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3

The Perceptual and Cognitive Effects of Action Video Game Experience

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Introduction

For decades, the prevailing view in the field of cognitive neuroscience was that, upon reaching maturity, the adult brain settles into a relatively fixed, unchanging state. Consistent with such an interpretation, for instance, significant effort was put into delineating more or less plastic stages of development (e.g., critical periods; Wiesel & Hubel, 1963). More recently, however, this view has shifted substantially, with current research establishing that the brain possesses an enormous capacity for reorganization throughout the lifespan (Bavelier, Levi, Li, Dan, & Hensch, 2010). Even some critical periods that were previously believed to be quite rigid have since been shown to be flexible and in fact can often be reopened via behavioral means (e.g., through dark exposure; He, Ray, Dennis, & Quinlan, 2007). Such research on neural plasticity has spurred tremendous interest in the development of training regimens to improve brain function in domains ranging from motor skill, to vision and hearing, to broader classes of high-level cognition.

However, while we now know that the human brain retains some level of plasticity even into old age (obviously not at equivalent levels in each age range), a major obstacle remains. This obstacle has been dubbed the "curse of specificity" (Bavelier, Green, Pouget, & Schrater, 2012), and it refers to the fact that although humans show increases in performance on virtually any task given appropriate practice, the enhancements are typically limited to the exact characteristics of the trained task; little or no transfer of learning is observed to even seemingly highly similar untrained tasks (Fahle, 2005). For instance, in seminal work by Fiorentini and Berardi (1980) in the domain of perceptual learning, participants were trained to discriminate between two complex gratings. Over the course of three sessions of training, performance improved from chance levels all the way to ceiling levels. Yet, when the gratings were altered in seemingly minor ways (e.g., in orientation or spatial frequency), subject performance returned to chance levels. Similar specificity has been seen for low-level features such as retinal location, motion direction, motion speed, or even the trained eye. Furthermore, although such specificity has been perhaps most thoroughly described in the field of perceptual learning, it has been documented in essentially all fields that focus on learning, including motor learning, training of high-level cognitive skills such as working memory, and even in education (Barnett & Ceci, 2002; Redick et al., 2013; Tremblay, Houle, & Ostry, 2008). It should be intuitively obvious how significant an impediment such specificity can be for those whose goal is to construct learning paradigms for practical purposes such as rehabilitation (where success necessarily requires benefits that extend beyond the exact laboratory setup).

Interestingly, there are a variety of types of experience, which often correspond to real-world activities that have been shown to produce learning that extends beyond the specifics of the trained contexts. Music training is one such domain. In one study, for example, children who received musical training (vocal or keyboard), showed significantly larger improvements on the Wechsler Intelligence Scale for Children (which clearly bears little resemblance to vocal or keyboard training) than did children who received drama training (Schellenberg, 2004). Similarly, in the athletics domain there are myriad examples wherein individuals with extensive experience playing a given sport demonstrate enhanced abilities at basic laboratory tests (Kida, Oda, & Matsumura, 2005; Lum, Enns, & Pratt, 2002). There is the further focus of this review—playing action video games (Green & Bavelier, 2012).

Before examining these effects, we briefly discuss what makes a game an "action" video game. While there are no quantitative rules that can be applied to perfectly separate the various video game genres, there is a set of qualitative features that all action games share. In particular, action video games are those that involve exceptional speeds (both in terms of the velocity of moving items and the brevity of transient events). These games also involve extraordinary perceptual load (whereby the individual must track many objects), cognitive load (which entails considering many possible outcomes), and/or motor load (which involves engaging in multiple action plans). The games also involve temporal and spatial unpredictability and require a high degree of peripheral processing. Games that fit these criteria include so-called first-person shooter games like the *Call of Duty* series, third-person shooter games like the *Gears of War* series, and some car driving games. To one not familiar with the various video game genres, these may seem like unimportant points, but we have seen that the effects of playing various video games depends highly on the games' content and structure (Cohen, Green, & Bavelier, 2007). Simply put, not all games produce the same types of benefits, if they provide benefits at all.

