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Enhancing Attentional Control: Lessons from Action Video Games

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The possibility of leveraging video games for enhancing behavior and brain function has led to an emerging new field situated at the crossroads of cognitive neuroscience, health science, educational interventions, and game design. Here we review the impact of video game play, in particular action video game play, on attentional control. We also examine the underlying neural bases of these effects and the game design features hypothesized to drive the plastic changes. We argue that not all games have the same impact, with both differences in the characteristics of the games themselves as well as individual differences in player style determining the final outcome. These facts, mixed with changes in the game industry, (e.g., greater mixing of genre characteristics; greater freedom of player experience) calls for a paradigm shift relative to the approach taken in the field to-date, including iteratively alternating between targeted game design and efficacy evaluation.

Over the past thirty years, video games have grown from a reasonably niche hobby to a pervasive part of modern culture. The most obvious area of growth is within the entertainment sphere. In terms of dollars grossed, the video game industry has out-earned the film and music industries combined in each of the past eight years (LPE, 2018). Video games are also increasingly challenging the sports industry, with some estimates suggesting that eSports viewership will exceed the viewership of every major American professional sport other than football by the year 2021 (Syr.edu, 2019). However, beyond simple entertainment, video games are increasingly found in many other areas of daily life. For instance, video games are now recognized as a new form of art, as testified by numerous video game exhibits in high profile museums and academic discussion of video games as a means of creative expression (Eveleth, 2012; Naskali et al., 2013). Video games are likewise ever more commonly found in educational settings. Interestingly, the games found in the educational sphere are not just "educational games" (i.e., video games designed for the express purpose of teaching educational content such as *Prodigy* or *Quest Atlantis*; Li and Tsai, 2013), but also include a host of commercial titles as well (e.g., *Civilization*, *Portal*, and *Minecraft*; Nebel et al., 2016; Steinkuehler and Squire, 2014). Finally, video games are also ever more commonly seen in the medical realm, whether it may be as a means to reduce pain in patients (Sil et al., 2014) or as a way to teach young cancer patients about their disease and treatment (*Re-Mission*; Kato et al., 2008).

Interestingly, as we will see below, many of the characteristics inherent in good video games, in addition to undoubtedly playing a role in their mass popularity, also make them excellent tools for the study of human learning and neuroplasticity. These include providing strong reward signals, which is key not only for driving the type of long-term motivated behavior that is capable of producing learning and neuroplasticity but also for activating neural systems that place the brain in a more plastic state. It also includes placing sustained load on different behavioral systems (be they motor, perceptual, or cognitive), which in turn necessitate a change in neural functionality.

Yet an important lesson in the scientific literature to-date is that not all games are created equal with respect to their impact on behavior and brain function. The term "video game" encompasses an enormous variety of possible experiences—from relatively slow-paced and heavily cerebral games (i.e., where players have as much time as necessary to come up with long-term plans) to frantic "button-mashers" (i.e., where the goal is simply to press a button as quickly as possible). Most of the literature we will review here focuses on one particular genre of video game, termed "action video games," as the impact of other video game genres on the brain and behavior has been much less studied. This state of affairs finds its roots in a chance discovery around the year 2000, whereby players of action video games, defined as first- or third-person shooter games, were noted to have outstanding attentional skills (Green and Bavelier, 2003). This initial result in turn guided much of the subsequent research in the field.

While research on the impact of action video games has dominated the cognitive psychology literature to-date, the video game ecosystem has evolved quickly since the turn of the century, undergoing both pronounced diversification as well as significant cross-fertilization across game genres. Most video games in the mid-1990s to early 2000s could be reasonably organized into a small set of genres based upon common mechanics (e.g., shooter, adventure, strategy, role-playing, fighting, etc.). In contrast, today there are more than 50 distinct game genres listed by the industry (Wikipedia Contributors, 2019). Moreover, as the field has developed, video games have tended to blend mechanics across genres, for instance by intertwining role-playing game mechanics with shooting game mechanics (e.g., *Skyrim* and *Mass Effect*). Given that previous research on video games has utilized game genre as a proxy for game mechanics, such cross-fertilization has had, and will continue to have, a direct impact on the research in this field (Dale and Green, 2017b). In particular, nearly all of the existing research on action video games was predicated on the idea that games from the action video game genre included gameplay elements that placed heavy load on the attentional systems in a manner that other game genres did not. Yet as the newer generation of video games increasingly mixes in action elements with elements from other genres, the well-specified and roughly one-to-one mapping between genre and mechanics has all but disappeared (Faisal and Peltoniemi, 2015). This has at least two main consequences for the neuroscience of video games. First, as games become richer and more varied, it will become harder for researchers to identify which specific aspects of gameplay truly foster cognition, or any other aspect of human behavior under study. Second, as genres become less well defined, it is likely that we will see video game play, at least as studied so far (i.e., by separating games by genre and then contrasting across genres) having a less focused and overall weaker impact. These two effects will likely conspire to create some confusion about the impact of video game play in the years to come and will call for a paradigm shift compared to much of the research reviewed below. We return to this point in our discussion.

Theoretical Framework—Reward and Attentional Control as Drivers of Learning and Brain Plasticity

In asking how and whether video games can be used to foster learning and brain plasticity, the existing research has been influenced by theoretical constructs that are shared across many domains that focus on the science of learning. In particular, this work has generally recognized at least two key drivers of learning: (1) reward, and the motivated behavior that it stimulates, and (2) attention, or the selection of task-relevant information and simultaneous suppression of task-irrelevant information (Kiili, 2005; Watanabe and Sasaki, 2015). The reward system clearly plays a direct role in learning, in that individuals learn the value of their actions and increase the frequency of actions that bring them closer to their goals. These reward systems, at the same time, are also known to be permissive to plasticity. Activation of the mesocorticolimbic dopaminergic projection is not only associated with reward-related cognitive behavior, but it also induces a brain state whereby connections between neurons are more easily modifiable (Kilgard and Merzenich, 1998). The attention system, at least in part, works in concert with reward systems. This includes magnifying the processing of information that is important for attaining reward and at the same time attenuating the processing of information that is goal-irrelevant (Leong et al., 2017). The attention system also acts as a guide to which information and processes are worth consolidating and automatizing to augment task performance. Note that the impact of both reward and attention are likely to apply at essentially every level of processing, from “low-level” perception and motor processing to “higher-level” conceptual representations. Yet, across all levels, these two mechanisms provide the necessary cornerstones to build rich internal models of the world. A growing literature in the neurosciences has proposed that such learning is likely mediated by a constant interplay between subcortical structures that support automatization, such as the basal ganglia, and frontal structures that support executive functions, such as goal maintenance, cognitive flexibility, memory updating, and inhibition (Botvinick, 2012).

Critically, not only are the reward and attentional systems major drivers of learning, but both are also highly engaged by action video games. For instance, essentially all good video games make use of both internal and external rewards to drive motivated behavior. External routes include rich incentivization systems whereby players are rewarded or punished based on their decisions, both in the moment and in future play, in a manner much akin to operant conditioning (Drummond and Sauer, 2018). Consistent with known best practices in driving animal behavior via the application of rewards, game designers often make use of variable-ratio reward schedules (usually multiple schedules running simultaneously) to ensure that players never know when the next action could produce a sizeable reward (Hodent, 2017). At the same time, game designers tend to limit major punishments, as punishment often produces unwanted side effects such as anger, hostility, or avoidance. Internal routes to reward include designing game play in order to satisfy certain basic human needs such as the needs for autonomy (i.e., the ability to make meaningful choices for oneself), competence (i.e., the ability to successfully reach goals), and social connectedness (Przybylski et al., 2010).

