in Experiment 2, these results demonstrate that both groups were engaged in their training and showed improvement on the training task.
Table 1.

% Change

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<th>Deaths</th>
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<td>226.3</td>
<td>-64.1</td>
</tr>
<tr>
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</tr>
<tr>
<td>5</td>
<td>52.0</td>
<td>-32.3</td>
</tr>
</tbody>
</table>

6.2.2. MOT Performance

As in Experiment 2, no effect of gender was found in preliminary analyses, and as such, a 2(trained game: action/control) x 2(test: pre/post) x 7 (number of circles to track) ANOVA was run on accuracy. Again, only the trials where subjects did not break fixation were used (as in Experiment 4, eye-movements occurred in only approximately 5% of trials). Also, as previously observed, there was no effect of trained game or test on the number of eye movements (p > .6) and again eye-movements did not appear to affect accuracy.

The expected main effect of number of circles was found, F(6,180) = 155.6, p < .001 with accuracy decreasing with increasing numbers of circles to track. Also a main effect of test was found. pre: 75.3+/-1.2% correct, post:78.1+/-1.1% correct, F(1,30) = 5.1, p = .03. Most importantly for our hypothesis, however, an interaction between trained game and test was found, F(1,30) = 13.4, p = .001, indicating an unequal effect of training with the action group improving approximately 7.5% whereas the control group remained stable (Figures 5A and 5B).
Separating the groups, and running a 2(test:pre/post) x 7(number of circles) ANOVA revealed that only the action group showed a main effect of test, F(1,15) = 15.5, p = .001 as well as a test x number of circles interaction, F(6,90) = 2.3, p = .04. No effect of test or any interactions with test were found in the control group.

Figure 5

A. Multiple object tracking performance – Action game: Those subjects trained for 30 hours on an action video game show a marked improvement in their MOT performance as compared to their pre-test scores.

B. Multiple object tracking performance – Control game: Performance was identical before and after training in the control group. These results rule out test-retest as a source of confounding as well as increases in visuo-motor coordination.
6.3. Discussion

Experiment 5 demonstrates that relatively little video game play leads to substantial differences between groups and further demonstrates that the effects observed in Experiment 4 were not due to an inherent population bias.

7. General Discussion

The five experiments presented demonstrate that action video game play increases the number items that can be enumerated and tracked simultaneously over time. In Experiment 1, habitual action video game players display enhanced enumeration accuracy as compared to non-players. Experiment 2 establishes a causal role for action video game play, as NVGPs specifically trained on an action video game show similar enhancements. Experiment 3 demonstrates for the first time a dissociation between accuracy and reaction time measures of the subitizing range and establishes that action game playing does not modify the number of items that can be immediately apprehended, but rather enhances accurate counting. By making use of the multiple object tracking paradigm, Experiment 4 demonstrates an effect of VGP status on the ability to simultaneously track multiple objects over an extended period of time. The significant improvement in MOT performance seen in NVGPs after action game training in Experiment 5 demonstrates that action video game playing has a causal role in the measured effects.

Taken together, these five experiments suggest that action video game play may enhance some aspects of visual working memory. Several lines of evidence
point to this conclusion. First, VGPs demonstrate enhanced enumeration accuracy even at very high numerosities. Second, this enhanced accuracy is accompanied by an increase in RTs. Although this pattern would be the expected speed/accuracy trade-off in a system in which evidence accumulates over time but does not decay, the behavior under study relies on visual short-term memory in which representations are known to decrease in fidelity over time (Lee & Harris, 1996; Nilsson & Nelson, 1981; Sperling, 1960; Vogels & Orban, 1986). Delaying responses in studies of short-term memory does not lead to increased accuracy, but rather decreased accuracy as the memory representations have more time to fade. Thus, an alternative explanation seems warranted in which video game experience leads to enhancements in some aspect(s) of visual short-term memory. At least two alternatives are possible, one based on the durability of the memory trace and another on the speed of cycling through the memory trace. In the first case, action video game experience may lead to a more durable visual memory trace. This view would be consistent with the accuracy and reaction time data as well as the average response data where NVGPs begin to underestimate the number of squares well before the VGPs. One may speculate that after a certain period of time, NVGPs begin to “drop” items from visual memory, and at this point they simply make their best guess (from viewing Figures 1C and 3B, one can surmise that the NVGPs RTs appear to plateau at around eight items). Conversely, if it were the case that VGPs possess a more durable memory trace, they would be able to continue counting beyond the point where the NVGPs have stopped, which would account for both the greater accuracy and longer RTs. In
addition, this process may also sustain better tracking ability in the MOT by allowing more durable indexing of the dynamics of the objects to be tracked. However, a change in the fidelity of working memory representations in gamers is only one possible explanation for the observed results. A possible alternative hypothesizes that items in working memory are not necessarily kept simultaneously active, but instead one or a few items are constantly refreshed by a visit from a single focus of attention that moves from item to item in a cyclical fashion. As the speed of cycling through the items increases, the number of items that could be successfully maintained in short term memory would correspondingly increase. It is therefore possible to capture the present findings by assuming that the speed of cycling through memory traces is faster in VGPs than NVGPs, thus accounting for both the better counting and multiple object tracking performance. It should be further noted that factors unrelated to visual short-term memory, such as estimation ability and response bias, may also be at work in the enumeration paradigm, particularly for high numerosities. For instance, VGPs may be better able to judge when “the most” number of squares were presented, without necessarily being able to explicitly count each item. Also, as previously mentioned, because the maximum response was capped at some maximum value, a bias toward underestimation for the larger numerosities is created that may not be exactly equal in the two populations. A role for these differences in estimation/bias cannot be ruled out in interpreting some of the current results, especially at high numerosities, but they remain an unlikely explanation at lower
numerosities where the accuracy breakpoint is seen to shift between NVGPs and VGPs.

Beyond the effect of action video game play, these findings also lend strong support to models of enumeration performance that propose relatively distinct constraints for the two components of the enumeration performance curve. The dissociation between the accuracy and RT breakpoints in gamers is probably the most robust indication to-date of separate mechanisms, one that is sensitive to gaming (counting) and one that is not (subitizing). Similarly, the comparison of two different fields of view in Experiment 1 indicates that the mechanism(s) behind subitizing are less malleable that those behind counting. Indeed, in Experiment 1, performance over the subitizing range was quite similar across visual field conditions. Only in the counting range did performance differ with more accurate performance for the smaller field of view and denser displays. Models that suppose fundamental differences in the characteristics of the display (density, patterns, etc) between low and high numerosity stimuli cannot readily account for the overall pattern of results reported here, be it the effect of gaming or that of visual field size. Models of enumeration studies which posit two separate mechanisms - a fast and parallel one for subitizing and a more serial process for counting – more naturally capture the main findings. Under this view, the mechanism underlying subitizing would show little to no sensitivity to gaming or visual field size, and be highly specific to the enumeration of low numerosities. In contrast, the mechanism underlying counting would be much
more plastic, showing enhancement with gaming and be facilitated by the use of a small visual field.

Although some have suggested a link between immediate apprehension in the enumeration task and performance on the MOT paradigm (for instance, that they may both utilize preattentive mechanisms, or FINSTs - Pylyshyn, 1989; Trick & Pylyshyn, 1994), our results suggest that the subitizing range does not index the same process as the MOT. VGP s demonstrate no enhancement in subitizing range as measured by RT, but do demonstrate an enhancement in MOT ability. Also, while there is virtually no cost in terms of speed or accuracy moving from one to three items in the enumeration paradigm, a clear decrease in accuracy is observed with each additional item in the MOT paradigm (even moving from one to two items). Thus, it appears that the number of items that can be immediately apprehended as measured by RT measures in enumeration studies is not necessarily a good predictor of the number of items than can be simultaneously tracked. Although our data do not allow us to draw strong conclusions, our findings suggest that the number of items that can be accurately counted may be a better correlate of tracking capabilities, as both of these measures are found to improve with gaming.

This study establishes that when it comes to the number of objects that can be attended, a distinction should be drawn between a fast, parallel behavior that displays little plasticity and a more serial behavior that displays a range of plastic behaviors. As such these studies make several contributions, both to our understanding of the processes indexed by the enumeration and MOT paradigms, as well as to our
understanding of the nature of the changes that occur as a result of action video game play. It will be, however, for future experiments to fully characterize the consequences of these results for models of attention and working memory.
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References


   Evidence from target merging in multiple object tracking. *Cognition, 80*, 159-177.


1.1.1.5. Increased accuracy observed in VGPs: Conclusion

In each of the tasks above, VGPs were seen to exhibit superior accuracy compared to NVGPs, with each individual result suggesting an enhancement in some independent aspect of visual attention. In the UFOV, superior localization accuracy at all tested eccentricities, with and without distractors, suggests an enhancement of the spatial distribution of visual attention. In the crowding experiment, smaller center-to-center distances could be tolerated between the target and the distractors in the VGP group, suggesting an increase in the resolution of visual attention. In the AB, VGPs more accurately detected the presence of the second target, particularly at short T1-T2 lags, suggesting an enhancement in the temporal dynamics of visual attention. Finally, in the MOT, VGPs more accurately tracked numerous moving objects, suggesting an increase in the capacity of visual attention.

Each of these paradigms was designed to test what are thought of as relatively independent aspects of visual attention (for instance, one would expect that you could theoretically alter capacity without affecting resolution). However, the question is nevertheless begged, rather than positing a separate independent mechanism underlying each of the observed differences, could there instead be a single common underlying mechanism that can account for all of the results? However, before considering what form such a mechanism may take, it is worth considering the second complementary branch in the literature on video game effects, reaction time studies, as such a mechanism should account for changes in performance between VGPs and NVGPs regardless of the dependent measure that is used to assess said performance.
1.1.2. Decreased reaction time observed in VGPs

While the work from our lab has focused almost exclusively on tasks where accuracy is the primary dependent measure, one could argue that the most consistent finding in the gaming literature is that VGPs have substantially faster RTs than NVGPs. This basic result has been reported and repeatedly replicated for nearly 20 years using a wide variety of paradigms. In fact, it is interesting to note that besides RT being the primary dependent measure (and as will be described, VGPs demonstrating faster RTs than NVGPs), there are few obvious links between the experiments. Perhaps even more so than in the accuracy literature, each of these RT tasks was designed to test a very different aspect of perceptual or cognitive performance and as such, the results have been interpreted as enhancements in a range of different processes in VGPs.