Here we review the ever-growing literature on the effects of video game experience on vision, attention, and cognitive skills. Although the paradigms that will be reviewed were designed to test processes that are thought to be

relatively independent, at the conclusion we will suggest that the results of each can potentially be accounted for by a single common underlying mechanism. As the majority of the literature has compared the performance of expert action video game players (VGPs: usually defined as individuals who play more than five hours a week of action video games) against non-action video game players (NVGPs: who play no action games, though they may play other game genres), we will adopt this focus for our review. However, as simple population differences do not themselves prove a causal link, we will specifically highlight studies that have demonstrated such a link through well-controlled training paradigms.

Spatial Characteristics/Resolution of Vision and Attention

Results from several different paradigms have established an enhanced ability to process spatial information across the visual field in VGPs. For instance, a number of labs have now compared VGP and NVGP performance on the Useful Field of View (UFOV) task, a modified visual search task initially developed by Ball, Beard, Roenker, Miller, & Griggs (1988). Briefly, this task requires participants to localize a very quickly flashed target shape from among a field of distractor shapes. VGPs have demonstrated far superior localization performance on this task as compared to NVGPs in both college-aged adults (Feng, Spence, & Pratt, 2007; Green & Bavelier, 2003, 2006a) and school-aged children (Dye & Bavelier, 2010). Furthermore, the same result has been repeatedly observed in NVGPs specifically brought to the lab and trained on action video games, thus establishing a causal link between video game playing and enhanced performance (Feng et al., 2007; Green & Bavelier, 2003, 2006a; Spence, Yu, Feng, & Marshman, 2009). Similar results have been also seen in the "swimmer task" developed by West and colleagues (West, Stevens, Pun, & Pratt, 2008), and the crowding paradigm (Green & Bavelier, 2007), which both require participants to localize targets from within a field of distracting objects. It is worth noting that in each of these cases, the stimuli did not in any way resemble the rich and complex environments of action video games (they instead used incredibly simple sets of lines and basic shapes). Performance was also tested well into the periphery of the field of vision (e.g., as far as 25° to 30°), which is beyond the typical field of view used while playing (Green & Bavelier, 2007). This type of transfer across both stimulus type and retinal location stands in stark contrast with the perceptual learning literature reviewed previously. Finally, the VGP advantage in spatial abilities is not limited to tasks that have employed displays with extremely limited presentation times. A clear VGP advantage has also been shown in visual search tasks that use reaction time as the primary dependent measure (i.e., the search display is present until the subject finds the target and presses the relevant key). More specifically, these studies have shown that VGPs require less time to process each item across the display (Castel, Pratt, & Drummond, 2005; Hubert-Wallander, Green, Sugarman, & Bavelier, 2011).

Differences in low-level spatial resolution in tasks that are not commonly thought to be limited by visual attention have also been considered (i.e., tasks in which targets appear at a known time and place in the absence of distractors and thus "attention" as it is typically conceived of would not be called upon). For instance, acuity was measured by assessing the smallest T that could be correctly identified as right side up or upside-down (Green & Bavelier, 2007). Similarly, contrast sensitivity was measured via a 2-interval forced choice (2IFC) task in which one interval contained a low-contrast Gabor patch—that is, a sinusoidal grating vignetted by a Gaussian envelope (Li, Polat, Makous, & Bavelier, 2009). In both cases VGPs demonstrated enhanced performance compared to NVGPs (although only in the latter case was there a significant effect of action video game training). Together this overall body of results demonstrates an enhancement in the spatial characteristics and resolution of visual and attentional processing that is due to playing action video games.

Temporal Characteristics/Resolution of Vision and Attention

Differences in the temporal characteristics of vision in VGPs have been measured using a variety of paradigms. For instance, in the standard attentional blink paradigm (Shapiro, Arnell, & Raymond, 1997), participants view a stream of visually presented letters, all of which are black except one target letter, which is white. Although participants can typically successfully identify the white letter, its presence creates a momentary "blink" of attention and thus they often fail to detect a second target that is presented shortly after. The magnitude of this blink is significantly reduced in both adult and child VGPs (Dye & Bavelier, 2010; Green & Bavelier, 2003) and in adults after action video game training (Green & Bavelier, 2003). Similarly, VGPs are capable of performing orientation discrimination tasks at a significantly shorter presentation time than NVGPs (Li et al., 2009) and have significant reductions in the negative effects of backward masking (Li, Polat, Scalzo, & Bavelier, 2010). Again, as was true of the spatial tasks, these temporal processing measures were sterile laboratory tasks completely unlike action video game environments. Thus, these findings suggest that a more general enhancement occurs in the temporal characteristics of visual processing after action video game training.