Interestingly, while the reward-related manipulations in games are clear at the behavioral level (Filsecker and Hickey, 2014), there are only few empirical studies explicitly examining the different ways video games engage reward-related brain systems. For example, one early study described heightened dopamine release during the play of a simplified shooter game (Koepp et al., 1998). More recently, players of a lab-designed video game that contained rewards outperformed individuals playing the same game without rewards on a declarative memory task (Prena et al., 2018). Such a result is consistent with the known dependencies between hippocampal learning, dopamine activity, and other reward-related mechanisms (Miendlarzewska et al., 2016). A few recent fMRI studies further make it clear that the reward system, in particular the striatum and its frontal projections, is activated during game play and may preserve reward responsiveness in the face of repeated exposure (Kühn et al., 2011; Lorenz et al., 2015). Finally, in a longitudinal study, Gleich et al. (2017) showed that passively watching rewarding in-game experiences was associated with greater hippocampal recruitment and lesser dorsolateral prefrontal cortex (DLPFC) engagement when participants had been playing the game compared to when they were unfamiliar with the game. This result is in line with the established role of the hippocampus in memory re-activation and that of the DLPFC in executive functions (as new situations are more likely to be effortful than familiar ones). However, it does not squarely demonstrate how video game play may exploit reward or punishment to impact learning (Howard-Jones and Jay, 2016), and thus more studies are needed to solidify our understanding of that set of relationships.

Considerably more work has focused on how video game play calls upon the attentional systems to eventually potentiate learning. Here we refer to attentional control as the ability to focus on the task at hand and to ignore sources of distraction or noise while at the same time constantly monitoring one’s

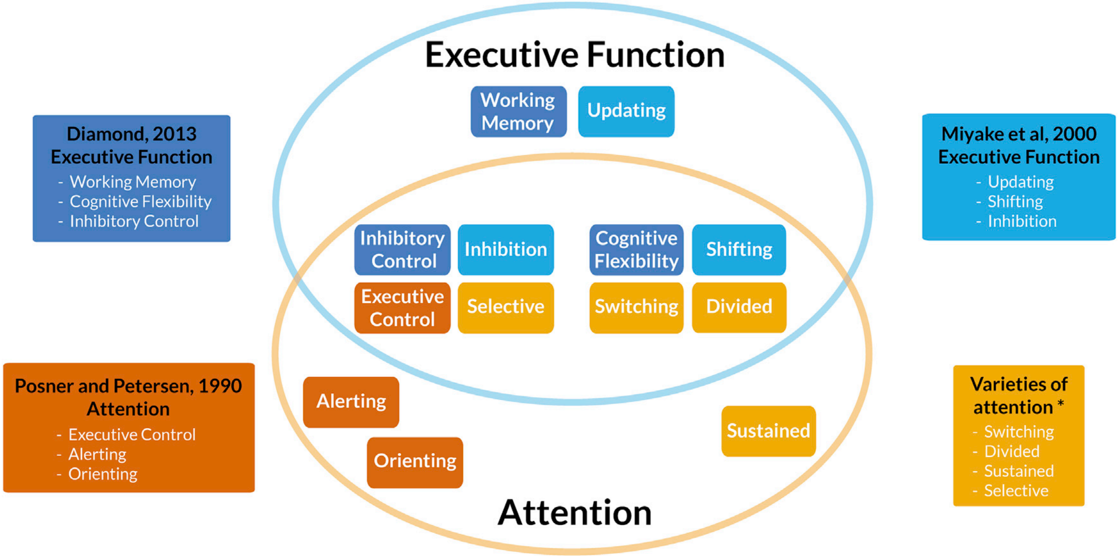

Figure 1. Depiction of Attentional Control Processes Showing the Overlap with Sub-processes from Either the Executive Function and Attention Literature

In this view, attentional control loads upon working memory/updating as well as cognitive flexibility/shifting/attention switching/divided attention. Note that under "Varieties of Attention," we refer the reader to Parasuraman and Davies (1984), Näätänen (2018), and Treisman (1969)—adapted from Peterson et al. (2016).

environment for new sources of information. Under this definition, attentional control thus not only entails what would traditionally be labeled selective attention (amplifying task-relevant information and dampening task-irrelevant information) but also shifts between selective and divided attention to allow a rich and fast changing environment to be consistently monitored. This definition also encompasses sustained attention, or at least a form of sustained attention whereby the player is engaged in cognitively demanding decision-making processes over long periods of time. Given these characteristics, our description of attentional control is likely to heavily overlap with key constructs from the executive function literature. For example, borrowing the terminology of Diamond (2013) and of Miyake et al. (2000) respectively (Figure 1), attentional control would certainly implicate the construct of cognitive flexibility (respectively shifting), which encompasses the processes involved in swiftly shifting between attentional states (i.e., from divided to focused and from focused to divided) on demand. Our description of attentional control also shares components of the construct of working memory (respectively updating), which encompasses the processes involved in active memory, including keeping main goals and sub-goals active and dynamically revising those goals as the situation warrants. Finally, to the extent that inhibition is required both in shifting and in updating, attentional control is also likely to encompass some inhibitory skills. Critically, not all types of video games are likely to place sustained load upon attention as formulated above. Action video games, given their speed, the constant need to select targets from among distractors and to switch between a more diffused attentional state (monitoring for enemies) and a focused attentional state (engaging enemies), certainly do place such load upon the attentional system. Conversely, many video games do not require decisions under time pressure and focus primarily on long-term planning, such as within puzzle games or turn-based strategy games.

We note that our conceptualization of attentional control does not encompass more exogenous forms of attention such as orienting and alerting, whereby attention is directed by salient external cues to be re-allocated either in space or in time (Fan et al., 2002). Such exogenous forms of attention are typically associated with sub-cortical structures and the ventral attention processing stream. Instead, in this view, attentional control is more likely mediated by top-down attentional processes and thus by the dorsal attention network, although the need to constantly re-evaluate attentional demands as bottom-up sensory information changes is certainly a core function when switching between different attentional states (Vossel et al., 2014).

The theoretical proposal that learning is facilitated by proper reward contingencies and heightened attentional control predicts that any experience that properly addresses these two constraints should in turn enhance learning. It is in that sense that we proposed earlier that action video games may provide exemplary learning experiences (Bavelier et al., 2012b).

Impact of Video Game Play on Human Performance

Action video game play has been associated with enhanced attentional control and, in turn, better cognition. Before reviewing the work linking action game play to enhanced attention, we introduce the two main methodological approaches by which the impact of video game play on the brain and behavior has been studied (Figure 2). One approach utilizes a cross-sectional design wherein self-declared action video game players (AVGPs) are contrasted against individuals who seldom play video games (non-video game players or NVGPs). The second approach utilizes a true experimental or intervention design, wherein