Greenfield and colleagues (Greenfield, DeWinstanley, Kilpatrick, & Kaye, 1994) were among the first researchers to test the effects of video game experience on cognitive performance. As many games present multiple objects that must be attended to, or switched between, Greenfield and colleagues tested the ability to divide attention between two locations and/or to reorient attention to a relevant location after it has been improperly drawn to another location. Subjects were told they should press a button as soon as they saw a briefly flashed target stimulus that could only appear at one of two locations, A or B. They were warned that on 80% of the trials the target would appear at Location A while the target would only appear 10% of the trials at Location B (the remaining 10% were catch trials). The logic of
this type of experiment is that by manipulating the probability of occurrence at each location, subjects will become biased to allocate more attention to the high probability location and less attention to the low probability location. Accordingly, subjects are generally faster to respond to high probability targets and much slower to respond to low probability targets, a fact that is taken to reflect the difference in attentional allocation.

In an initial experiment, Greenfield and colleagues pitted VGPs against NVGPs on this divided attention task (along with a control condition in which the stimulus appeared at each location equally often). First, replicating previous findings in the video game literature, VGPs were found to have an overall faster RT than NVGPs. Also, as is consistently found in the attentional literature, they found that NVGPs responded faster to stimuli presented at the 80% location and slower to stimuli presented at the 10% location compared to their reaction times when the probabilities were equal (a condition that theoretically represents an even division of attention). Interestingly, while the VGPs showed a benefit (decreased reaction time) at the 80% location, their reaction time for the 10% location was the same as what was observed during the control condition. One item of particular note is that the VGPs responded at least as fast, if not faster, in the 10% condition (the hardest condition) as did NVGPs in the 80% condition (the easiest condition). Importantly, no difference in accuracy was observed, which may have indicated a simple speed-accuracy trade-off. This finding indicated to the authors that the efficiency with which attention is divided is greatly increased in VGPs.
Castel and colleagues (Castel, Pratt, & Drummond, 2005) used the widely known Posner exogenous cueing paradigm to examine the effects of video game experience on the temporal dynamics of attentional orienting. The task was a standard inhibition-of-return type task in which two boxes were presented, one to the left and one to the right of fixation. A target would appear in either of the two boxes and the subject’s task was to simply press the spacebar as quickly as possible once the target appeared. Performance was manipulated by the presentation of an exogenous (flashed) cue prior to the target’s appearance. The cue could be either compatible (on the same side as the target) or incompatible (on the opposite side as the target), and several stimulus-onset asynchronies (SOA - time between the onset of the cue and the onset of the target) were tested, as performance on this task is known to be a function of both cue-target compatibility and SOA. Subjects are typically faster to respond to compatible cues than incompatible cues when the SOA is short (< 100 ms), while the opposite is true when the SOA is long (> 100 ms). This finding is thought to capture a fundamental principle of human orienting – if attention is allocated to a location, but no target appears, attention is disengaged from that location and is inhibited from returning to that same location for several hundred milliseconds. The authors found that both VGPs and NVGPs displayed this typical pattern of results. However, VGPs were found to respond far faster than the NVGPs without a corresponding increase in error rate. This effect was of such a size that the slowest condition for the VGPs (compatible cue, 600 ms SOA) was faster than the quickest condition for the NVGPs (incompatible cue, 400 ms SOA). However, the lack of a 3-way interaction between
VGP experience, SOA, and compatibility, led the authors to conclude that although VGPs respond much faster, the basic orienting mechanisms in VGPs and NVGPs are similar.

Castel and colleagues (Castel et al., 2005) also examined the rate of visual search in VGPs and NVGPs. In this task, some number of letters (4-26) was presented, with one of the letters always being a ‘b’ or a ‘d’. The subject’s task was to find the ‘b’ or ‘d’ and respond accordingly, with the primary dependent measure being reaction time. Two conditions were run that differed in the composition of the remaining (non-target/distracting) letters. One condition was what is known as an “easy” search (also known as parallel/feature/efficient search). In this condition, each of the non-target letters was the letter ‘k’. Performance on this task is known to be very fast, accurate, and relatively independent of set-size (number of distracting letters). The second condition was what is known as a “hard” search (also known as serial/inefficient search). In this condition, each of the non-target letters was a random member of the alphabet (other than ‘b’ or ‘d’, non-repeating). Performance on this task is known to be a function of the set size with speed (and to some extent accuracy) decreasing with increasing set sizes. As predicted, both VGPs and NVGPs performed according to previous results in both the easy and hard searches. However, as predicted, the VGPs responded far faster than the NVGPs without a decrease in accuracy. In the hard search, VGP RT for a set-size of 26 was considerably below that of NVGPs for a set-size of only 18. While a significant interaction between set-size and VGP status suggested an increase in the efficiency of
search in the VGPs, the authors argued that their results might also be understood as a difference in stimulus-response mapping.

Bialystok (Bialystok, 2006) examined the effects of video game experience on the Simon task. The Simon effect is a well-known phenomena wherein subjects are faster to make responses when the stimulus appears on the same side as the response key and slower when the stimulus appears on the opposite side as the response key (for instance, pressing the left key to respond to a stimulus on the left side of the screen is faster than pressing the left key to respond to a stimulus on the right side of the screen). In one version of the task, colored squares were presented either to the left or right of fixation, with the two different colors corresponding to left/right key presses. In another version, arrows pointing left/right appeared on the left or right of fixation, with the direction of the arrow indicating the correct key press. As in the previous literature, VGPs were seen to respond faster than NVGPs in all conditions (compatible, incompatible, and control) with equivalent error rates. The fact that the RT advantage was reasonably consistent regardless of display type led the author to conclude that video game experience leads to a general increase in the speed of processing, rather than any specific enhancement in executive function (as might have been suggested if the VGP advantage was particularly large for incompatible trials).

Work from our lab has addressed the common belief that video game players may show more impulsivity than NVGPs. To assess this issue, the Test of Variables of Attention (T.O.V.A.; (Leark, Wallace, & Fitzgerald, 2004)) was administered to VGPs and NVGPs. Briefly, this test requires subjects to monitor a display and make a
timed response to a stimulus if it appears at one location, while withholding a
response to the same stimulus if it appears at another location (a go/no-go task). In
different blocks of trials, the target (go) can appear either frequently or infrequently.
The T.O.V.A. therefore offers a measure of both impulsivity (Is the subject able to
withhold a response to a non-target when most of the stimuli are targets?) and a
measure of sustained attention (Is the subject able to stay on task and respond quickly
to a target when most of the stimuli are non-targets?). VGPs responded more quickly
than did NVGPs on both task components, with equivalent accuracy. The fact that
the advantage was equivalent regardless of block (mostly go trials or mostly no-go
trials) suggests that VGPs are faster but not more impulsive than NVGPs and equally
capable of sustaining their attention.

We have also examined the efficiency of what some authors have called the
three basic attentional systems – alerting, orienting, and executive (Fan, McCandliss,
Sommer, Raz, & Posner, 2002). We administered the Attentional Network Test
(ANT) to action game players and non-playing controls aged between 7 and 22 years.
The subject’s task was to indicate the direction (left/right) either a fish (children’s
version) or an arrow (adult version) was facing with the corresponding arrow key.
The target could appear above or below fixation, either alone (neutral) or flanked by
distractors (which may point the same way as the target or the opposite direction),
and several types of cues that indicate the position or stimulus onset time could
precede the target. By comparing performance in these various conditions, one can
examine the effect of knowing the exact onset time of the target versus having no
temporal information (alerting), knowing both the onset time and position of the target versus knowing only the onset time (orienting), and the influence of incompatible distractors (executive). Again as predicted, VGPs responded significantly faster than NVGPs, while making an equivalent number of errors. However, the lack of any relevant interactions with cue or distractor type suggested that VGPs were similar in terms of the performance of these basic attentional systems.

Clark and colleagues examined the possibility that video game training could reverse the age-related decline in performance on speeded tasks (Clark, Lanphear, & Riddick, 1987). Seven subjects with a mean age of 65 years underwent a 7-week video game training treatment. Prior to and after video game training the subjects (as well as a group of control seniors) underwent a reaction time experiment, testing the effect of stimulus-response compatibility. The seniors were seated in front of two lights, under which were two buttons. In one block of trials the seniors were to press the button below the light that went on as fast as possible (compatible condition). In the second block, they were to press the button beneath the light that did not go on (incompatible condition). Normal individuals are generally much quicker when the response is compatible with the cue than when the response is incompatible. The fact that this cost is particularly magnified in the elderly is taken to reflect an age-related decline in response selection (mapping a stimulus onto an appropriate action). During 7 weeks of video game training, the seniors in the experimental group practiced one of two games (Pac Man and Donkey Kong) for at least 2 hours per
The effect of this video game training on reaction time was indeed significant as the experimental group’s average reaction time dropped approximately 25 milliseconds in the compatible condition and an even more impressive 80 ms in the incompatible condition, while the control group (which received no video game experience) did not improve. The authors argue that because the largest improvement was in the incompatible condition, the video game experience led to enhancements particularly in response selection in addition to the widely reported decreases in simple reaction time.

Many other authors have reported speeded responses in VGPs or as a result of video game experience in a wide variety of tasks from simple RT (Orosy-Fildes & Allan, 1989; Yuji, 1996), to tasks used to train jet pilots (Gopher, Weil, & Bareket, 1994) and laparoscopic surgeons (Rosser Jr., Lynch, Cuddihy, Gentile, & Klonsky, 2007).