Capacity/Flexible Allocation of Attentional Resources

In addition to the spatial and temporal aspects of attention, one's attentional capacity and how these attentional resources are distributed are also modified via action video game training. For instance, the multiple object-tracking task measures the number of moving target items that can be successfully tracked within a field of moving items, which act as distractors and are visually identical to the target items. In one version of the task, VGPs were able to track approximately two more items than NVGPs at a criterion level of performance (Green & Bavelier, 2006b) with similar effects being reported in child action gamers (Dye & Bavelier, 2010; Trick, Jaspers-Fayer, & Sethi, 2005). A training study showed the same results, demonstrating a causative link (Green & Bavelier, 2006b). The same basic enhancement in capacity has also been observed in an enumeration paradigm. In this task, white squares were briefly flashed on a black background followed by a mask. Participants were asked to determine the number of squares that were presented. VGPs were able to accurately count a greater number of quickly flashed items than NVGPs given the same display duration (Green & Bavelier, 2006b).

Executive Functions

Several authors have noted performance increases in action video game players on tasks that are commonly thought to tap executive functions. For instance, one common measure of executive function and attentional control is the time it takes to switch between competing tasks. Many different labs have noted a reduction in the size of this "switch cost" in VGPs and in action game trainees (Colzato, van Leeuwen, van den Wildenberg, & Hommel, 2010; Karle, Watter, & Shedden, 2010; Strobach, Frensch, & Schubert, 2012). Furthermore, in our own work we have shown that this effect is not due to a simple increase in the ability of VGPs to map decisions onto button presses (Green, Sugarman, Medford, Klobusicky, & Bavelier, 2012). Indeed, the overall size of the VGP advantage held even when all participants were allowed to give a vocal response rather than to execute a button press response (the assumption being that VGP participants should not be disproportionately practiced at speaking). A second executive-type skill on which VGPs show an advantage is multitasking. For instance, the UFOV task discussed earlier can be performed with or without a concurrent central identification task. While the presence of this additional task greatly interferes with the ability of NVGPs to search, VGPs are able to perform both tasks with little performance decrement (Green & Bavelier, 2006a).

Work from our lab has also addressed the common belief that the RT differences can be explained by video game players potentially showing more impulsivity than NVGPs (Dye, Green, & Bavelier, 2009b). To assess this issue, the Test of Variables of Attention (TOVA) was administered to VGPs and NVGPs. This test requires participants 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 (i.e., the test is a go/no-go task). In different blocks of trials, the target (go) can appear either frequently or infrequently. The TOVA therefore offers a measure of both impulsivity (i.e., whether the subject is able to withhold a response to a nontarget when most of the stimuli are targets) and a measure of sustained attention (i.e., whether the subject is able to stay on task and respond quickly to a target when most of the stimuli are nontargets). 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.

Possible Neural Changes Underlying These Effects

There are several underlying neural mechanisms that may support the enhanced attentional skills noted in VGPs. One that has been recently tested is the ability of VGPs to filter or suppress task irrelevant items. Mishra, Zinni, Bavelier, and Hillyard (2011) measured EEG signals while VGPs and NVGPs performed a selective attention task. Multiple streams of letters flashed to the left, right, and above fixation, but on any given trial the participants were instructed to attend to only one stream (looking for the occasional digit to appear in the stream) and ignore the other streams. To quantify neural processing, the authors made use of the Steady State Visually Evoked Potential (SSVEP) technique, wherein the various streams are presented at different temporal frequencies (i.e., one stream might be presented at a rate of one item every 83 ms or 12 Hz; another stream might be presented at a rate of one item every 67 ms or 15 Hz, etc). Because neural populations tend to phase lock, the amount of power at these frequencies can then be extracted from the EEG signal and used as a measure of the amount of processing devoted to the stimuli flashing at each frequency. The authors were thus able to assess the neural processing devoted to both the attended and unattended streams. While the two groups showed an equivalent increase in processing devoted to the attended stream, the VGPs showed far greater suppression of processing resources devoted to the unattended stream. Other recent work also indicates major changes in the brain systems that mediate top-down attention in VGPs. For example, a recent fMRI study indicates that recruitment of the fronto-parietal network thought to underlie attention is weaker as attentional

demands increase in VGPs, which is consistent with the proposal of increased efficiency in top-down attention in VGPs (Bavelier, Achtman, Mani, & Focker, 2011). Indeed, a decrease in blood-oxygen-level-dependent (BOLD) signal along with enhanced behavioral performance (e.g., faster reaction times or higher d') appears to be a signature of skills that become less effortful and more automatized (Raichle et al., 1994).