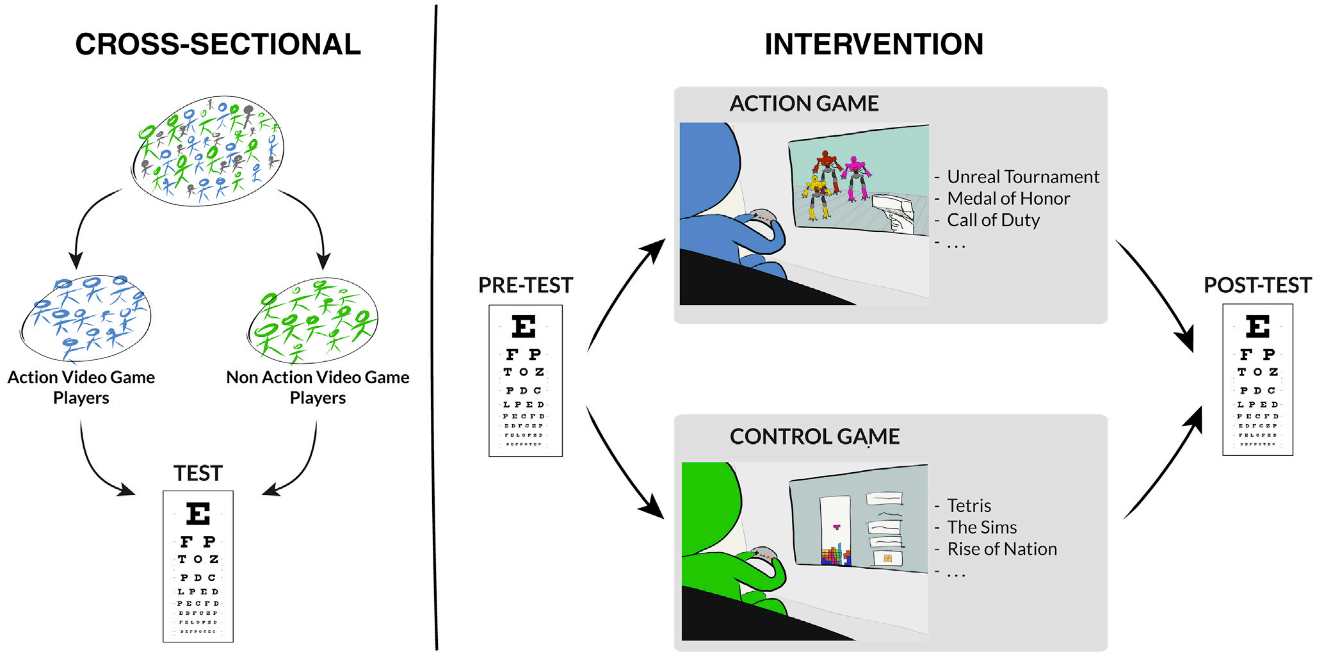

Figure 2. Illustration of the Two Main Experimental Designs Used So Far in the Video Game Literature: Cross-Sectional or Intervention Experiments

(A) Cross-sectional work in the domain has largely relied upon comparing self-described action video game players with individuals who play little-to-no action games and engage in little video game playing overall. More recently, researchers have attempted to perform correlational studies (i.e., treating video game experience as a continuous variable; [Moisala et al., 2017; Unsworth et al., 2015; Waris et al., 2019]), but as raised by Green et al. (2017), these suffer from serious limitations.

(B) Intervention studies in the domain have followed a standard pre-test → training → post-test design with one experimental arm (usually training on an action video game) and one active control arm (training on another commercial video game title without action mechanics).

individuals are randomly assigned to play a certain type of video game, and the impact of this play on cognition is assessed by comparing measures taken before and after training.

Methodological Approaches

Both types of studies above have added substantial value to the field. For instance, while cross-sectional designs, like all forms of correlational work, cannot be used to establish a causal relation between game play and behavioral outcomes, given the relative ease of running such studies as compared to true experiments, investigators have frequently utilized cross-sectional designs to identify areas where true experiments were worth running. Such true experiments could then be used to investigate possible causal relations in multiple directions. The most typical causal direction investigated in the field thus far is from action game experience to increases in cognitive skill. For instance, a cross-sectional study demonstrating that action video game players show better task-switching skills than non-action video game players inspired an intervention study to determine if deliberate training on action video games causes improvements in task-switching abilities above and beyond deliberate training on other genres of video games (Green et al., 2012). A less typical, but growing trend with the rise of eSports is to deploy intervention studies testing causation in the other direction. In other words, the same cross-sectional study above, indicating that action video game players show better task-switching skills than non-action video game players, could suggest that good task-switching skills are important for action video game success. Investigators could thus examine whether deliberate task-switching training enhances performance on action video games. Such a movement is already visible, with many eSports competitors making use of cognitive training products in which tasks were inspired by measures of attentional control (e.g., variants of the Multiple Object Tracking task; Neuron Academy, Neurotrainer, Neurotracker, etc.; Appelbaum and Erickson, 2018). Finally, beyond providing inspiration for intervention designs, cross-sectional work has value in and of itself. For example, such work can be utilized to develop purely correlational selection criteria. If certain patterns of cognitive abilities are shown to predict high-levels of performance on a certain eSports game, measures of those abilities could be used in the recruitment process in a manner equivalent to 40-m dash times and bench press repetitions, which are used in more traditional athletics.

As noted above though, in order to use lessons from cross-sectional work for real-world translational purposes (e.g., in rehabilitation or educational goals), it is critical to establish the causal link between game play and cognitive performance through intervention studies. We focus here on true experiments whose goal was to enhance cognition via game play (in contrast to enhancing game play via cognition). The main study design employed in the field to-date closely mirrors best practices in randomized control trials (RCTs). Specifically, two active intervention arms are contrasted. Participants randomly assigned to one arm are forced to train on the experimental (usually action) video game. Participants randomly assigned to the other control arm play a commercial video game that, while matching the experimental game in many aspects (e.g., enjoyment, engagement, opportunity to progress, etc.), does not engage the same cognitive constructs as the experimental game. While in an ideal circumstance, the control game would effectively eliminate concerns related to non-specific placebo-based mechanisms, the proper implementation of behavioral intervention studies to accomplish those aims has been the topic of much recent discussion (Boot et al., 2013b; Green et al., 2019; Simons et al., 2016). Determining the best experimental methodology involves navigating myriad delicate issues, such as the proper choice of the control intervention arm, how to keep investigators blind to treatments, and how to avoid and/or measure possible participant expectation effects (as participants in behavioral training studies cannot be truly blinded to their assigned interventions). These important issues go beyond the present review, but we refer the interested reader to a recent consensus report on design issue in behavioral intervention work (Green et al., 2019). For ease of discourse in the remainder of the paper, when studies are discussed as contrasting ''video game players'' versus ''non-players,'' this will always refer to cross-sectional designs; when studies are discussed as ''training'' participants, this will always refer to true experiments, intervention studies.

As alluded to in the introduction, video game play is a rich and complex experience, bound to result in a variety of impacts on human behavior and brain organization. And indeed, it is already known that not all video games have the same impact. For the purpose of neuroscientific research, we argue that video games are best conceived as a heterogenous domain made of many sub-categories, each with their own impact. Recognizing this diversity of impact is crucial to guide our understanding of how video game play may act as a learning experience. Indeed, if there is one lesson from the field of brain plasticity and learning, it is that training outcomes tend to be highly specific to the exact nature of the training, a phenomenon also known as the curse of learning specificity. If we consider video games as heterogenous, it makes little sense to ask about the overall effect of video games on brain and behavior; rather, it will be of the utmost importance to consider the exact demands the gameplay puts on the player when considering possible impact (Dale and Green, 2017b; Dobrowolski et al., 2015). We will therefore, in almost all cases, review the impact of different video game genres separately. The one exception to this is when considering speed of processing. Here, we also include studies that look at the impact of video game play and specifically do not differentiate between genres, since it is common across a wide variety of video game genres to require decisions under time pressure.