1.1.2.1. Decreased reaction time observed in VGPs: Brinley Plot

Throughout the RT literature, VGPs have been seen to exhibit faster RTs compared to NVGPs. As was true of the accuracy studies, each of the reaction time studies was designed to test a different aspect of perception or cognition, including the ability to divide attention, the temporal dynamics of attentional orienting, impulsivity, stimulus-response conflict resolution, alerting, executive functioning, distractor rejection, serial search ability, and so on. However, unlike the common thread of “visual attention” in the accuracy studies, no correspondingly obvious link
pops out that binds the reaction time studies together. To examine the possible connection between VGP and NVGP performance on these tasks in more detail, we employed what is known as a Brinley plot (Cerella, 1991). Commonly used in the gerontology literature, a Brinley plot allows one to examine the relationship between what may seem to be very disparate reaction time tasks, with the goal of uncovering a factor common to all tasks. To construct this plot, each condition of each experiment is plotted as a single point, with the x-coordinate corresponding to the mean NVGP RT in that condition, and the y-coordinate corresponding to the mean VGP RT in that same condition. The logic of the plot is that if a single underlying variable explains the difference in performance between two groups across many types of tasks, a clear correlation should be visible. If no such single variable exists, one would predict a more scattered plot, wherein one group has more or less of an advantage depending on the specific task or condition within a task. As is clearly evident in Figure 1, the data strongly favors the former interpretation. Regardless of the task, condition within the task, or total RT, VGP RT is approximately 12% faster than NVGP RT. This is particularly notable because a priori there would be no reason to suspect that because VGPs are 12% faster than NVGPs at a go/no-go task, that they would also be 12% faster at visual search, resolution of stimulus-response conflict, or orienting. However, the fact that such a clear relationship does exist is strongly indicative of a common underlying change in VGPs that explains the difference in performance across all of the different tasks.
Several research studies, using a variety of experimental paradigms, have now observed decreased RTs in individuals who play action video games. In this Brinley plot, eighty-four experimental conditions from nine studies are plotted, with the x-coordinate of each point corresponding to the mean NVGP RT in a given task condition and the y-coordinate corresponding to the mean VGP RT in the same task condition. Plotting the data in this fashion demonstrates a clear linear relationship, wherein VGPs respond approximately 12% faster than NVGPs regardless of task or task condition. This pattern strongly suggests that a common underlying factor is responsible for much of the VGP RT advantage.

1.2. Hypothesis: Faster integration of perceptual information

Based on the totality of the gaming literature, any possible single mechanistic explanation must be able to predict an increase in VGP accuracy in accuracy-based experiments (which largely consist of making a perceptual judgment about a quickly flashed stimulus display) and decreased RT in reaction time tasks (which must be proportional to the total task RT - VGPs 12% faster than NVGPs). Perhaps the simplest single mechanism that could potentially explain these results is an increase in the rate at which perceptual information is integrated. According to this view,
VGPs would be more accurate than NVGPs on accuracy-based tasks because they are able to extract more information from the flashed displays, while in reaction-time tasks this faster integration would be manifested as quicker RTs.

However, none of the previous tasks are ideal to examine this hypothesis. A change in the rate of information accrual will lead to both a decrease in response time and an increase in accuracy – RT and accuracy should be explicitly linked. If one dependent measure changes without the other, or if they change in opposing directions (for instance, faster RTs, but lower accuracy), then other hypotheses need to be considered. Therefore, to fully evaluate the hypothesis, one would preferably want a task where the accumulation of information over time can be measured by examining both RT and accuracy. The experiments in the current gaming literature are lacking in one dimension or the other. The accuracy literature is obviously lacking in RT information, while in the RT literature accuracy is typically at ceiling levels and thus not informative.

Therefore, to specifically test the hypothesis that VGP experience results in faster integration of sensory information, we made use of a perceptual decision making task, known to require the integration of information over time, and where both RT and accuracy measures provide information about the rate at which this integration occurs.
CHAPTER 2 – Motion Coherence Decision Task

2.1. Introduction

A well-studied model of decision-making in the field of neuroscience is one in which subjects accumulate evidence about a sensory stimulus over time, with the goal of executing the proper motor action for that particular sensory stimulus and task requirement. In particular, the coherent dot motion direction discrimination task has been used extensively both in the human (Palmer, Huk, & Shadlen, 2005) and animal (Roitman & Shadlen, 2002) literatures to assess the rate at which sensory information is accumulated over time. In this task subjects are asked to determine the motion direction of many simultaneously moving dots. RT and accuracy in this task are known to reflect the information that is accumulated until the subject makes a decision and executes a motor response. When many of the dots move in a consistent direction (high coherence), RTs are generally very fast and accuracy is high. Conversely, when very few dots move in a consistent direction (low coherence), RTs are slow and as the percentage of consistently moving dots approaches zero, accuracy approaches chance-level.

It is important to stress the fact that RT and accuracy in this task are tightly coupled. Any processing change will alter the shape of both the RT and accuracy functions in a predictable fashion. If the difference between VGPs and NVGPs is truly a simple increase in the rate at which information accumulates in the VGP group, one would predict both a decrease in RT as well as an increase in accuracy in
the VGP group. Graphically, as a function of coherence, this would be visualized as a shift of both the VGP RT and accuracy plots to the left (faster/more accurate for lower levels of coherence). This is intuitive if one considers that an increase in integration rate/sensitivity is functionally equivalent to an increase in stimulus strength; for the same reason that all subjects respond faster and are more accurate when, for instance, contrast is increased in a visual display, a subject that accrues sensory information more quickly will also respond faster and more accurately.

Another possible mechanistic explanation, at least for the reduction in RT seen in the VGP population, is a reduction in decision criterion (speed-accuracy trade-off). While a tendency to trade accuracy for increased speed could not explain the increase in VGP accuracy in those tasks wherein accuracy was the primary dependent measure, it could possibly explain the reduction in VGP RT seen in tasks wherein RT was the primary dependent measure. Although accuracy was never observed to differ statistically between VGPs and NVGPs in those tasks, accuracy was also typically near ceiling, where statistically significant differences would be difficult to obtain. Graphically, as a function of coherence, a simple speed-accuracy tradeoff would be visualized as a shift of both the VGP RT plot to the left (faster for lower levels of coherence), but a shift of the accuracy plot to the right (less accurate for lower levels of coherence).

While the qualitative predictions regarding the raw accuracy and RT that could be expected are clear, this motion direction discrimination task is of particular interest, as psychometric models of this decision task indicate that performance (both
accuracy and RT) on the task can be captured by three main variables: (1) the rate at which information is accumulated over time, which is a function of both the quality of the stimulus itself as well as the sensitivity of the system to the stimulus (how well the system is able to detect the given stimulus) (2) the stopping rule, or the threshold at which the system stops accumulating evidence and the motor decision is made and (3) a residual amount of time that is common to all tasks and reflects motor planning and execution (independent of the stopping rule and accumulation rate). This formalism allows us to not only examine the qualitative pattern of results, but also to ask in a quantitative fashion which component of the decision making process is modified by action video game experience.

2.2. Methods

2.2.1. Participants

Twenty-three males with normal or corrected-to-normal vision were placed into one of two groups, VGP or NVGP, based upon their responses to a questionnaire given prior to the experiment. Only males underwent testing because of the relative paucity of females with sufficient video game experience.

The criterion to be considered a VGP was a minimum of 5 hours per week of action video game usage for the previous six months. Eleven males with a mean age of 18.8 years fell into this category. A highly abridged list of the games reported as
played includes Grand Theft Auto: San Andreas, Counterstrike, Dead Rising, Splinter Cell, F.E.A.R., and Halo 2.

The criterion to be considered a NVGP was little, although preferably no, action video game usage in the past six months. Twelve males with a mean age of 20.6 years fell into this category. All twelve males reported no action video game experience in the past year, and little to no video game experience of any type (two subjects reported playing sports games for 1 hour per month).

Written informed consent was obtained from each subject and each subject was paid $8 for each hour of participation.

### 2.2.2 Apparatus

The apparatus consisted of an Apple G4 computer running a program to present stimuli and collect the data using the MATLAB computer language (The Math Works Inc., Natick, MA) and the Psychophysical Toolbox routines (Brainard, 1997; Pelli, 1997) (http://psychtoolbox.org). The stimuli were displayed on a 20” flat screen NEC Dimaondtron MultiSync FP2141SB CRT driven at 75Hz, 1600x1200 resolution.

### 2.2.3. Stimulus/Procedure

Each observer viewed the display binocularly at a test distance of 59 cm. The stimuli were designed to be qualitatively the same as Palmer et al (Palmer et al., 2005). The motion stimulus was created by presenting a sequence of frames
containing small white dots (0.1° square, density = 16.7dots/deg²/sec) within a gray circular aperture (5° diameter). On each trial, although much of the dot motion was random, coherent motion in a certain direction (left/right) and of certain strength was always present. Seven levels of motion coherence were fully intermixed (0.8%, 1.6%, 3.2%, 6.4%, 12.8%, 25.6%, 51.2%) corresponding to the probability that a given dot would be replotted in motion, as opposed to randomly replotted. In accord with previous work on this paradigm, 3 interlaced sequences were used, meaning that a dot in frame 1 that was selected to be replotted in motion, would be replotted 0.2° in the given direction 40 ms later in frame 4. This method ensures a limited dot lifetime and also eliminates the ability to perform the task by comparing a given dot’s position across successive frames. The subject was instructed to press the key on the keyboard corresponding to the direction of the coherent motion (left/right arrow keys) as quickly and accurately as possible. Subjects were told to respond at any point after the onset of the motion up to a maximum of 2 seconds (after 2 seconds the motion stimulus stopped and subjects were prompted for a response). After each trial, auditory feedback was given (high tone = correct, low tone = incorrect) and after a delay of 1 second the next trial began.

As this task is extremely challenging for novice observers, subjects first completed three practice sessions (over the course of no more than 5 days). Each practice session was composed of 100 trials per level of motion coherence (split evenly between left and right motion) for a total of 700 trials per session, run in pseudorandom fashion. Subjects then completed the experimental session within two
days of their final training session (also 100 trials per level of motion coherence, 700 total trials). Only the results of this final experimental session will be considered in the analyses that follow.

2.3. Results

2.3.1. Raw Data

Accuracy was analyzed in a 2 (VGP Status: VGP/NVGP) x 7 (Coherence: 0.8, 1.6, 3.2, 6.4, 12.8, 25.6, 51.2%) ANOVA (see Figure 2, top panel). The expected strong main effect of coherence was observed (F(6,126) = 219.3, p < .001, partial eta-squared = .91) with accuracy increasing with increasing coherence (.52, .55, .57, .65, .76, .93, .98). However, no main effect of VGP Status was observed (VGP = .71+/-.02, NVGP = .71+/-.02; F(1,21) = 0.2, p = .65, partial eta-squared = .01) nor was an interaction between VGP Status and coherence (F(6,126) = 0.57, p = .76, partial eta-squared = .03). Although one obviously cannot accept the null hypothesis, there is no statistical indication that the groups differ in accuracy.

