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The Effect of Playing Video Games on Visual Perceptual Skills

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The Effect of Playing Video Games on Visual Perceptual Skills

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Psychology

by

Maggie Shannon Yeh

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ABSTRACT OF THE DISSERTATION

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on Visual Perceptual Skills

by

Maggie Shannon Yeh

Doctor of Philosophy in Psychology

University of California, Los Angeles, 2024

Professor Zili Liu, Chair

Video games have become ubiquitous as 21st century entertainment media, but the effects of such an immersive visual experience are an area of active research. Action video games (AVGs), a genre that commonly encompasses first-person shooter (FPS) and third-person shooter games, have been a particular focus for the video game research field given their unique combination of time pressure, speed, and challenge. Research has suggested that AVGs may benefit a wide variety of visual skills ranging from low-level perceptual skills such as orientation discrimination and contrast sensitivity function, to higher-level skills such as multiple object tracking or attentional blink. These promising results have spurred interest in using video games for skill training or even for medical treatment of visual disorders. However, the exact range and limitations of AVG training is still widely unknown, and there continues to be active debate in the field over which visual skills AVGs can transfer to. Furthermore, the mechanisms by which AVGs affect vision are still unknown. A related field of research, visual perceptual learning (VPL), may be able to offer insight into the limitations and the mechanisms of AVG transfer given that VPL is a field that has long investigated the mechanisms and limitations of low-level visual learning. Therefore, in this dissertation, I combined the perspectives of both fields in order to investigate AVG transfer further. First, I compared AVG to psychophysics training as typically used in VPL research, which allowed me to quantify the effects of AVG transfer to low-level visual skills (Study 1). This study demonstrated that AVG training did not transfer to motion discrimination tasks, as psychophysics training resulted in significantly more transfer. Second, I investigated the ability of AVG training to transfer to untrained regions of the visual field, and did not find any significant difference between trained and untrained visual field (Study 2). Both studies also served to further test the limitations of AVG transfer to lower-level visual skills, which have been less frequently investigated in AVG literature compared to higher-level visual skills. I did not find evidence of significant AVG transfer to any of the visual tasks tested, suggesting that AVGs, while widely considered to be beneficial for attention-based visual tasks, may not be as beneficial for lower-level visual perception. These results suggest that AVGs may affect vision via higher-level mechanisms, which would have implications for further determination of how AVGs may affect various visual skills or be used in practical application.

The dissertation of Maggie Shannon Yeh is approved.

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- Lin, C.*, **Yeh, M.***, Shams, L. (2022) Subliminal audio-visual temporal congruency in music videos enhances perceptual pleasure. ***Neuroscience Letters***.
- "Assessing action video games as visual perceptual training". CogFog Lab Meeting (UCLA Bjork Lab), Los Angeles, CA, November 2021.
- "The Effect of Multisensory Temporal Congruency on Pleasure". International Multisensory Research Forum. Toronto, Canada, June 2018.

Chapter 1: General Introduction

Video games as a form of entertainment media have become more popular and accessible in the 21st century, resulting in rising interest in the psychological effects of video gaming. Given that video games, especially in the action genre, can include violence, it is unsurprising that much of the research into video games has focused on how they might impact aggression or other socioemotional factors. However, another research area of interest has been video game potential for inducing visual learning, which has become more popular for the past two decades since Green & Bavelier's (2003) publication claiming visual benefits of video games. While video games are not explicitly designed as visual training programs, it cannot be denied that they are purposefully designed to be visually engaging, and at times, challenging. Green & Bavelier's (2003) study started a chain of research that has specifically referred to the genre of games most effectual for visual learning as "action" (Figure 1), although they recently have acknowledged the lack of practical classification or utility in that label (Bavelier & Green, 2019; Dale et al., 2020). What has followed is research into the potential transfer of learning from action video games (AVGs) to a variety of visual skills.

Remarkably, many of these video game studies have found transfer from video game play to visual skills ranging from contrast sensitivity (R. Li et al., 2009) to multiple object tracking (e.g. Green & Bavelier, 2006) to task-switching (e.g. Strobach et al., 2012). The variety of skills and the multiple levels of processing (affecting vision and attention) that video games appear to transfer to is promising for potential future use of video games in skill training or even medical treatment. However, in this dissertation, we are particularly interested in the unusual transferability of video game training in the context of low-level visual perceptual skills, such as contrast sensitivity (R. Li et al., 2009) or orientation discrimination (Bejjanki et al., 2014).