Speed of Processing and Video Game Play

A common feature of many video games is that players are required to make decisions and execute motor actions under severe time constraints. While there are certainly some game titles devoid of such time pressure (e.g., turn-based role-playing games), many game genres, including the action video game genre, require players to accurately choose among several possible options as quickly as possible. Accordingly, players of many different video game genres exhibit faster reaction times than non-game-playing individuals, as established by both cross-sectional and intervention designs (Dye et al., 2009b; Orosy-Fildes and Allan, 1989; Torner et al., 2019). This result has been documented via a variety of possible motor responses including manual, vocal, and saccadic responses and across a wide variety of task types (Green et al., 2012; Heimler et al., 2014; Mack and Ilg, 2014; West et al., 2013; Zhang et al., 2015). A review of studies contrasting reaction time in action video game players and non-game players indicated that action video game players tended to respond about 10% faster than non-video game players. Interestingly, this relation held across a reasonably wide range of average reaction times (e.g., from simple RT tasks where responses were made on the order of 200 ms to complex visual search tasks where responses took several seconds; Dye et al., 2009b)

Importantly, there are multiple possible processing routes to overall faster RTs. One possible route is faster motor execution—in other words, speeding up of the time between when a decision is reached and when that decision is physically executed. Such repeated practice, in the context of a rewarding and arousing activity, is likely to enhance cortical excitability and associated plastic processes (Bütefisch et al., 2000; Nitsche et al., 2007). A number of video games, or at least parts of video games, strongly emphasize the physical act of fast motor execution without any meaningful real-time cognitive processing. This is sometimes referred to as ''button-mashing.'' For instance, a video game boss may be defeated by rapidly pressing the ''X'' button (this is sometimes also called a quick-time event). A second route to quicker reaction times is via faster throughput or accumulation of information up to the decision point. For instance, a game might require a different attack to be utilized depending on which of two monsters are present on the screen. A player that more quickly accumulates evidence in favor of one monster or the other will reach a final decision faster as to which attack to choose. Critically, neither of the two routes above should result in a concomitant drop in accuracy (i.e., neither route involves a speed-accuracy trade-off, which would be a third possible route to faster RTs). And indeed, the decrease in reaction times observed in action video game players is usually accompanied by no change in accuracy. While both motor execution and faster information accumulation are potentially at play in video games, research has suggested that the overall enhancement in action gamers is best attributed to faster information accumulation, rather than a change in motor response mappings (Mack et al., 2016). For example, using a drift-diffusion model, Green et al. (2010) showed that action video game play was associated with a greater slope in the rate of evidence accumulation, but essentially no difference in simple motor response times. Although this effect has been found in both cross-sectional and intervention experiments, as is true in all learning domains, how training is distributed over time and assessed appears important in inducing the effect (see van Ravenzwaaij et al. (2014) for a failure to induce training effects when using massed practice). Massed practice is almost always less effective than distributed practice, a finding that holds true when training with video games as well; more generally, learning with video games appears to be under the same constraints as any other form of learning (Stafford and Dewar, 2014).

The net decrease in RT associated with playing video games in general, and action-based games specifically, bears a number of potential direct consequences for everyday life. For example, video game training has been used to try to speed up processing in domains as varied as reading or surgery. Playing action-like video games has been found to accelerate naming speed during reading in dyslexic children (Franceschini et al., 2013), while playing action or fast-paced video games has been associated with faster surgery times in laparoscopic surgeons (Rosser et al., 2007). Another possible future impact concerns the gender gap within video game players. While women and men are roughly matched in terms of total video game play, there is a sharp difference in the genres of video games men and women choose to play. Although men and women seem to reap similar benefits from playing fast-paced games (Gorbet and Sergio, 2018), men are considerably more likely to choose to play genres where speed is placed at a premium, while women are disproportionately attracted to puzzle or social simulation games (Yee, 2017). As a result, video game use in the wild may in turn give rise to differences in terms of speed of processing between men and women. This gender gap is a source of possible worry, as faster reaction times are often linked with generally enhanced cognitive abilities. For example, speed of processing is known to be a strong predictor of a host of higher cognitive abilities, from fluid intelligence to executive functions (Ball et al., 2007; Edwards et al., 2002). Note that it remains unknown whether the speed enhancement driven by video game play reinforces that link or, on the contrary, weakens it by adding a separate source of variance.

Finally, given their processing demands, it is perhaps not surprising that video game play has been associated with neural changes at all levels of processing, from sensory to motor pathways (Gong et al., 2016, 2019). For instance, increased white matter integrity in video game players as compared to non-players has been found in both visual and motor pathways, with the same basic findings being observed in both adults and in children (Gong et al., 2017; Pujol et al., 2016; Zhang et al., 2015). Importantly, these specific changes have been directly linked to changes in speed of processing. Outside of early sensory-motor pathways, video game players have been shown to exhibit greater recruitment of other areas associated with visuo-motor coordination and learning as compared to non-gamers (Granek et al., 2010; Kühn and Gallinat, 2014). The brain changes seen as a result of video game play though are not limited to perceptual or motor dominated areas. For example, daily gaming activity, irrespective of the specific game genre, has been shown to affect the prefrontal cortex (Moisala et al., 2017). One longitudinal intervention study evaluated the structural changes in the dorsolateral prefrontal cortex resulting from two months of training with *Super Mario 64*, a 3D platformer game that requires navigational skills, as compared to a passive control group (Kühn et al., 2014a). The results indicated that playing this video game increased the gray matter volume in the right dorsolateral prefrontal cortex. Consistent with this result, a correlational study reported that the self-reported weekly hours that adolescents spent playing video games correlated positively with the thickness of their left dorsolateral prefrontal cortex and left frontal eye fields (Kühn et al., 2014b). However, in general, the neural changes associated with video game play that have been documented so far have largely not differentiated between game genres and have predominantly used cross-sectional or correlational designs. These two facts put serious limits on any conclusions that can be drawn. As is the case for behavioral impact, how certain game genres load upon the cognitive architecture appears key in characterizing the brain changes that those game genres will induce. This thus argues against merging games as if all games drive comparable brain changes (Palaus et al., 2017). Furthermore, the relative paucity of intervention studies examining induced brain changes prevents any inference about the causal impact of game play in general.

Attentional Control and Action Video Game Play

A fundamental building block of cognition altered by action video game play is attentional control. Action video game play enhances various aspects of top-down attention, an effect seen both in cross-sectional and in intervention studies (Bediou et al., 2018; Chisholm and Kingstone, 2015b; Colzato et al., 2013; Oei and Patterson, 2013; Schubert et al., 2015) (Hedge's g of 0.62 in cross-sectional studies and of 0.31 in intervention studies). These effects are seen whether attention has to be deployed (1) over space, as measured, for example, by Useful Field of View paradigms or variants thereof, (2) over time, as measured, for example, by the attentional blink, or (3) over objects, as measured, for example, by the Multiple Object Tracking task (Chisholm and Kingstone, 2015a; Green and Bavelier, 2015). Although these changes were initially reported as changes in "selective attention," they are now perhaps better understood as changes in attentional control, or the capacity to swiftly shift between attention modes based on task demands. This shift may affect the spatial resolution of attention, as when switching between a distributed versus a focused attentional state, or its temporal resolution, as when switching between allocating one's attention over a short versus a long timescale. In all cases, enhanced attentional control leads to a better ability to focus on task-relevant information.

Attentional control also entails reducing the extent to which task-irrelevant information distracts from the task-relevant goals. Interestingly, although one common marker of such an attenuation process is a reduction in so-called "flanker effects" (i.e., where task irrelevant flankers reduce the efficiency of responses to task-relevant targets), there exists an added complication, in terms of the amount of attentional resources of the participant. The attentional load theory of Lavie et al. (2004) predicts that individuals with greater attentional resources, such as action video game players, will disproportionately continue to process task-irrelevant information (and thus continue to exhibit flanker interference effects) while still showing efficient processing of task-relevant items. This all-encompassing processing is expected to shift toward selective task-relevant processing when the perceptual load of the task becomes high enough to restrict the distribution of attention to just task-relevant information. In this view, action video game players, owing to their greater attentional resources, would be expected to show sizeable, if not larger flanker effects, at low perceptual loads. Then, as perceptual load is increased, non-gamers should show a reduction in the magnitude of the flanker effect more quickly than action gamers (i.e., because non-gamers' attentional resources would be exhausted as comparatively lower levels of perceptual load, compared to action gamers as discussed in Dye et al. (2009a). This is indeed what was observed in Green and Bavelier (2003). This has led to some confusion in the literature about how to interpret greater interference/flanker effects, as larger flanker effects may correspond to enhanced attentional resources, as per the attentional load theory framework, or worse selective attention under the view that such effects correspond to a failure of selective attention (Irons et al., 2011; for a fuller discussion see section 4.1 Supplementary Info of Bediou et al., 2018). Researchers should thus take careful note of this ambiguity in the interpretation of flanker effects and preferentially utilize tasks with less uncertainty regarding the direction of interpretation when possible.