Mean reaction time for correct trials was also analyzed in a 2 (VGP Status: VGP/NVGP) x 7 (Coherence: 0.8, 1.6, 3.2, 6.4, 12.8, 25.6, 51.2%) ANOVA. As in the accuracy analysis, a strong main effect of coherence was observed (F(6,126) = 48.5, p < .001, partial eta-squared = .70) with mean reaction time decreasing with increasing motion coherence (.788, .803, .776, .757, .691, .596, .505). However,
unlike the accuracy analysis, both a strong main effect of VGP status (VGP = .592+/-.018, NVGP = .803+/- .020; F(1,21) = 18.9, p < .001, partial eta-squared = .47) and a VGP status x coherence interaction (F(6,126) = 3.5, p = .002, partial eta-squared = .15) were observed. The main effect of VGP status is in agreement with the majority of the gaming literature, as VGPs were seen to have significantly shorter mean RTs than NVGPs, while the interaction suggests that this difference is largest at low coherences when total RTs are slowest (see Figure 2, bottom panel).
Figure 2. VGP and NVGP Performance: Motion Direction Discrimination

VGPs and NVGPs demonstrate nearly identical accuracy (Top Panel) across levels of motion coherence (x-axis), while VGPs respond substantially faster than NVGPs (Bottom Panel). The VGP RT advantage is largest at low levels of coherence, but remains quite significant even at the highest level of coherence.

*Note – For illustration only, model fit corresponds to best fit to the mean data rather than the mean of the individual fits.

2.3.2. Discussion: Raw Data

As predicted by the gaming RT literature, VGPs responded much more quickly than NVGPs. However, in terms of accuracy, there was no evidence to suggest either a shift of the function to the left (toward higher accuracy, which would
have been indicative of faster sensory integration) or a shift of the function to the right (toward lower accuracy, which would have been indicative of a reduction in the decision criterion). This does not appear to be due to a lack of statistical power (improperly rejecting the alternative hypothesis). Rather, it appears that the two groups truly do have very nearly identical accuracy (within 1% at 6 of 7 coherence levels). Therefore the data are inconsistent with any single simple interpretation (faster sensory integration or reduced criteria). The data are also inconsistent with any interpretation positing a simple reduction in motor execution or stimulus-response mapping, as the significant VGP status x coherence level interaction in the RT analysis suggests that the RT difference between the groups depends on the total task difficulty. Instead, the data suggest a more complicated pattern wherein multiple factors play a role.

2.4. Introduction: Diffusion-to-bound model

In order to quantitatively assess the individual contribution of integration rate and criterion, individual data were fit with the proportional-rate diffusion model proposed by Palmer and colleagues (2005). This model visualizes the motion coherence task as a simple noisy diffusion process, wherein information accumulates over time until the amount of accumulated information hits a bound, which then triggers a response. Importantly, the model predicts that both RT and accuracy are a function of this diffusion process and should therefore be controlled by the same set of parameters. The model has two main parameters that control how quickly and
accurately a decision is reached – the mean drift rate (how quickly information accumulates) and the position of the bound. The mean drift rate grows proportionally with two factors – the stimulus coherence and the individual subject’s sensitivity. If either coherence or sensitivity increases, the rate at which information is accrued will increase correspondingly. This increased rate will in turn lead to faster RTs and more accurate responses. As the stimulus coherence is known, the only free parameter needed to fit the rate of accumulation is the individual subject’s sensitivity. The second main parameter, the position of the bound, controls the amount of information that must be accumulated before the subject initiates a response. Decreasing the level of the bound will lead to faster RTs, but less accurate responses (as the likelihood that noise will lead to the incorrect bound being reached will increase). As both accuracy and RT are hypothesized to be a function of the same process, the psychometric and chronometric functions are fit simultaneously to give the parameters that best capture overall performance.

Accuracy is modeled as a simple logistic function:

\[ P_c(x) = \frac{1}{1+e^{-2Ax}} \]

x: % coherence (motion strength)

k: sensitivity

A: bound/criterion
with ‘x’ being the stimulus strength, ‘A’ being the bound, and ‘k’ the sensitivity. If any of the three are equal to zero, percent correct goes to chance level (50%). This is quite intuitive; if there is no motion present, the subject has no ability to detect motion, or they wait for no motion to appear, the best they will be able to do is chance. Conversely, as any of the three parameters increase, percent correct will increases. Again, this is quite intuitive; it is much easier to discriminate the direction of 100% coherent motion than 1% coherent motion, a subject who is extremely sensitive to motion will be more accurate than a subject with little motion sensitivity, and the higher one sets their bound, the less likely the bound will be hit by chance.

RT is modeled as a hyperbolic tangent:

\[ RT(x) = \frac{A}{kx} \tanh (A k x) + TR \]

Unlike in the accuracy equation, wherein changes in bound and sensitivity lead to similar directional changes in accuracy, for reaction time, the rate and bound parameters come in opposite to one another. As the rate of integration is increased (either by increasing motion coherence or sensitivity), RT will decrease. However, RT increases as the bound parameter increases. Again the intuitions are clear.
Higher levels of motion coherence or higher motion sensitivity means more motion information available per unit time. Thus, increases in either parameter will lead to faster RTs. Conversely, increasing the bound means more information needs to be accrued before the bound is reached and thus will slow RTs. The final parameter (residual time – TR) is a post-decision additive component that reflects the portion of the total reaction time that is independent of the task parameters (motor execution, stimulus-response mapping, etc).

Each subject’s psychometric and chronometric functions were fit to the model simultaneously by maximizing the average variance explained in the two functions. The resulting best fitting parameters then offer a quantitative measure of the contribution of sensitivity/rate of integration, bound, and non-decision components in creating the observed pattern of differences between the VGP and NVGP.

2.4.1. Results: Diffusion-to-bound model

The model fits were good ($r^2_{\text{VGP}} = .93$, $r^2_{\text{NVGP}} = .90$) and equivalent in the two groups ($t(21) = 0.93$, $p = .36$). Each of the three model parameters (A/bound, k/sensitivity, and TR/residual time was analyzed in a t-test comparing the values in VGP and NVGP. The bound parameter A, was seen to be significantly lower in the VGP than the NVGP (VGP: $0.533 +/- 0.05$, NVGP: $0.732 +/- 0.03$; $t(21) = 3.6$, $p = .002$). The rate/sensitivity parameter k was seen to be significantly larger in the VGP than the NVGP (VGP: $10.94 +/- 0.9$, NVGP: $7.6 +/- 0.9$; $t(21) = 2.6$, $p = .02$). Finally, no
significant difference was seen between the groups in the residual reaction time parameter TR (VGP: .345+/-.02, NVGP: .356+/-.03; t(21) = 0.3, p = .76).

2.4.2. Discussion: Diffusion-to-bound model

As predicted by the analysis of the raw data, the pattern of results (VGPs significantly faster than the NVGPs, but equally accurate) could not be captured by manipulating a single parameter (rate of integration or bound), but instead appears to reflect an interaction between the main parameters. A larger value of the rate/sensitivity parameter is observed in the VGPs, indicating that the VGPs accumulate sensory information more quickly than the NVGPs. All other parameters being equal, this would tend to lead to both faster RTs and higher levels of accuracy. However, all other parameters are not equal; VGPs have a smaller value of the bound parameter, indicating that they make a decision sooner than the NVGPs. This reduction in bound in VGPs contributes in the same direction as the increase in rate for RTs, but directly counters the effect of sensitivity for accuracy. At the population level, the rate and bound parameters trade-off nearly perfectly, which leads to substantially faster RTs in the VGP population but nearly identical accuracy in the two groups.

2.5. Discussion: Motion Coherence Decision Task

As has been observed throughout the gaming literature, VGPs were seen to respond considerably faster than NVGPs. Alone, this reduction in RT would be
consistent with at least two simple mechanistic explanations, (1) an increase in sensitivity/rate at which sensory information is accrued or (2) a reduction in decision criterion/speed-accuracy trade-off. The first explanation, increased sensitivity, would predict an increase in accuracy in the VGP population, while conversely the second would predict a decrease in accuracy. Interestingly however, neither possibility was observed, with instead VGP accuracy matching NVGP accuracy nearly identically across all levels of motion strength. This pattern of drastically faster RTs, but equivalent accuracy is indicative of a more complicated explanation wherein changes in both sensitivity and criterion contribute to the final level of performance. In order to quantify the relative involvement of sensitivity and criterion, the data was fit using the proportional rate diffusion-to-bound model put forth by Palmer and colleagues (2005). As indicated by the raw data, neither a change in integration rate nor a reduction in bound could account for the data. Instead, it is the confluence of the two factors (an increase in the rate of integration along with a reduction in bound) that results in the difference in observed performance in the two populations.

The most obvious testable hypothesis based on these results is therefore that if criterion was removed from the equation, VGPs should demonstrate an advantage in accuracy compared to the NVGPs. In other words, if VGPs are truly able to extract more sensory information per unit time, then if the same motion stimulus was presented for the same amount of time to both the VGPs and NVGPs, the VGPs should demonstrate a higher level of accuracy than the NVGPs.
CHAPTER 3 – Motion Coherence Presentation Duration Task

3.1. Introduction

In an attempt to only measure the rate of sensory integration uncontaminated by criterion, the stopping point was set experimentally, rather than allowing the subjects to determine for themselves when “enough” information had accrued. By presenting the motion stimulus for short periods of time and assessing accuracy as a function of stimulus duration, the resulting function offers an excellent measurement of the rate at which a subject acquires information. This type of task has been used in the contrast sensitivity literature to assess the rate at which low contrast information is acquired (Rovamo, Leinonen, Laurinenn, & Vursu, 1984).