Figure 1. Examples of action games

Note. From top-left, clock-wise: *Call of Duty: Modern Warfare 2* (Activision, 2009); *Borderlands 2* (2K, 2012); *Tom Clancy's Ghost Recon Wildlands* (Ubisoft, 2017); *Fortnite* (Epic Games, 2017). The first two are examples of first-person shooter games, while the latter two are examples of third-person shooter games.

The reason for our interest in video game transferability is due to the pattern of results that has typically been found in visual perceptual learning (VPL) research – a field that has some intersection with video game improvements to vision. Specifically, the field of VPL focuses on researching the characteristics and mechanisms of learning in lower-level vision, which means that some of their paradigms and findings might synchronize well with video game transfer to low-level vision. However, there is a major difference between the two fields as they currently stand. Specificity, or lack of transfer of learning from one situation to another, is known as the unique finding characteristic of VPL. In contrast, video game research has generally suggested the utilizing AVGs as training creates widely generalizable learning that can affect both low-level and high-level vision.

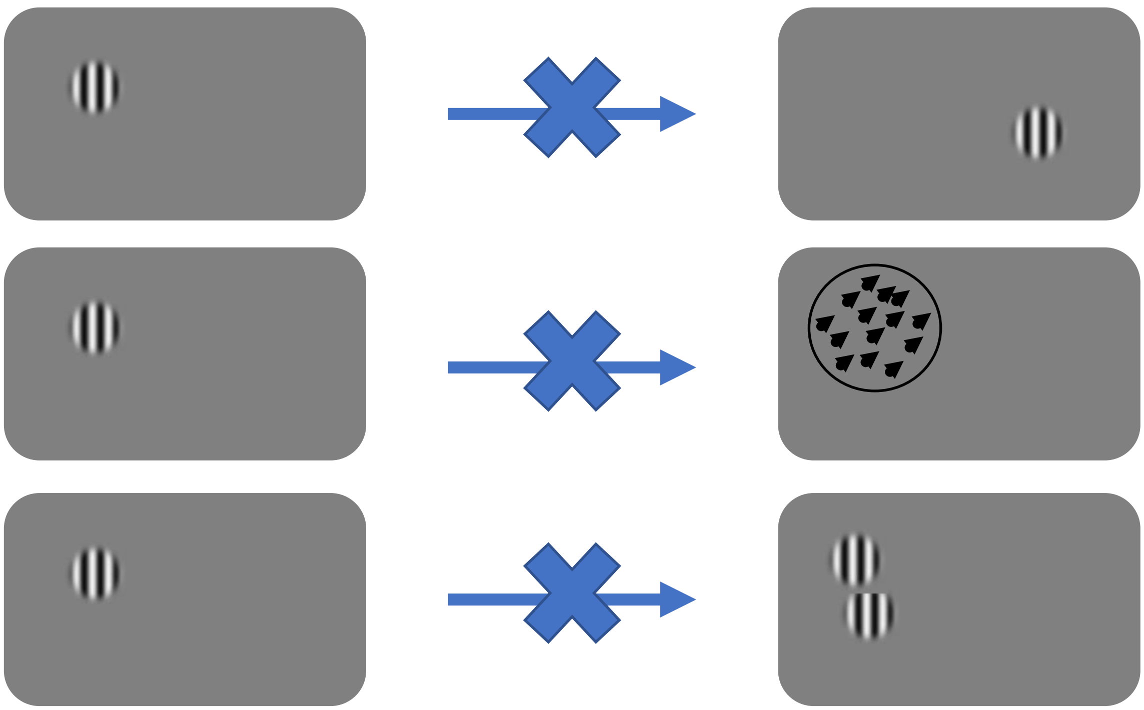
To a VPL researcher, the characteristics of video game learning are surprising, considering that much of VPL research is focused on the occurrence and overcoming of specificity. Despite this, video game researchers have rarely utilized VPL paradigms in studying the effects of video game experience. Many video game studies are cross-sectional in nature – simply comparing experienced video game players (VGPs) to non-video game players (NVGPs) in correlational analyses. Of the studies that have utilized training paradigms, only a few have explicitly referenced VPL techniques or literature (Bejjanki et al., 2014; Jacques & Seitz, 2020). The results of these studies provide an intriguing alternative perspective on video game training, and are an example of how video games can be studied further from a VPL perspective. Jacques & Seitz (2012), for example, attempt to explicitly tie levels of attentional ability and video game experience to the ability to transfer learning between visual perceptual tasks. Bejjanki et al. (2014) take another approach and apply the training study paradigm from video game research to contrast thresholds for orientation discrimination, and apply a perceptual template model to the results. Therefore, from these examples we can see two approaches for studying video games from the VPL researcher's perspective: 1) exploring the extent to which video game experience might transfer to visual perceptual abilities; and 2) testing the applicability of different potential learning mechanisms to visual learning induced by video games.