In the action video game literature, steady state evoked potentials (SSVEPs) have been exploited as another possible indirect measure of distractor processing at the neural level. This electrophysiological technique takes advantage of the tendency of neural populations to generate electrical activity frequency locked to flashing visual stimuli. By presenting objects that flash at different rates, it is thus possible to examine the extent to which those objects are being processed. Action video game players have been reported to better exclude task-irrelevant information as compared to NVGPs as measured by a stronger reduction in the SSVEP frequencies associated with to-be-ignored stimuli under relatively high perceptual loads (Krishnan et al., 2013; Mishra et al., 2011). Similarly, irrelevant moving stimuli led to comparatively lower activation in the motion sensitive area MT/MST of AVGPs as compared to NVGPs, at least when they were highly salient and thus more distracting (Bavelier et al., 2012a). By requiring players to constantly monitor their environment for task-relevant information at different spatial and temporal scales, all the while actively suppressing varying sources of noise or distraction, action video games clearly load on both target enhancement and distractor suppression. The cognitive training literature suggests, however, that training distraction suppression, rather than target enhancement, is most likely key given the goal of reducing distractibility. For example, Mishra et al. (2014) showed that adaptively asking participants to ignore more and more salient distractors led to lesser distractibility. In contrast, training focused on selectively enhancing task-relevant information, through adaptive targets among fixed distractors, did not have the same impact on distractor processing (de Villers-Sidani et al., 2010). These results are in line with a rich literature showing that training focused on enhancing task-relevant information triggers the development of perceptual or conceptual representations that match task-relevant information. As these representations are rather specific to the exact training, they are of limited value to new contexts (Green et al., 2018). In contrast, training that focuses on limiting distractor processing is more likely to lead to generalizable attentional effects.

A key issue regarding action video games has been to identify the point in the neural processing stream at which the enhanced attentional control manifests. Several studies have tested the hypothesis that the superior performance action gamers show in selective attention tasks arises via greater attentional modulations early in the visual pathway. Yet, whether using ERPs or fMRI, no such evidence has been found. AVGPs were found to display similar early attentional modulations as non-gamers, whether in terms of P1 and posterior N1 in visual selective attention tasks (Föcker et al., 2019; Wu et al., 2012) or in anterior N1 in an auditory selective attention (J. Föcker, M. Mortazavi, W. Khoe, S.A. Hillyard, and D.B., unpublished data). Similarly, in a recent fMRI study, attentional modulations in retinotopic areas were comparable in AVGPs and NVGPs (unpublished data). These null results suggest that the greater attentional control seen in AVGPs is not mediated by enhanced early attentional selection. Instead, superior attentional performance in AVGPs may be due to better late attentional selection. In this view, to the extent that their greater attentional capacities are not exhausted, AVGPs would let both task-relevant and task-irrelevant information flow through early processing stages. Task-relevant information would only be selected for additional processing later in the stream, closer to the time of decision making. While this view remains to be tested, late selection could be advantageous in terms of cognitive flexibility, as it means information from one's surrounding remains available until the very stage where a decision signal will be made.

We note that not all aspects of attention are equally impacted by action video game play. In particular, top-down attention appears to be disproportionally enhanced after action video game play as compared to bottom-up attention. Indeed, several studies have failed to show differences between AVGPs and NVGPs in either the likelihood of attentional capture or the speed with which exogenous attention is initially summoned (Chisholm et al., 2010; Hubert-Wallander et al., 2011). As expected from enhanced top-down attention, however, several studies have shown that when attention has been wrongly allocated, as is the case in invalidly cued trials for example, AVGPs recover from this misallocation more swiftly (Cain et al., 2014; Chisholm and Kingstone, 2012). This state of affairs may initially come as a surprise given that action video game play does place sizeable demands on bottom-up attention. For instance, the presence of enemies in action video games is often first indicated by motion or luminance transients (e.g., the flash of a gun being fired) that bear strong resemblance to the types of cues used in the study of exogenous attention. The fact that few changes in bottom-up attention abilities are noted as a consequence of action video game play may potentially reflect the fact that bottom-up attention mechanisms are simply less plastic than top-down processes. Indeed, there are major differences in both the developmental trajectory of these different attentional abilities, as well as in the brain areas that underlie them. Top-down attention or more generally attentional control, by calling upon cognitive flexibility, working memory and some forms of inhibitory control, is likely highly plastic (Posner, 2011). Several pieces of work point to the possibility of enhancing aspects of executive functions such as working memory or cognitive flexibility (with N-back training: Au et al., 2015; but see Melby-Lervåg et al., 2016; Soveri et al., 2017; and with video games: Homer et al., 2018; Parong et al., 2017), although we recognize that the extent to which these constructs can be trained remains a controversial issue in the field.

Other Cognitive Outcomes

Spatial Cognition. Action video game play enhances spatial cognition, which together encompasses the ability to both remember and to manipulate in memory visuo-spatial information, whether that be spatial locations, objects, or visual characteristics (Bediou et al., 2018; Spence and Feng, 2010). Spatial cognition in gamers has been assessed with a variety of tasks. These include standard visuo-spatial working memory tasks, such as the Corsi block tapping task, to complex span tasks, to various spatial forms of the N-back task (Appelbaum et al., 2013; Blacker and Curby, 2013; Waris et al., 2019; Wilms et al., 2013). For example, in terms of reasonably simple spatial memory tasks, Sungur and Boduroglu (2012) found action video game players to have more precise visual working memory for colors than non-gamers on an adapted color-wheel task. Similarly, Green and Bavelier (2006) reported enhanced performance on an object enumeration task both in cross-sectional work comparing AVGPs with NVGPs as well as in an intervention study testing the causal role of action video game training. In terms of spatial cognitive tasks that require manipulation in addition to simple storage, Feng, Spence, and Pratt (2007) showed that action video game players outperformed non-gamers on a mental rotation task. They then demonstrated that 10 h of action video game training could enhance mental rotation abilities. Interestingly, while this research group's initial results indicated that female participants reaped greater benefits from action video game training than male participants, it was later suggested that this may have been due to females starting from a lower level of spatial skill (rather than a true gender effect of training per se). When performance levels were matched at baseline, females benefitted to the same extent as males (Spence et al., 2009) (although note that this latter work did not use a mental rotation task but rather a visuo-spatial attention task). In all, when considered in a recent meta-analysis, the effect of action video game on spatial cognition appear to be of small to medium size (Hedge's g of 0.75 for cross-sectional studies and of 0.45 for intervention studies).

The impact of video game play in general, and action video game play more specifically, continues to be an area of substantial research interest given the known links between enhanced spatial cognition and performance in STEM classroom domains (Uttal et al., 2013b). Some early studies suggested that just a few hours of video game play with action mechanics could facilitate future learning of plate tectonics (Sanchez, 2012). Yet, while the existing literature certainly provides a great deal of optimism that spatial cognitive skills can be enhanced via dedicated training and that this in turn could positively impact educational attainment (Uttal et al., 2013a), how to maximize the efficacy of such training via games remains an area in need of substantial research, since games that, on their surface, would appear to have useful training characteristics for spatial cognition have not always been seen to positively impact spatial skills (Pilegard and Mayer [2018], but see Valadez and Ferguson [2012]).