3.2. Methods

This experiment was always run within two days of the completion of the fourth (experimental) session of the motion decision task (Chapter 2). The subjects, apparatus, and stimuli were identical to the previous experiment, with the exception of two changes. First, rather than allowing the subjects to decide when to respond, stimuli were presented for fixed durations and the subjects were instructed to watch the entire motion stimulus and only make a decision after the dots stopped. Seven such presentation durations were presented in fully intermixed fashion (50, 100, 200, 400, 800, 1600, 3200 ms). Also, only three coherence levels were tested – 6.4%,
12.8%, and 25.6% - as performance at these coherence levels in the decision task was neither at floor nor at ceiling, and would thus be maximally informative. Subjects completed 50 repetitions (25 left, 25 right) for each of the duration/coherence pairs for a total of 1050 trials presented in pseudorandom order.

3.3. Results

3.3.1 – Results: Raw Data

Accuracy was analyzed in a 2 (VGP Status: VGP/NVGP) x 3 (Coherence: 6.4, 12.8, 25.6%) x 7 (Presentation Duration: 50, 100, 200, 400, 800, 1600, 3200 ms) ANOVA. As was seen in the decision task, a strong main effect of coherence was observed with accuracy increasing with increasing levels of coherence (6.4%: .62, 12.8%: .72, 25.6%: .85; F(2, 42) = 341.5, p < .001, partial eta-squared = .94). As predicted, a main effect of presentation duration was also observed, with accuracy increasing with increasing presentation duration up until around 800 ms where it reached an asymptote (.54, .60, .70, .78, .82, .82, .85; F(6, 126) = 209.0, p < .001, partial eta-squared = .91). An interaction between coherence and presentation duration indicated that accuracy grew more quickly with time as coherence increased (F(12, 252) = 17.1, p < .001, partial eta-squared = .45). Finally, an interaction in the predicted direction was observed between presentation duration and VGP status with accuracy growing faster with time in the VGPs (F(6, 126) = 2.1, p = .03: one-tailed, partial eta-squared = .09). The main effect of VGP status was not significant,
although it was in the predicted direction (VGP: .87+/- .03, NVGP: .83+/- .04; F(1, 21) = 2.4, p = .13, partial eta-squared = .10).

Figure 3. VGP and NVGP Performance: Motion Presentation Duration

VGP and NVGP accuracy is plotted as a function of presentation duration. While VGP and NVGP accuracy is reasonably equivalent at both extremely short presentation durations (both groups near chance-level performance) and at extremely long presentation durations (both groups reach a common asymptotic level of performance), VGP accuracy grows more quickly than NVGP accuracy in the critical region between chance and asymptote. This pattern is particularly evident in the region between .04 seconds and .5 seconds wherein VGP accuracy is easily distinguished as higher than NVGP accuracy for both levels of motion coherence.

*Note – Model fit corresponds to best fit to the mean data rather than the mean of individual fits.

3.3.2 – Discussion: Raw Data

Qualitatively, the data is quite consistent with the diffusion-to-bound model from Chapter 2. Accuracy grew as a function of time and grew more quickly for
higher levels of coherence. The interaction between VGP status and presentation duration is also consistent with the results of Chapter 2, in which VGPs were seen to accumulate information more rapidly than NVGPs. However, in order to obtain a more quantitative measure of the actual rate at which information accrues in the two populations, a standard model in the psychophysical field was fit to the data.

### 3.3.3 – Introduction: Model

Performance is modeled as a simple exponential rise to an asymptote (see (Carrasco, Giordano, & B., 2004; Dosher, 1979) although note that the procedure and interpretation of the function is quite different from the current design):

$$\%\text{Correct}(t) = \lambda (1 - e^{\beta(t-\delta)}) + 50\%$$

where lambda ($\lambda$) is the level of asymptotic performance, beta ($\beta$) is the rate at which accuracy grows as a function of time, and delta ($\delta$) is the intercept or the time at which accuracy rises above chance levels. 50% is added to the function to convert from percent above chance to percent correct. The main prediction based on the earlier findings is a greater rate ($\beta$) value in the VGPs.
3.3.4 – Results: Model

As the model fits were generally quite poor ($r^2 < .7$) for the lowest level of coherence (6.4%) only the two higher levels of coherence (12.8% & 25.6%) were included in the analysis. Also, one NVGP was excluded because of poor model fits at each of the coherence levels ($r^2 < .6$). For the models included in the analysis, fits were good ($r^2_{12.8\%}: .88, r^2_{25.6\%}: .97$) and did not differ between the groups ($R^2_{VGP}: .94, R^2_{NVGP}: .92; F(1,20) = 0.5, p = .48)$. Each of the included model parameters (asymptote/$\lambda$, rate/$\beta$, intercept/$\delta$) was entered into a 2 (VGP Status: VGP/NVGP) x 2 (Coherence: 12.8, 25.6%) ANOVA. For the asymptote parameter $\lambda$, a main effect of coherence was observed, with asymptotic performance being higher for 25.6% coherence than 12.8% coherence (12.8%: .87, 25.6%: .99; $F(1,20) = 103.1, p < .001$, partial eta-squared = .84). However, neither the main effect of VGP status, nor the interaction between coherence and VGP status approached significance. For the rate parameter $\beta$, a main effect of coherence was also observed, with the rate being higher for the higher level of coherence (12.8%: 4.4, 25.6%: 8.4; $F(1,20) = 13.0, p = .002$, partial eta-squared = .39). It is interesting to note that the rate parameter ($\beta$) in the current model behaved almost exactly as would be predicted by the diffusion-to-bound model of Chapter 2. In particular, the diffusion-to-bound model predicts that if % coherence is doubled, the rate at which information accrues should double as well, which is precisely what is observed. The significant main effect of VGP status indicates a higher rate in the VGP group (VGP: 8.2+/-.1.3, NVGP: 4.8+/-.06; $F(1,20)$
= 4.5, p = .045, partial eta-squared = .19). The interaction between coherence and VGP status did not approach significance. Finally, for the intercept parameter $\delta$, neither the main effects of coherence and VGP status, nor the interaction approached significance.

3.4 – Discussion: Motion Coherence Presentation Duration Task

As predicted, VGP accuracy exceeded NVGP accuracy when short clips of motion were presented. The accuracy advantage was particularly evident for intermediate motion durations, between 50 ms (when little to no motion information is present) and 800 ms (when subjects receive enough information to reach asymptotic levels of accuracy). Fitting the raw data with an exponential approach to an asymptote quantified the increased rate of accrual in the VGP population. These results, together with the findings in Chapter 2, offer strong support for the hypothesis that the rate at which sensory information accrues is greater in VGPs than NVGPs.
CHAPTER 4 – Auditory Localization Decision Task

4.1. Introduction

The data from the coherent motion direction discrimination task suggests an increase in the rate at which VGPs extract information from a visual display. However, it is unknown whether this increase is specific to the visual modality or whether it also generalizes to other senses. Indeed, the entire body of literature on the effect of video game experience on perception has focused exclusively on the visual system. While audio in early video games was largely inconsequential (i.e. background music that was often uncorrelated with game conditions/performance), in today’s games it is often reasonably informative (primarily in orienting players to unseen foes). However, it is certainly still the case that the primary focus of video games continues to be vision (most games can be completed without any sound whatsoever). Therefore, whether action video game experience affects auditory integration in a manner similar to what was observed in the visual modality is unclear.

To determine whether the increase in the rate at which sensory information is accrued is seen in audition as well as vision, an auditory analog of the motion direction task was developed. A pure tone embedded in a white noise mask was presented in one ear, while white noise alone was presented in the other (both were normalized to the same mean amplitude). The subjects’ task was to indicate the ear in which the tone was presented as quickly and accurately as possible. In a manner
consistent with adjusting the coherence level of the motion stimulus, the ratio of the amplitude of the target tone to the white noise mask was manipulated in order to test performance across the range of possible accuracy levels and reaction times. As in the motion task, performance on the task requires the accumulation of information over time, the intuitions regarding sensitivity and criterion are similar and thus will be modeled in the same manner.

4.2. Methods

4.2.1. Participants

The subjects were the same as those in the previous two experiments (Chapter 2 and Chapter 3).

4.2.2 Apparatus

The apparatus consisted of an Apple G4 computer running a program to present stimuli and collect the data using the MATLAB computer language (The Math Works Inc., Natick, MA) and the Psychophysical Toolbox routines (Brainard, 1997; Pelli, 1997) (http://psychtoolbox.org). The stimuli were presented binaurally using Sennheiser HD 250 II headphones.
4.2.3 Stimulus/Procedure

On each trial the subject was presented with, in one ear, a white noise stimulus, and in the other, a 1000Hz tone of a variable amplitude added to the same white noise stimulus. The absolute amplitude of the stimuli in both ears and across sine wave amplitudes was fixed at 50 dB with the real modification being the ratio of maximum noise amplitude to sine wave amplitude, which ranged from 1:1 (maximum noise amplitude = maximum sine wave amplitude) to 64:1 (maximum noise amplitude = 64x maximum sine wave amplitude). Eight signal-to-noise ratios (SNRs) were tested in log spaced steps (1:64, 1:32, 1:16, 1:8, 1:4, 1:2, 1:1). The subject’s task was to press the arrow on the keyboard corresponding to the ear that contained the sine wave as quickly as accurately as possible. The auditory stimulus was present for a maximum of 1.5 seconds during which time the subject was free to respond. After 1.5 seconds the auditory stimulus ceased and subjects were prompted for a response. Visual feedback was given with a rectangle in the center of the screen (green for a correct response and red for an incorrect response).

As with the motion task, this task is extremely challenging for novice observers. As such two practice sessions were completed (over the course of no more than 4 days) prior to the experimental session. Each session contained 100 trials per SNR (split evenly between left and right ear) for a total of 800 trials presented in pseudorandom fashion. As was the case in the motion experiment, only the data from the final experimental session will be considered in the analyses that follow.
4.3. Results

4.3.1. Results: Raw Data

Accuracy was analyzed in a 2 (VGP Status: VGP/NVGP) x 8 (SNR: 1:64, 1:32, 1:16, 1:8, 1:4, 1:2, 1:1) ANOVA (see Figure 4, top panel). The expected strong main effect of SNR was observed \((F(7, 147) = 411.7, p < .001, \text{partial eta-squared} = .95)\) with accuracy increasing with increasing SNR (.52, .51, .60, .83, .95, .98, .98, .98). However, no main effect of VGP Status was observed \((\text{VGP} = .78 +/- .04, \text{NVGP} = .80 +/- .04; F(1,21) = 1.0, p = .32, \text{partial eta-squared} = .05)\) nor was an interaction between VGP Status and SNR \((F(7,147) = 0.4, p = .90, \text{partial eta-squared} = .02)\). As was the case of motion accuracy, one cannot accept the null hypothesis, however, there is no statistical indication that the groups differ in accuracy.