Exogenous Attention Does Not Appear to Be Strongly Affected by Action Game Experience

Not all aspects of visual processing appear to be altered via experience with action video games. Interestingly, an aspect that one may have predicted a priori to be significantly taxed by action video games—namely the ability to orient attention toward exogenous cues—does not appear to be altered via action video game experience. Several studies, using both the classic Posner cueing paradigm and the Attentional Network Test, have now examined the time course with which attention is automatically pulled by exogenous cues (Castel et al., 2005; Dye, Green, & Bavelier, 2009a; Hubert-Wallander et al., 2011). Although, as has been seen throughout the literature, VGPs responded faster to targets independent of cueing condition, there was no systematic change indicative of an enhancement of exogenous attention (although see West et al., 2008, for a positive result).

A Common Mechanism—Faster Integration

Based on the results reviewed thus far, any possible single mechanistic explanation must be able to predict (1) increases in VGP accuracy in tasks where participants are asked to make unspeeded perceptual judgments about quickly flashed displays; and (2) decreased RTs in tasks where participants are asked to respond to perceptual stimuli as quickly as possible, noting that previous work has eliminated explanations that refer to additive components of a task, such as simple speeding up of motor execution once response selection has occurred (Dye et al., 2009b). 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 should be more accurate than NVGPs in accuracy-based tasks because they are able to extract more information from the flashed displays, whereas in speeded tasks this faster integration would be manifested as quicker RTs.

However, while certainly suggestive, none of the previous tasks previously reviewed were ideal to examine this hypothesis. Therefore, as a more specific test of the hypothesis that VGP experience results in faster integration of information, we made use of a perceptual decision-making task that requires the integration of information over time (Green, Pouget, & Bavelier, 2010).

The coherent dot motion direction discrimination task has been used extensively both in the human literature (Palmer, Huk, & Shadlen, 2005) and animal literature (Roitman & Shadlen, 2002) to assess the rate at which information is accumulated over time. In this task participants 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, as the percentage of consistently moving dots approaches zero, RTs become slow and accuracy approaches chance-level.

The motion direction discrimination task is of particular interest because 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 examine the qualitative pattern of results, and to ask in a quantitative fashion which component of the decision making process is modified by action video game experience.

As predicted based on the wealth of previous experimental data reviewed above, VGPs were found to be significantly faster than NVGPs across all levels of coherence. A significant interaction between coherence and group indicated once again that an additive component could not explain the results. Interestingly however, accuracy was perfectly equivalent between groups. While fitting this particular pattern of results (nonadditive reduction in reaction time and equivalent accuracy) using standard quantitative models (Palmer et al., 2005) requires a perfect trade-off between an increase in sensitivity and a decrease in decision threshold, we found—using a newly proposed neural model of the task (Beck et al., 2008)—that the difference between VGPs and NVGPs could be captured via a change in a single parameter, namely, the conductance of the connections between the input and integration layers. Consistent with our hypothesis above, this parameter does indeed control the amount of information that is processed per unit time.

Furthermore, because the prediction of an increase in the rate at which information is processed need not include only *visual* information, an auditory analog of the motion direction task was also developed. In this experiment, 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 participants' 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 was the case in the motion discrimination task, VGPs were found to be significantly faster than NVGPs, but with equivalent accuracy. Again, this pattern was well-captured by a single change in the conductance parameter of the neural model.