Perception. Outside of attentional control, the sub-domain of cognition where the greatest amount of work has been conducted examining the impact of action video games is within the domain of perception. Here, most of the existing literature has specifically focused on visual perception, with only a handful of studies examining auditory or multi-modal perception. In particular, a number of studies have shown that action video game training results in enhanced thresholds on perceptual tasks, such as those that require participants to identify low contrast targets or small letters in crowded visual fields (Green and Bavelier, 2007; Li et al., 2009). Although these perceptual effects appear trainable (Hedge's g of 0.77 in cross-sectional studies and of 0.23 for intervention studies), an examination of the size of training effects as a function of training duration suggested that 20 h or more are needed to begin to see differences as a function of training video game (Chopin et al., 2019). This may explain the rather modest effect size seen in intervention studies, and certainly calls for more studies with larger Ns and longer training durations. Interestingly, although this sub-domain is framed as examining perception, in many cases the hypothesized mechanism starts with differences in attentional control. Enhancements in attentional control allow participants to better focus on perceptually diagnostic information in their environment and in turn learn faster how to perform the specifics of the perceptual tasks used to measure performance in the laboratory (Bavelier et al., 2012b). Accordingly, action video game players have been shown to not only benefit from better perceptual templates, but also to develop such templates faster (Bejjanki et al., 2014). Although this effect needs replication, the possibility of enhanced perceptual learning abilities in AVGPs has also been illustrated not just in terms of faster learning overall, but also in terms of a reduction in interference between learning episodes (Berard et al., 2015). In this work, the learning of a first perceptual task led to lesser proactive interference on the learning of a second task in AVGPs as compared to NVGPs. All told then, the extent to which improvements in perceptual tasks reflects changes in ''perception'' per se, or rather reflects improvements in attention, is thus an area of ongoing research and debate.

How Action Video Game Play May Shape Development. The literature on the impact of action video game play on cognitive abilities in children is relatively sparse, mainly owing to the fact that most commercially available action video games are not developmentally appropriate. The few studies available, however, do point to comparable impact in children as in adults. For example, a handful of cross-sectional studies demonstrated similar degrees of enhanced attentional control in children who report playing action video games as is seen in adult AVGPs. Dye and Bavelier (2010) reported that action-video-game-playing children as young as 7–10 years old displayed similar performance as non-game playing adults in terms of the dynamics of their attentional recovery. Similar enhancements were reported for spatial attention and for object-based attention (Dye and Bavelier, 2010). A handful of intervention studies have also documented enhanced visuo-spatial selective attention after 12 h of action-like video game play in clinical pediatric populations, mostly 8–12-year-old dyslexic children (Franceschini et al., 2013, 2017). The view that playing action video games accelerates the maturation of attentional control skills, and thus may lead to more mature-like processing, has been recently put to the test in the case of multi-sensory integration. Children, unlike adults, do not optimally weigh multi-sensory information during perception (Dekker et al., 2015; Nardini et al., 2008). Children between 4–5 years of age trained for 45 min per day for 2 weeks showed more optimal cue integration in a visuo-haptic task than children in the control groups. A proposed mechanism of action has been that the enhanced attentional control induced by action-like video game play may in turn facilitate multisensory integration (Talsma et al., 2010), owing to the link between these two constructs.

Exploring Genres to Elucidate Mechanism

More recently, other video game genres beyond the action genre have also been documented to enhance cognition. Most of this work has been cross-sectional in terms of methodology. Enhancements in terms of speed of processing (e.g., simple discrimination reaction time) and attentional control (e.g., Useful Field of View, Multiple Object Tracking) have been documented in players of certain types of racing games, action-role-playing game hybrids, and real-time strategy games (Anguera et al., 2013; Dale and Green, 2017a; Dale et al., 2019; Kim et al., 2015; Tsai et al., 2013; Wu and Spence, 2013). The finding of such enhancements may not be surprising given the clear links between these genres and the action video game genre. For example, some (but not all) racing games entail some degree of focused attention on the track along with the need to switch to a more diffuse attentional state to monitor for incoming distractors (*Mario Kart* and more ‘‘combative’’ racing games, as compared to NASCAR-like games where players largely drive a track without engaging with other cars or sources of distraction). Action-role-playing game hybrids meanwhile are a direct mix of first- or third-person shooter mechanics (i.e., the exact mechanics that dominate action video games) with traditional role-playing elements. Meanwhile, like action video games, real-time strategy games require that all decisions be made in quickly in real-time against an opponent. Similar results have also been observed in players of the multi-player online battle arena (MOBA) genre (Kokkinakis et al., 2017). This genre is sometimes referred to as the action-real-time strategy genre, as it mixes elements of action games and real-time strategy games, and in particular the main mechanics of decisions under time pressure, divided attention needs, and high demands on switching modes of processing. Specifically, in one recent study, MOBA game performance was found to be correlated with overall faster reaction times and better multiple-object tracking abilities (A.M. Large, B. Bediou, Y. Hart, D.B., and C.S.G., unpublished data). Finally, at least one intervention study using the real-time strategy game (*StarCraft*) has demonstrated a causal role in enhancing cognitive control, which is in parallel to what has been seen in intervention studies utilizing action video games (Glass et al., 2013).

In all, then, this latest work exploring new genres of video games has been largely consistent with the general theoretical framework developed through the study of action video games. However, given the incredible paucity of intervention studies utilizing these new game genres, caution is warranted, and many unanswered questions remain. For instance, because action-role-playing games involve a mixture of standard role-playing mechanics (e.g., dialog trees used to develop relationships among characters; skill progression trees; character development; etc.) along with standard action mechanics (e.g., combat is usually first-person-shooter- or third-person-shooter-based), one might predict that such action-role-playing games would be less efficient as cognitive training platforms when compared to action video games. This would be for the simple reason that less of the total gaming time is spent under speed of processing/attentional control load in an action-role-playing game than in an action game. On the other hand, the role-playing elements inherent in action-role-playing games are clearly important for both internally and externally derived reward signals. Indeed, in an action-role-playing game, the player’s avatar is nearly always one that they themselves have personalized, nurtured, and inculcated. This is in contrast with a standard first-person shooter action game, where the avatar is generally one-size fits all and depersonalized from the perspective of the player. Given the substantive links between reward-system activity and neuroplasticity, this difference in identification with character could potentially make action-role-playing games more effective training platforms than action video games. The ability to ask more mechanistically sophisticated questions such as these will undoubtedly be the focus of a great deal of future work utilizing these new game genres.

Video Game Features for Brain Plasticity

As reviewed above, a number of new genres, while not being traditional action games, nonetheless share similar cognitive impacts to action video games. Conversely, other genres of entertainment video games, such as social simulation games, music/rhythm games, or turn-based strategy games, do not have such cognitive impact. We can draw several lessons from this contrast. First, a recurrent finding in the training literature is that transfer is a tall order. Yet, in the case of action video games, those games not only result in better performance on the games themselves, but also in better performance on laboratory tasks that bear little surface resemblance to playing an action video game. Such transfer of learning certainly has much to owe to the diversity of cognitive skills that action video game play taps. Yet, while such diversity is undoubtedly desirable, and likely even necessary in a training regimen, it is almost certainly not sufficient. After all, turn-based strategy games also heavily weigh on a variety of cognitive skills, but do not lead to similar enhancement in attentional control that occurs with action video game play (Cohen et al., 2007).

The qualitative analysis of the game genres associated with similar attentional control enhancement as action video games and of those genres that are not associated with such enhancements has led us to three potentially key mechanics that must be present in an interactive environment to foster augmented attentional control (Cardoso-Leite et al., 2020): (1) pacing, or the need for making decisions under time pressure, (2) a load on divided attention, or the need to filter distractors and sustain attention over a large part of one’s environment for a significant period of time, and (3) the need to switch between modes of processing, such as the many switches from a divided attention state and a more focused attentional state as a function of the ever-changing game contingencies in action video games.

Pacing

Pacing refers to need to make decisions and execute motor commands under time pressure. Although the speed at which a game unfolds will certainly determine the absolute pace of a game, pacing here rather qualifies the subjective time pressure felt by a player, rather than the absolute game speed. In other words, games that positively impact speed of processing and attentional control tend to put time pressure on the player. The extent to which a given game loads upon pacing will, of course, thus be partially dependent on the player. A game that places pacing load upon an older adult may not place pacing load upon a younger adult. And a game that places pacing load upon a younger adult may not place pacing load upon a professional game player. Critically, pacing is not necessarily equivalent to actions completed per unit time. For instance, many video games involve automatizing certain action sequences. Although these sequences may be quite long, sometimes involving tens of distinct button presses or actions in rapid succession, in practice these are better considered to represent a single decision point (e.g., as is the case in so-called ''combos''). Furthermore, the extent to which a game loads on pacing is not necessarily static through time. Instead, gameplay aspects that load upon pacing as an individual is learning a game may fail to load upon pacing once certain stimulus-response mappings have been automatized. In the end, what is important for pacing is that the player makes informed decisions under time pressure relative to their own abilities.