Mean reaction time for correct trials was also analyzed in a 2 (VGP Status: VGP/NVGP) x 8 (SNR: 1:64, 1:32, 1:16, 1:8, 1:4, 1:2, 1:1) ANOVA. As in the accuracy analysis, a strong main effect of SNR was observed \((F(7, 147) = 77.0, p < .001, \text{partial eta-squared} = .79)\) with mean reaction time decreasing with increasing SNR (.808, .789, .742, .629, .495, .448, .425, .418). However, unlike the accuracy analysis, both a strong main effect of VGP status \((\text{VGP} = .488 +/- .023, \text{NVGP} = .802 +/- .021; F(1,21) = 20.6, p < .001, \text{partial eta-squared} = .50)\) and a VGP status x SNR interaction \((F(7,147) = 5.2, p < .001, \text{partial eta-squared} = .2)\) were observed. The main effect of VGP status is in agreement with the majority of the gaming literature (along with the results of Chapter 2), as VGPs were seen to have
significantly shorter mean RTs than NVGPs, while the interaction suggests that this difference is largest at low SNRs, when total RTs are slowest (see Figure 4, bottom panel).

Figure 4. VGP and NVGP Performance: Auditory Localization

VGPs and NVGPs demonstrate nearly identical accuracy (Top Panel), while VGPs respond substantially faster than NVGPs (Bottom Panel). The VGP RT advantage is largest at low SNRs, but remains quite significant even at the highest SNR.

*Note – Model fit corresponds to best fit to the mean data rather than the fit given by the mean of individual fits.
4.3.2. Discussion: Raw Data

The observed pattern of results is remarkably similar to what was observed in the motion analog of the task (Chapter 2) and therefore, the intuitions that can be drawn are also similar. As was the case in the motion task, the VGPs and NVGPs demonstrate nearly identical levels of accuracy, while the VGPs perform the task substantially faster than the NVGPs, a relationship that is inconsistent with a single simple interpretation (i.e. faster integration rate or reduced criteria). In order to elucidate the relative contributions of integration rate and decision bound, the same diffusion-to-bound model as was employed in Chapter 2 was fit to the data.

4.3.3. Results: Diffusion-to-bound model

The model fits were good ($r^2_{VGP} = .90$, $r^2_{NVGP} = .91$) and equivalent in the two groups ($t(21) = 0.91$, $p = .37$). Each of the three model parameters ($A$/bound, $k$/sensitivity, and $TR$/residual time) was analyzed in a t-test comparing the values in VGPs and NVGPs. The bound parameter $A$, was seen to be significantly lower in the VGPs than the NVGPs (VGP: $.538 +/-.05$, NVGP: $.712 +/-.05$; $t(21) = 2.6$, $p = .02$), while the rate/sensitivity parameter $k$ was seen to be significantly larger in the VGPs than the NVGPs (VGP: $23.9 +/-.98$, NVGP: $19.2 +/-.80$; $t(21) = 3.8$, $p = .001$). No significance difference was seen between the groups in the residual reaction time parameter $TR$ (VGP: $.303 +/-.013$, NVGP: $.378 +/-.040$; $t(21) = 1.9$, $p = .07$).
4.4. Discussion: Auditory Localization Decision Task

As was the case in Chapter 2, VGPs were seen to respond considerably faster than NVGPs, but with equivalent accuracy, a pattern of results that suggests changes in both sensitivity and criterion. In order to quantify the relative involvement of sensitivity and criterion, the data were again fit using the proportional rate diffusion-to-bound model put forth by Palmer and colleagues (2005) and again, the difference in VGP performance was well captured by an increase in the rate of information accrual along with a concomitant decrease in decision criteria. As in Chapter 3, the next step is to directly test the rate at which information accrues, uncontaminated by differences in criterion.
CHAPTER 5 – Auditory Localization Presentation Duration Task

5.1. Introduction

The results of the auditory localization experiment suggest that VGPs acquire sensory information more rapidly than NVGPs. All other parameters being equal, this would lead to an increase in accuracy in the VGP group. However, as the VGP group exhibits a reduction in decision criteria in addition to the increase in sensory integration rate, an increase in accuracy relative to the NVGPs is not observed. Therefore, if, as in Chapter 3, the stopping point is set experimentally, rather than being under subject control, the VGPs should exhibit greater accuracy than the NVGPs.

5.2. Methods

All subjects underwent the experiment within two days of completing the final auditory decision task session. The subjects, apparatus, and stimuli were identical to the previous experiment, with the exception of two changes. First, rather than allowing the subjects to decide when to respond, stimuli were presented for fixed durations and the subjects were instructed to watch the entire motion stimulus and only make a decision after the dots stopped. Seven such presentation durations were presented in fully intermixed fashion (20, 40, 80, 160, 320, 640, 1280 ms). Also, only three SNR levels were tested – 1:32, 1:16, 1:8 - as performance at these
coherence levels in the decision task was neither at floor nor at ceiling, and would thus be maximally informative. Subjects completed 50 repetitions (25 left, 25 right) for each of the duration/SNR pairs for a total of 1050 trials.

5.3. Results

5.3.1 – Results: Raw Data

Accuracy was analyzed in a 2 (VGP Status: VGP/NVGP) x 3 (SNR 1:32, 1:16, 1:8): x 7 (Presentation Duration: 20, 40, 80, 160, 320, 640, 1280 ms) ANOVA (see Figure 5). As was seen in the decision task, a strong main effect of SNR was observed with accuracy increasing with increasing levels of coherence (1:32: .60, 1:16: .76, 1:8: .88; F(2,42) = 444.7, p < .001, partial eta-squared = .96). As predicted a main effect of presentation duration was also observed, with accuracy increasing with increasing presentation duration up until around 320 ms where it reached an asymptote (.56, .63, .72, .77, .82, .86, .87; F(6, 126) = 235.4, p < .001, partial eta-squared = .92). An interaction between SNR and presentation duration indicated that accuracy grew more quickly with time as SNR increased (F(12, 252) = 17.0, p < .001, partial eta-squared = .45). Finally, an interaction in the predicted direction was observed between presentation duration and VGP status with accuracy growing faster with time in the VGPs (F(6, 126) = 1.9, p = .04 - one-tailed, partial eta-squared = .08). The main effect of VGP status was also significant with VGPs being more accurate than NVGPs (VGP: .78+/- .02, NVGP: .72+/- .012; F(1,21) = 6.5, p = .018, partial eta-squared = .24).
Together, these results are consistent with the hypothesis that sensory information is integrated more rapidly in the VGP population. However, to more explicitly model the rate at which the auditory information accrues, the same model as was used for the motion task (exponential approach to an asymptote) was fit to the data.

Figure 5. VGP and NVGP Performance: Auditory Presentation Duration

VGP and NVGP accuracy is plotted as a function of presentation duration. While VGP and NVGP accuracy is reasonably equivalent at both extremely short presentation durations (both groups near chance level performance) and at extremely long presentation durations (both groups reach a common asymptotic level of performance), VGP accuracy grows more quickly than NVGP accuracy in the critical region between chance and asymptote. This pattern is particularly evident in the region between .04 seconds and .2 seconds wherein VGP accuracy is easily distinguished as higher than NVGP accuracy for both levels of motion coherence.

*Note – For illustration purposes, model fit corresponds to best fit to the mean data rather than the fit given by the mean of individual fits.
5.3.2 – Results: Model

As the model fits were generally quite poor for the lowest level of SNR \((r^2_{1:32} < .7)\) only the two higher levels of SNR (1:16 & 1:8) were included in the analysis. For the models included in the analysis, fits were good \((r^2_{1:16}: .92, r^2_{1:8}: .94)\) and did not differ between the groups \((R^2_{VGP}: .94, R^2_{NVGP}: .92; F(1,21) = 1.7, p = .21)\).

Each of the included model parameters (asymptote/\(\lambda\), rate/\(\beta\), intercept/\(\delta\)) was entered into a 2 (VGP Status: VGP/NVGP) x 2 (SNR: 1:16, 1:8) ANOVA. For the asymptote parameter \(\lambda\), a main effect of SNR was observed, with asymptotic performance being higher for the higher level of SNR \((1:16: .93, 1:8: .98; F(1,21) = 20.8, p < .001)\). A main effect of VGP status was also significant, with VGPs demonstrating higher asymptotic accuracy \((VGP: .98+/- .01, NVGP: .94+/- .01; F(1,21) = 4.8, p = .039)\). However, the interaction between VGP Status and SNR did not approach significance. For the rate parameter \(\beta\), a main effect of SNR was also observed, with the rate being higher for the higher level of SNR \((1:16: 10.9, 1:8: 26.1; F(1,21) = 27.2, p < .001)\). A main effect of VGP status indicates a higher rate in the VGP group \((VGP: 24.5+/- 4.7, NVGP: 12.9+/- 1.7; F(1,21) = 4.5, p = .045)\). The interaction between coherence and VGP status did not approach significance. Finally, for the intercept parameter \(\delta\), only a main effect of SNR was observed with performance rising above chance levels earlier for the higher SNR \((1:16: .015, 1:8: .004, F(1,21) = 9.9, p = .005)\).
5.4. Discussion: Auditory Localization Presentation Duration Task

As predicted, VGP accuracy exceeded NVGP accuracy when short clips of the auditory stimulus were presented. The accuracy advantage was particularly evident for intermediate presentation durations, between 20 ms (when little to no localization information has become available) and 320 ms when subjects have reached asymptotic levels of accuracy. Fitting the raw data with an exponential approach to an asymptote quantified the increased rate of accrual in the VGP population. These results, together with the findings in Chapter 4, offer strong support for the hypothesis that the rate at which auditory information accrues is greater in VGPs than NVGPs.
CHAPTER 6 – Video Game Training

6.1. Introduction

The previous 4 chapters have indicated an increase in the rate of sensory integration in VGPs. While our hypothesis is that extensive video game experience is at the root of this enhanced skill, it could also be the case that VGPs are individuals who have been born with better perceptual skills. Such individuals would tend to succeed at action video games, and therefore find such games rewarding, whereas individuals born with poorer skills would tend to eschew those games that exceed their capacity. Therefore, in order to establish that video game experience is sufficient to drive an increase in the rate of sensory integration, a selection of NVGPs underwent extensive video game training on either an action video game or a control video game. If action video game experience does enhance the rate of sensory integration, larger improvements should be noted in the action-trained group than in the control group.