Although a thorough discussion is beyond the scope of this review, it is interesting to examine these results through the theory of Bayesian decision-making. From this perspective, the best a subject can do is to calculate the probability that the various possible options are correct given the current evidence, a probability distribution known as the posterior distribution over choices (denoted $p(c|e)$ where c are the choices and e is the evidence). According to Bayes's rule, calculation of the posterior depends on knowledge of the likelihood, or the statistics of the evidence (denoted $p(e|c)$)—or in other words, given that the correct option is choice n, what is the probability of receiving the current evidence? Initially, there is no way for participants to know this (i.e., because they have never before seen choice n, there is no way to know the probability of receiving various types of evidence given n) and thus the posterior over choices that they compute will be suboptimal. Over time, the statistics of the evidence can be learned, which in turn will lead to a more accurate posterior being calculated. All of the tasks that have been reviewed in this paper can be formalized in this manner with one slight addition: the insertion of time into the equation. Although it may be initially unintuitive for those tasks employing briefly flashed displays, each of the tasks is an integration task at its root; information is presented over time that must be accumulated. The quantity of interest is therefore the probability of the choice given the evidence that has accrued from the beginning of the trial until the current time. Assuming independence across time, this quantity is simply the product of the posterior at each time step. Failing to perform this multiplication step accurately at each time step will also result in the computation of a suboptimal posterior. The reason this situation is of particular interest to us is that the neural model used to fit the data above has a clear probabilistic interpretation. Increasing the conductance parameter is the same as having better knowledge of the statistics of the evidence or more accurately performing the above multiplication step. Because, as mentioned above, there is no a priori way for participants to know the statistics of the evidence, this suggests that the VGP advantage may be explained in terms of the ability to very rapidly and accurately learn these statistics—in essence the VGPs have "learned to learn."

Summary of the Effects of Action Video Games

Over the past decade, a growing body of literature has indicated that action video game experience has the potential to enhance basic perceptual, motor, or cognitive processes. While each report in the literature has 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 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. Such a mechanism would indeed predict the major patterns of results that have been seen. Tasks with accuracy as the primary dependent measure largely consist of quickly flashed displays. An increase in the efficiency with which sensory information is accumulated from the display would result in greater accuracy, which is what is observed in VGPs. In tasks with RT as the primary dependent measure, accuracy is typically near ceiling, making these tasks essentially a "race" toward the correct answer. An increase in the rate at which information is accumulated would result in faster RTs, which again is what is observed in VGPs. From a Bayesian perspective, the ability to accumulate sensory evidence depends highly on knowledge of sensory statistics, which must be learned through experience with a task. Viewed through this framework, what action video game experience teaches individuals is to quickly and accurately learn these statistics—essentially to "learn to learn." This type of learning would explain why the effects of video game experience transfer so widely beyond the game environment and may serve as a hallmark for training regimes that will lead to highly general learning.

Lessons for Educational Games

Although researchers and entrepreneurs alike have recognized the potential of video games to make real-world impact in classroom settings, thus far the successes have been somewhat limited, particularly in contrast to the widespread benefits to general perceptual and cognitive abilities conveyed by action video games. A number of key differences between commercial action video games and typical educational games may explain this disparity in outcome. First, action video games, as part of the very nature of the experience, place players in biophysiological states known to promote learning and plasticity. For instance, for more than one hundred years psychologists have argued that some level of physiological arousal, such as that engendered by action video games (Barlett, Branch, Rodeheffer, & Harris, 2009), more strongly promotes learning than very low arousal states (Yerkes & Dodson, 1908). Furthermore, the emotional content and richly structured storylines and scenarios result in strong activation of the dopaminergic system (Koepp et al., 1998), which in addition to being implicated in the processing of reward (Dayan & Daw, 2008), also appears to play a role in permitting plasticity (Bao, Chan, & Merzenich, 2001). Educational games in contrast have often eschewed these factors in favor of utilizing the highly repetitive "practice-makes-perfect" structure that is easily afforded by computerized paradigms. Unfortunately, doing so strips games of any potential power, instead creating what amounts to little more than flashcards. Among those that create and study video games, these types of games have earned the pejorative nickname "chocolate covered broccoli" in that they are little more than basic and boring drills dressed up in a thin video game shell. Furthermore, in addition to arousal and reward, there are a number of other factors present in action video games (and indeed, in most successful commercial games in general), which theoretical work suggests should strongly promote transfer (Bavelier et al., 2012; Schmidt & Bjork, 1992). Perhaps most important is that in most commercial games, the information to be learned is used in many contexts and domains. Such variety has often been lacking in educational games, which may further explain their relative lack of efficacy. Finally, the idea of "learning to learn" is not a new one in psychology (Binet, 1909; Harlow, 1949; Thorndike & Woodworth, 1901). It may be worth considering how to structure an educational video game such that it not only promotes the learning of the specific material at hand but also enhances the ability of users to acquire content in new situations (Bavelier et al., 2012).

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