Divided Attention, Distractor Suppression, and Sustained Load

One common mechanic found across game genres that load upon attentional control is the need to maintain a divided attentional state over a significant time period. While many video games require sustained attention, not all require concurrent divided attention. Games like *Ballance*, *Marble Madness*, or *Super Monkey Ball* (where the player navigates a tight maze and seeks to avoid falling off the path) all require focused attention on one specific object at a time and put a premium on visuo-motor coordination rather than divided attention. In contrast, action video games typically require players to consistently monitor the entire visual scene so as to detect new incoming enemies, health packs, or other items while avoiding distractions. The notion that engaging divided attention over long periods of time may enhance aspects of attention is supported not only by the action video game literature, but also by training studies based on adaptations of the MOT. The MOT task requires individuals to divide attention across multiple targets (so as to differentiate the targets from visually identical distractors), to constantly update the tracked objects in working memory, and to do so over a protracted period of time. The task thus clearly loads upon both divided and sustained attention. Consistent with this, Faubert and Sidebottom (2012) have developed a 3D MOT task which appears to be a good predictor of a variety of skills in elite athletes. Furthermore, these relations are not just correlational in nature. Although this work is in its relative infancy, dedicated 3D MOT task training has been reported to improve attention, visual information processing speed, and working memory in young and in older adults (Legault and Faubert, 2012; Parsons et al., 2016; Vartanian et al., 2016) as well as facilitate soccer player performance on the field (Romeas et al., 2016). An adaptation of the MOT was also found to be valuable to enhance vision in low vision patients (Nyquist et al., 2016).

Switches between Attentional Modes

Finally, while the need to maintain a divided attentional state over a significant time period appears to be key, it appears to be similarly important that games emphasize some degree of switching between this divided state and other modes of processing, such as a more focused attentional state. For instance, while first-person shooter games do indeed commonly require players to monitor the entirety of their environment for possible targets of interest, these periods are frequently interrupted by periods of focused engagement with specific enemies. When an enemy is found and a decision is made to engage the enemy, the fine aiming movements that are required to shoot at the enemy necessarily involve a degree of focused attention. This is all the more true because such enemies are rarely static targets, but instead are moving and thus must be carefully tracked through the simulated 3D environment. Again, the notion that the need to fluidly switch between attentional states is important for enhancing aspects of attentional control is supported by other literatures than just the action video game literature (Dajani and Uddin, 2015). For instance, task-switching paradigms are among the more frequently utilized paradigms in executive function training batteries.

Crucially, it has been our experience that each of these three characteristics on its own does not guarantee cognitive impact, at least when it comes to attentional control enhancements. Rather, action video games are unique in that they naturally layer these three game characteristics within the same overarching game play. For example, games that put a premium on just one characteristic such as pacing do not seem to similarly enhance attentional control and other aspects of cognition (e.g., *Tetris*).

Notably, action video games align these three main game characteristics all the while respecting a few main tenets of learning and brain plasticity. First, they attempt to consistently keep the player/learner in their zone of proximal development via proper selection of entry levels and incremental step-sizes in difficulty. In doing so, they aim at delivering a constantly challenging, yet doable, experience. If this condition is unmet, such as when asking older adults to play action video games designed for young and already familiar players of the genre, no cognitive enhancement is found, but rather learned helplessness seems to arise (Boot et al., 2013a). Second, action games naturally embed these three key characteristics in an extremely rich environment. While in most situations, individuals will attempt to automatize skills that are recurrently under demand, action video games constantly introduce new situations or contingencies. AVGPs are continuously subjected to new environments, new goals, and new rules, whether in new levels or new seasons of the same game or in new game titles. Third, action video games incentivize the game play through rewarding experiences whether through score boards or social emulation. By increasing motivation to play, video games target a major driver of brain plasticity and learning (Bavelier et al., 2010; Roelfsema and Holtmaat, 2018). In this sense, action video games obey all the same rules as any other training regimen; they just happened to have found new and powerful ways to harness principles that have been well known for more than a century to facilitate learning and brain plasticity (Gentile and Gentile, 2008).

Given the substantial amount of data covered above demonstrating that playing different video game types results in differential impact on the brain and behavior, it should not come as a surprise that player style also modulates the type of brain changes noted. Indeed, in addition to the major shifts in genres that have occurred over the past decade (e.g., inter-mixing of genres), another major trend in the commercial video game sphere is an influx of ''open-world'' or ''sandbox'' games (i.e., games that allow for substantial freedom for players to determine how they want to accomplish game goals). For example, in a game like *Skyrim*, one player may only ''snipe'' enemies from afar, never coming within 30 m of an enemy player. Another player may only use melee weapons (i.e., attacking enemies hand-to-hand). Another player may larger eschew combat all together and focus mainly on the role-playing elements of the game. Thus, even though all three players would have ''played *Skyrim*,'' their experiences, and thus the impact of those experiences on the brain, are quite different.

The degree of freedom offered by modern games is greater than any point previously. However, although not systematically documented, it has been our anecdotal experience that, in intervention studies, those individuals who are less active during their assigned action video game play (i.e., players that adopt a strategy of hiding and rarely interacting with enemies) show little to no cognitive benefits from the game play. The impact of play style on induced neural changes is arguably best documented by the burgeoning research looking at the impact of video game play on the hippocampal formation. Here, as in much of the previously examined literature, there is evidence showing associations between different game play habits and differences in hippocampal volume. Playing puzzle/platformer games is associated with increased volume; playing action video games is associated with a reduction in volume (Kühn and Gallinat, 2014; West et al., 2017a; West et al., 2017b). Interestingly, follow-up work has suggested that these trends may be mediated by player strategy. For instance, West et al. (2015, 2018) found that the reduction in hippocampal volume associated with action video game play was largely only observed in players who utilized non-spatial strategies when playing those games. Players that utilized a spatial strategy while playing action video games actually showed an increase in hippocampal volume. This state of affairs makes it clear that the impact of video game play on brain organization needs to be qualified according to the processes the players engage while playing. As video games span widely different experiences, looking for the neural correlates of video game play in general is likely to remain an ill-posed research question.

Action Video Games for Impact

Over the past 10 years, the possibility of leveraging video games for social impact, such as transmitting educational content or rehabilitating patients, has led to the development of a vibrant community that brings together educators, clinicians, neuroscientists, and psychologists with game designers, graphic artists, sound experts, and programmers (De Freitas, 2018; Griffiths, 2019; Mayer, 2016). These are only the early days; the richness of approaches and of potential applications is recognized by all as extremely vast. Yet, one of the main lessons for scientists is that designing games for impact requires close collaboration with experts in the gaming industry to ensure translation from the lab to a greater audience. A major challenge for those games targeting long lasting impact through brain plasticity is that they need to deliver tens of hours of gameplay. The first 15 min of any game can be easily engaging; keeping this freshness for hours on end is a totally different level of game play design, both in terms of expertise and of cost. Thus, while video games are often branded as a motivational media that will ensure time on task, delivering video games for impact that cross that motivational barrier and can compete with commercially available titles is a tall order. We review below a few applications that have been driven by applying principles developed in the action video game literature.