6.2. Methods

6.2.1. Participants

The study enrolled 25 NVGPs, none of whom had taken part in previous experiments. The criteria for being considered an NVGP remained the same as in
previous experiments. All subjects underwent training as described below. In all, 7 females and 7 males (mean age = 25.7) made up the final experimental group, while the final control group consisted of 7 females and 4 males (mean age = 24.7).

6.2.2. Testing Methods

All subjects underwent the same two decision tasks described previously (motion coherence decision task - Chapter 2, auditory localization decision task – Chapter 4) as well as several other tasks not relevant to the work at hand, both before and after video game training (described below).

6.2.3. Training methods

6.2.3.1. Training apparatus

Both groups played on 20” Dell LCD monitors.

6.2.3.2 Training procedure

For both groups, training consisted of playing the pre-determined video game for 50 total hours. The subjects were allowed to play a maximum of 2 hours per day and a maximum of 10 hours per week. No minimum amount of game play per week was enforced, but subjects were required to finish the 50 hours training in no more than 12 weeks. The subjects completed the 50 hours in an average of 44 days. All
training games covered the entire extent of the screen (approximately $15^\circ$ height x $18^\circ$ width from fixation).

The eleven members of the control group played the game The Sims 2. The Sims 2 is a simulation-style game, wherein the player takes complete control of the life of a character (or the lives of several characters). The player must ensure that the character meets all of his/her basic needs (cooking meals/eating, sleeping, using the restroom, bathing, etc), they must guide the character toward short-term wants (which can be buying a new curtain, kissing a neighbor, having a phone conversation with a parent, etc) and away from short-term fears (such as losing a job or starting a fire), and finally they must work the character toward the character’s long-term aspiration (such as having a family or making a fortune). Along the way, characters have jobs (which require the character to acquire various skills to be promoted), relationships with other characters (which with positive interactions improve and negative interactions decline), are married, have children, change houses, grow old, and die - essentially most of the things that characterize normal human life. As characters are added to the player’s the household, the player takes control of and is responsible for those characters as well. The control group played an average of ten different characters and lived in an average of four different houses during the 50 hours of training.

In an attempt to minimize the large inherent difference in the number of characters, goals, and available environments between the control game and a standard action game, the fourteen members of the experimental group played two
different action games (both chosen to be similar to those played by our VGPs). Both action games have a relatively simple interface, use first-person point of view, and require effective monitoring of the entire visual field. Unfortunately, even by using two action games, the control group played five times as many characters, had infinitely more (both in number and variety) immediate, short-term, and long-term goals, and more diversity in environment; the nature of video games simply made it impossible to fully equalize these parameters. As our hypothesis was that greater learning would be observed in the action group than the control group, we chose to have the action game trainees be at a disadvantage for these factors to ensure that amount of novelty could not be used to explain any improvements in the action group beyond what is seen in the control group.

During the first half of training, the experimental group played the game Unreal Tournament 2004 in Death Match mode. In this mode the character is in an abandoned warehouse with 32 computer-controlled artificial agents. The sole goal is for the player to kill as many of these agents as possible, while minimizing the number of times the player dies. Each training session was divided into 20-minute blocks. The difficulty of the block was adjusted based on the kill/death ratio. If in a block the player scored twice as many kills as they had deaths, the difficulty level was increased one level. Players were retested on lower difficulty levels in the middle and at the end of training to quantitatively assess improvement. During the second half of training, the experimental group played the game Call of Duty 2. This game puts the player into fictional or fictionalized World War II combat situations. Although Call
of Duty 2 has more goals than Unreal Tournament 2004®, they remained somewhat crude when compared with the control game (both in terms of variety – nearly all goals in Call of Duty 2 involved things like taking a bunker, a farmhouse, or a ridge – and in terms of the possible ways to reach the goal – all goals were accomplished simply by killing every possible enemy soldier). Because Call of Duty 2 did not provide quantitative data with which to assess improvement, subjects were retested on Unreal Tournament 2004 during the final two hours of training.

6.2.3.3. Game playing improvement

In order to quantitatively assess game improvement and engagement in training, several measures were used. For the control game, the best measure was money accumulated (which increases with positive actions such as being promoted or adding a member to the household and decreases with negative actions such as burning down one’s house or having a character die due to neglect). All subjects showed an exponential increase in accumulated wealth over the course of training. The time course of the accumulation was well fit by a polynomial function (wealth = 77(training hour)^2+1319(training hour) + 9191).

For the action game, kills and deaths in each block were used to calculate a skill metric ([Kills – Deaths]/[Kills+Deaths]). This score increased dramatically for all subjects at all levels of difficulty. For the easiest level of difficulty, the score went from .53 (around three times as many kills as deaths) to .97 (nearly zero deaths). For
the hardest difficulty level the score went from -.74 (around four times as many deaths as kills) to -.21 (approximately the same number of deaths and kills). These results demonstrate that both groups were engaged in their training and showed improvement on the training task.

6.3. Results

6.3.1. Motion coherence decision task: Raw Data

Accuracy was analyzed in a 2 (Test: Pre/Post) x 2 (Group: Action/Control) x 7 (Coherence: 0.8, 1.6, 3.2, 6.4, 12.8, 25.6, 51.2%) ANOVA (see Figure 6, top panels). The expected strong main effect of coherence was observed (F(6,138) = 513.7, p < .001, partial eta-squared = .96) with accuracy increasing with increasing coherence (.51, .53, .55, .61, .73, .89, .98). However, neither the main effect of test (Pre = .68+/-.05, Post = .69+/-.04, F(1,23) = 1.3, p = .26) nor any interactions with test approached significance. A significant interaction between group and coherence was observed (F(6, 138) = 2.4, p = .03, partial eta-squared = .08) with the action group having slightly higher accuracy at the 12.8% and 25.6% coherence levels, but as this was advantage was small and similar across tests it will not be considered further.

Mean reaction time for correct trials was also analyzed in a 2 (Test: Pre/Post) x 2 (Group: Action/Control) x 7 (Coherence: 0.8, 1.6, 3.2, 6.4, 12.8, 25.6, 51.2%) ANOVA (see Figure 6, bottom panels). As in the accuracy analysis, a strong main effect of coherence was observed (F(6,138) = 31.0, p < .001, partial eta-squared =
.57) with mean reaction time decreasing with increasing motion coherence (.834, .834, .821, .804, .759, .655, .551). However, unlike in the accuracy analysis, a strong main effect of test was observed (Pre = .823+/- .06, Post = .691+/- .05, F(1,23) = 12.2, p = .002, partial eta-squared = .35) as well as an interaction between test and group, with the action group demonstrating a larger decrease in RT than the control group between pre- and post-testing (Action: Pre = .809+/- .06, Post = .612+/- .05; Control: Pre = .691+/- .05, Post = .679+/- .05, F(1,23) = 9.6, p = .005, partial eta-squared = .29). While a significant interaction was also observed between test and coherence (F(6,138) = 2.6, p = .02, partial eta-squared = .05) with reaction time decreasing by a larger margin at low coherences than high coherences, the three-way interaction between test, group, and coherence was not significant (F(6,138) = 1.7, p = .12, partial eta squared = .07).

The qualitative pattern of results is consistent with the VGP/NVGP data from Chapter 2. No change in accuracy was observed in either group, however, the action-trained group demonstrated a large reduction in reaction time relative to the control trained group. As in Chapter 2, the diffusion-to-bound model was fit to the data in order to quantify the relative changes in integration rate and decision criteria.
Figure 6. Performance on Motion Discrimination Task Before and After Training

A. While no change in accuracy was observed in the group trained on the action video game (Top Panel), a sizeable reduction in RT was observed (Bottom Panel). B. The group trained on the control video game showed no change in either accuracy (Top Panel) or RT (Bottom Panel).

*Note – Model fit corresponds to best fit to the mean data rather than the fit given by the mean individual fits.

6.3.2. Motion coherence decision task: Model Data

The same diffusion-to-bound model as in Chapter 2 was fit to the data of the trainees. The model fits were good ($R^2 > .9$) and did not differ as a function of group or test (all $p > .1$). Each of the three model parameters (A/bound, k/sensitivity, and TR/residual time) was analyzed in a 2(Test: Pre/Post) x 2 (Group: Action/Control)
ANOVA. For the bound parameter A, both a main effect of test (F(1,23) = 7.4, p = .01, partial eta-squared = .24) and a test x group interaction (F(1,23) = 6.7, p = .02, partial eta-squared = .23) were observed. The bound parameter decreased in both groups (Action: Pre = .75+/-0.05, Post = .57+/-0.06; Control: Pre = .61+/-0.06, Post = .60+/-0.05), but by a larger margin in the action group. It should be noted that although the bound parameter was larger in the action group than the control group at pre-test, this difference was not significant in a post-hoc analysis (p = .11).

For the rate/sensitivity parameter k, both a main effect of test (F(1,23) = 17.0, p = .02, partial eta-squared = .2) as well as an interaction between test and group (F(1,23) = 19.6, p = .02, partial eta-squared = .23) were observed with the action group improving significantly at post-test while the control group did not change (Action: Pre = 6.9+/0.6, Post = 9.3+/0.6; Control: Pre = 7.1+/0.8, Post = 7.0+/0.7).

Finally, neither the main effect of test nor a group x test interaction approached significance for the residual reaction time parameter TR (all p’s > .8).

6.3.3. Auditory localization decision task: Raw Data

Accuracy was analyzed in a 2 (Test: Pre/Post) x 2 (Group: Action/Control) x 8 (SNR: 1:64, 1:32, 1:16, 1:8, 1:4, 1:2, 1:1) ANOVA (see Figure 7, top panels). The expected strong main effect of SNR was observed (F(7,161) = 608.1, p < .001, partial eta-squared = .96) with accuracy increasing with increasing SNR (.52, .52, .57, .78, .94, .97, .98). However, no other effects were significant.
Mean reaction time for correct trials was also analyzed in a 2 (Test: Pre/Post) x 2 (Group: Action/Control) x 8 (SNR: 1:64, 1:32, 1:16, 1:8, 1:4, 1:2, 1:1) ANOVA (see Figure 7, bottom panels). As in the accuracy analysis, a strong main effect of SNR was observed (F(7,161) = 62.0, p < .001, partial eta-squared = .73) with mean reaction time decreasing with increasing SNR (.855, .855, .824, .710, .565, .498, .465, .457 secs). However, unlike in the accuracy analysis, a strong main effect of test was observed (Pre = .704+/-.07, Post = .602+/-.06, F(1,23) = 15.3, p = .001, partial eta-squared = .40) as well as an interaction between test and group, with the action group having a larger decrease in RT than the control group between pre- and post-testing (Action: Pre = .659+/-.09, Post = .542+/-.07; Control: Pre = .644+/-.06, Post = .612+/-.05, F(1,23) = 5.4, p = .03, p-eta2 = .19). A significant interaction was also observed between test and SNR (F(7,161) = 4.1, p < .001, partial eta-squared = .15) with reaction time decreasing by a larger margin at low SNR than high SNR, but the three-way interaction between test, group, and coherence was not significant (F(7,161) = 0.7, p = .64, partial eta squared = .03). As was true in the motion task, the qualitative pattern of results is consistent with the pattern observed in the VGP/NVGP populations in Chapter 4. Mean accuracy did not change as a function of training or group. Mean RT decreased in both groups, particularly at the lower levels of SNR, but overall RT decreased by a larger margin in the action group. Again, the diffusion-to-bound model was fit to the data to quantify the changes in criteria and integration rate.
Figure 7. Performance on Auditory Localization Task Before and After Training

A. While no change in accuracy was observed in the group trained on the action video game (Top Panel), a sizeable reduction in RT was observed (Bottom Panel). B. The group trained on the control video game showed no change in accuracy (Top Panel) and a much smaller reduction in RT, mainly for those levels of SNR where accuracy was near chance (Bottom Panel).

*Note – Model fit corresponds to best fit to the mean data rather than the mean of the individual fits.

6.3.4. Auditory localization decision task: Model Data

The same diffusion-to-bound model as in Chapter 4 was fit to the data of the trainees. The model fits were good ($R^2 > .9$) and did not differ as a function of group or test. Each of the three model parameters ($A$/bound, $k$/sensitivity, and TR/residual time) was analyzed in a 2(Test: Pre/Post) x 2 (Group: Action/Control) ANOVA. For
the bound parameter A, only a main effect of test \( F(1,23) = 6.1, p = .02, \) partial eta-squared = .2 was observed. The test x group interaction was not significant \( F(1,23) = 1.7, p = .2, \) partial eta-squared = .07) as the bound parameter in both groups decreased at post-test (Action: Pre = .65+/- .06, Post = .50+/- .06; Control: Pre = .66+/- .05, Post = .62+/- .05).

For the rate/sensitivity parameter k, a main effect of test \( F(1,23) = 18.5, p < .001, \) partial eta-squared = .44) was observed. The interaction between test and group was marginally significant \( F(1,23) = 4.2, p = .026 \) one-tailed, partial eta-squared = .16) as both groups had an increase in k, but the difference was larger in the action group (Action: Pre = 17.6+/- 1.0, Post = 22.6+/- 1.0; Control: Pre = 15.8+/- 1.1, Post = 17.5+/- 1.5).

Finally, neither the main effect of test nor a group x test interaction approached significance for the residual reaction time parameter TR (all p’s > .7).

6.4. Video Game Training: Discussion

As was the case in the VGPs of Chapters 2 and 4, following 50 hours of action video game experience, reaction time dropped substantially without a concurrent drop in accuracy in both the motion direction discrimination task as well as the auditory integration task. This pattern was well fit in the diffusion-to-bound model by an increase in the rate of sensory integration along with a decrease in criterion. Significant interactions in both tasks between test and group indicated that the increase in the rate of integration was significantly greater in the action-trained group
than the control trained group. Therefore, these findings cannot be attributed to simple test-retest or Hawthorne-like effects. Although the bound parameter decreased in both tasks for the action-trained group, the group by test interaction was significant only in the case of the motion task. Therefore, although it appears that a reduction in criterion is associated with action video game experience, it is less clear-cut than in the case of an increase in the rate of sensory information accrual.
7. Conclusions

Over the past twenty-five years, a growing body of literature has indicated that video game experience has the potential to enhance basic perceptual, motor, and/or cognitive processes. While each report in the literature posited a different independent enhancement, whether in the capacity of visual attention, the spatial resolution or temporal resolution of visual attention, the ability to divide attention, the general speed of processing, the efficiency of visual search, the susceptibility to distractors, or the formation of stimulus-response mappings, we have put forth the hypothesis that a single mechanistic change, an increase in the rate at which sensory information accrues, can account for the majority of the findings in the literature. By making use of two sensory integration tasks, one in the visual modality and one in the auditory modality, we have demonstrated that indeed, video game experience is correlated with an increase in the rate at which sensory information accumulates. By training NVGPs on an action video game and observing similar changes, we have further demonstrated that the relationship between video game experience and this increased rate of sensory information accrual is causative.

However, while we have good evidence for this mechanistic change as a result of video game experience, it would be beneficial to explore how such a change in the rate of sensory integration could be exhibited neurally. A model developed by Pouget and colleagues attempts to model performance on the dot motion decision task in a neurally plausible manner. In this model, a layer of independent Poisson neurons with Gaussian tuning curves for motion direction represent area MT. These neurons
feed onto an integration layer composed of 100 linear/non-linear Poisson (LNP) neurons representing area LIP. These LIP neurons have lateral connections and a long time constant, which in essence makes them near perfect integrators of the sensory information being passed from MT (at least over the time scale of a typical trial). The weight on the feed-forward connection between area MT and area LIP determines the rate at which sensory information accrues (essentially acting similar to the sensitivity). A decision is made when the peak activity in a given LIP neuron reaches a certain rate in Hz. Interestingly, in a manner consistent with what was observed in the diffusion-to-bound model of Palmer and colleagues, the difference between VGP and NVGP performance can be well captured in this model by increasing the weight on the feed-forward connections as well as decreasing the stopping bound in the VGP group. Because “more” sensory information reaches area LIP from area MT, the rate at which sensory information grows over time is obviously greater in the VGP population. However, as was the case in the diffusion-to-bound model, a decrease in the stopping bound is required to match the particular pattern of results, with VGPs faster but with the same accuracy as the NVGPs.

Although the exact brain areas that contribute to performance in the auditory integration task are not known, the model of Pouget and colleagues suggests that a change in the rate of integration rate would likely be manifested as a change in the connections between sensory and integration areas (rather than for instance a change in the lateral connections between integration neurons). If the changes in rate are truly manifested at the level of connections between sensory and integration areas, it
would suggest that the rate at which auditory information is accrued might be reasonably independent of the rate at which motion information is accrued (there being no a priori reason to believe that, among those with normal vision and hearing, individuals with extremely good hearing would also have extremely good vision and vice versa). Conversely, one might imagine that the “bound” is set by a higher level structure that controls the integration of information across modalities. In this case one would expect to find a significant correlation between the bound parameters in the two integration tasks. Individuals who are willing to make decisions with less information would likely be willing to do so regardless of the task. These predictions are indeed born out by the data. No correlation is observed between the motion and auditory integration rates. Although VGPs tend to have higher integration rates for both motion and auditory information, there is no correlation in individual subject performance (see Figure 8A – Top Panel). Indeed, the VGP with the highest rate of auditory integration also showed the lowest rate of motion integration. The same pattern (or lack thereof) is observed in the data from the video game trainees (Figure 8A – Bottom Panel). Conversely, a strong linear relationship with a slope of approximately 1 is observed between the bound parameters (see Figure 8B – Top Panel). Again, while VGPs tend to have lower bound parameters than NVGPs for both the motion and auditory tasks, there is also a strong correlation in the bounds of individual subjects. For instance, the NVGP with the highest motion bound also demonstrated the highest auditory bound and the VGP with the lowest auditory bound
demonstrated the second lowest motion bound. Again, the same pattern was observed in the video game trainees (Figure 8B – Bottom Panel).

Figure 8. Correlations between auditory and motion parameters

A. No relationship is observed between the rate of auditory integration and the rate of motion integration in either the VGPs/NVGPs (Top Panel) or in the trainees (Bottom Panel). B. A strong linear relationship is observed between the auditory and motion bounds in the VGPs/NVGPs (Top Panel) as well as the trainees (Bottom Panel).

One might further wonder whether the bound and the integration rate are truly independent factors or whether they might be correlated. While this would not be
It will be for future work to determine why the VGPs, who acquire information more rapidly than NVGPs, manifest this enhancement through extremely fast RTs rather than extremely accurate responses. Theoretically, the VGPs could have chosen to wait as long as the NVGPs before making a decision and in doing so would have instead demonstrated an accuracy advantage.
One possible hypothesis is that subjects are attempting to maximize reward per unit time (Gold & Shadlen, 2002). If this is indeed the case, once given the rate of sensory integration, the residual time, the time between trials, and some quantization of the reward (i.e. – the utility of the reward), the value of the bound that maximizes reward per unit time can be calculated. When a simple linear mapping between correct beeps and reward (i.e. – one beep = one util with no temporal discounting) is employed, the trends are in the predicted direction with VGPs being closer to the optimal reward rate than the NVGPs. However, both VGPs and NVGPs demonstrate bounds that are substantially higher than those which would correspond to the optimal reward rate. This may reflect either a simple failure to maximize or may indicate that the simple linear mapping does not truly capture the utility of the “rewards” (correct/incorrect beeps). Our experimental design does not allow us to measure how rewarding subjects find the “correct beep” or “correct green square,” how punishing they find the “incorrect beep” or “incorrect red square,” or how they temporally discount those values (i.e. a reward right now is typically “worth more” than the same reward sometime in the future). Future directions in this field will therefore likely include quantitative measurements of the utility function, such that the amount of reward acquired per unit time can be more precisely calculated.
8. References