Amblyopia

There is a burgeoning literature examining the possibility of using video games to help patients suffering from amblyopia (colloquially known as lazy eye). Amblyopia affects 2%–3% of the general population and arises from abnormal visual experience early in life (e.g., misalignment of the eyes). This abnormal early visual experience results in one eye (the non-amblyopic eye) being cortically overrepresented and the other eye (the amblyopic eye) being underrepresented. As a part of this, there is a loss of binocularly sensitive cells and thus binocular vision is compromised in addition to acuity and contrast sensitivity in the amblyopic eye. The primary treatment for amblyopia in young children consists of patching the non-amblyopic eye in an attempt to drive greater representation of the amblyopic eye. However, patching is unsuccessful in 25–35% of the cases (Awan et al., 2010). Furthermore, even in cases where there is improvement in acuity and contrast sensitivity in the amblyopic eye, patching often fails to restore normal binocular vision. Once individuals reach late childhood, patching is widely considered to be ineffective and in general, if individuals reach adulthood with amblyopia, the reduction in vision has typically been considered permanent.

Yet, several recent unexpected and well-documented examples of recovery from adult amblyopia (e.g., Barry [2009] [''Fixing My Gaze''] and Bridgeman [2014] [a vision scientist who had been stereo deficient all his life, of experiencing stereoscopic depth perception after viewing the 3D movie Hugo]) have led to a rekindling of interest in developing more effective methods for treating amblyopia even into adulthood. It is now understood that treatment beyond the sensitive period is possible (Bavelier et al., 2010; Levi and Li, 2009); yet, most treatments, whether for pediatric or adult populations, are time consuming, typically quite dull, and potentially socially stigmatizing (patching). Video game play has been touted as a way to naturally deliver the high adherence needed for rehabilitation.

A number of early studies in adults or children using video games that are not action video games led to mixed results. A few small studies reported initially promising results, especially as an adjuvant to patching (Singh et al., 2017) or via specialized video game training whereby separate images were sent in each eye to better equate the cortical drive from each eye (Li et al., 2011). Yet, several recent multi-site studies failed to find long-term significant benefits of such games (Gao et al., 2018; Holmes et al., 2016). This includes a 4-week treatment with 130 7–12-year-olds that compared the impact of playing a dichoptic binocular platformer video game (''*Dig Rush*,'' Ubisoft) with simple continuation of the optical treatment in spectacles that was initially administered to all participants (Holmes et al., 2019).

When it comes to action video games, there are only a few studies using dichoptic adaptation of such games, and the effects remain modest, with on average a 1–2-line improvement on the eye chart (Gambacorta et al., 2018; Vedamurthy et al., 2015b). A main contribution of the existing work is to have clarified the need to go beyond dichoptic training, since diminishing inter-ocular suppression appears neither necessary nor sufficient for recovery from amblyopia (Levi et al., 2015; Vedamurthy et al., 2015a). Instead, retraining stereo vision appears to be a more promising target, whether using an off-the-shelf 3D first-person shooter video game with a Bangerter filter over the non-amblyopic eye or VR-based visuo-motor task (Li et al., 2018; Vedamurthy et al., 2016); in each case, prism corrections were applied if needed.

Overall, the literature on amblyopia illustrates both the promises and challenges of applying lessons from the neuroscience of video games to clinical applications. It is critical to identify the exact brain function(s) to be targeted when thinking through how to deliver the game play. It is then necessary to place mechanics that tap those functions within a video game that, at the same time, maximizes reward and attention so as to unleash the greatest brain plasticity possible. This will also ensure that the game produces the expected adherence level, as any must-do activity can quickly lose its appeal. Note that it is unlikely that the small, promising study using an off-the-shelf 3D first-person shooter video game could scale up to a multi-center study, as such commercially available video games are unlikely to provide the low skill entry levels necessary when considering a more diverse group of participants, and given their violent content, shooter video games are not age appropriate for children.

Attention during Reading

Reading is at its core a linguistic skill; yet, there are a multitude of roadblocks to achieving literacy. In particular, reading calls for efficient extraction of visual information from the page, putting special demands on eye movements and the attentional system that guides print acquisition across saccades (Grainger et al., 2016). Reading could be thus at risk because of deficient visual attention deployment over the page to be read. Following this line of thought, a few studies have asked whether action-like video games that are developmentally appropriate could facilitate literacy in children where the known source of difficulty is most likely due to attentional weaknesses (Antzaka et al., 2017; Franceschini et al., 2012). For example, Franceschini et al. (2013) trained Italian dyslexic children between 9–11 years of age, for 12 h, on one of two distinct groups of minigames from the game *Rayman's Raving Rabbids*. One group of participants played minigames that were selected as involving a substantial number of action mechanics. The other group of participants played minigames that limited-to-no action mechanics. The authors found that the action mechanic minigame group showed not only enhancements in measures of top-down attention but also faster reading speeds as compared to those individuals that played mini-games that did not have action mechanics. This result was further confirmed in English-speaking dyslexic children, showing some generalization beyond Italian (Franceschini et al., 2017; although see Łuniewska et al., 2018 for a failure to enhance reading in Polish dyslexic children using either an action or a phonological video game; note that the action game also did not enhance the attentional constructs measured).

This research is still in infancy with existing studies suffering from methodological weaknesses, in particular small samples and non-blinded evaluators. Another challenge for future work will be to further characterize the many aspect(s) of attention that may mediate enhanced literacy acquisition (Franceschini et al., 2015). A tight coupling between attention enhancement and reading improvement predicts that those children with the highest attention after training should also be the best readers; this will be an important prediction to test in future work. This work, while definitely distinctive by its focus on attention and action video game mechanics, is part of a larger endeavor to deliver technology-based intervention for reading acquisition. As a recent review points out, video games or gamification as a vehicle to expose educational content remains the exception, with less than 25% of the 32 reading programs reviewed relying on the game medium (Jamshidifarsani et al., 2018)

Future Directions

Our review highlights both the promises and the challenges that lay ahead to leverage video games for brain plasticity and learning. First, a paradigm shift is needed, since continuing to use game genres, which are defined by the entertainment industry, as proxies for game mechanics is likely to cause confusion when attempting to unravel the impact of game play on brain and behavior. While the problems associated with the use of currently defined genres is clear, solutions to it are more challenging. It has been recognized for at least 10 years that a video game taxonomy would be important to move the field forward; yet, a taxonomy based upon the cognitive components a video game loads on has proven elusive (Bedwell et al., 2012). This state of affairs, as discussed above, is further compounded by the existence of strong game play preferences or styles that will also alter the experiences a given player may be exposed to within the same game environment. It is thus becoming increasingly urgent that the community studying the brain and cognitive impacts of video game play integrates this diversity of experience within its work. Indeed, it is alarming to see meta-analyses published about the cognitive impact of "video games" (as if video game play is a unitary experience), or meta-analyses that, for instance, lump *Space Fortress*, the human-computer interface developed in the early 80s to study human multitasking, into the same category as *Team Fortress*, a highly successful commercial first-person shooter video game. The rise of machine learning may prove instrumental in classifying gamer types, assuming academic researchers can gain access to play logs; indeed, and unlike other constructs such as motivation to play (Kahn et al., 2015), gamers cannot be expected to intuit the cognitive demands of their game play, which calls for a data-driven rather than a self-report methodology. As the field matures, we should aim for a taxonomy that goes well beyond classifying video games, instead aiming for one that documents each game title according to the underlying cognitive, emotional, or social processes engaged while playing (Baniqued et al., 2013). Such knowledge will be key in attempting to understand the type of transfer that is expected from playing a given game title. We recognize that such a classification system is not yet within reach. A multi-disciplinary effort is likely needed that will bring together game analytics, cognitive science, game design, affective science, machine learning, and social science for a concerted effort in analyzing, developing, and testing video game titles at a scale that goes beyond what a single laboratory may be able to provide.

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DECLARATION OF INTERESTS

Daphne Bavelier is a cofounder of Akili Interactive, Boston, MA and a member of its scientific advisory board. C. Shawn Green declares no competing interests.

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