In the current project, we take aspects of both approaches. By doing so, we aim to combine techniques from both VPL and video game training literature to integrate the findings from both fields, while also potentially providing additional insight into the mechanisms of visual learning. In the following sections, we will review some of the most prominent theories of visual learning from the VPL literature. Then, we will discuss various experimental paradigms that have been developed in VPL research for overcoming specificity of learning. Finally, we will briefly review the current state of the field of video game transfer to vision, and outline the research covered in this dissertation.

Theories of visual learning

In general, specificity as a standalone finding is a hallmark of older VPL studies. This includes research in the late 80s through the 90s done by the likes of Fahle (1997), Karni & Sagi (1991), Shiu & Pashler (1992), Berardi & Fiorentini (1987), Ball & Sekuler (1982, 1987), and Ahissar & Hochstein (1996). The specificity that was observed by these researchers takes several forms: stimulus, location, and task specificity (Figure 2). Stimulus specificity refers to improvement on a specific stimulus that does not lead to improvement on a different stimulus used in the same task (e.g. Ball & Sekuler, 1982). For example, stimulus specificity might refer to learning to discriminate ±2 degrees of difference in orientation centered around a 65-degree tilt, that does not cause any improvement in discriminating ±2 degrees of difference in orientation centered around a 145-degree tilt. Another example of stimulus specificity would be learning to discriminate a 65-degree tilted Gabor, but showing no improved ability to discriminate a 65 degree tilted line. Location specificity, on the other hand, refers to the phenomenon of improvement in one retinal location in the visual field that does not lead to improvement in any other untrained retinal location in the visual field (e.g. Shiu & Pashler, 1992). Typically, the stimuli and task that are tested in the untrained retinal location are identical to that used in the trained location. Lastly, task specificity refers to improvement on one task that does not lead to any improvement on another task, often using the same stimuli (e.g. Fahle, 1997). An example of task specificity is if learning to discriminate orientation of a Gabor does not improve discrimination ability for motion direction of a dot stimulus. In classic VPL literature, features that they found stimulus specificity (and sometimes task and location specificity) for included orientation (Shiu & Pashler, 1992), spatial frequency (Fiorentini & Berardi, 1981), motion direction (Ball & Sekuler, 1982, 1987), and Vernier acuity (Fahle, 1997).

Figure 2. Three types of specificity



Note. The top row depicts an example of location specificity, where improvement with the stimulus in one retinal location does not transfer to the same stimulus in another retinal location. The middle row depicts an example of stimulus specificity, where improvement with judging orientation of a grating does not transfer to judging motion direction of a dot stimulus. The bottom row depicts an example of task specificity, where improvement with an orientation discrimination task does not transfer to improvement on a Vernier discrimination task using the same type of grating stimulus.

Based on these older findings, researchers typically have taken this as evidence for pointing toward a specific physical locus of VPL. Specifically, they have often pointed to these findings as evidence for what some call a neural representation theory (Jeter et al., 2010). The foundation of this theory is that there are specific neurons that embody different visual features, and so in order for learning to occur, these neurons must themselves change. For example, improvement in orientation discrimination might originate from individual neurons refining their tuning curves for orientation. This theory is also why primary visual cortex (V1) is often suggested as a possible location for VPL, because V1 is where the bulk of such specific neurons are located. We know for a fact that the neurons in V1 are specialized for specific orientations, spatial frequency, motion direction, and so on. This theory is also well-supported because it in turn reinforces the unique specificity finding from VPL research. If one assumes that training a specific feature in a specific retinal location only causes changes in the V1 neurons that were used for that task, then no transfer would be expected. Under this theory, neurons representing a different retinal location or different orientation would not be trained, so improvement would only be expected in the trained retinal location and features.

However, the neural representation theory is increasingly unpopular in VPL, primarily because evidence continues to accumulate to disprove it (e.g. Pavlovskaya & Hochstein, 2011; Wang et al., 2016; Xiao et al., 2008; Xie & Yu, 2019). Furthermore, even if aspects of this theory are based in truth, it is unlikely that neural representation theory encompasses the entirety of visual learning processes. If VPL only involves change in individual V1 neurons, then how do we learn to see the world around us in the first place when it's likely that we constantly encounter novel, untrained visual stimuli and characteristics?

This leads to the current most popular perspective on VPL, which is the reweighting theory of VPL. This theory argues that instead of individual neural units being the locus of change in VPL, it is instead the connections between neurons that are modified during learning. Thus, the reweighting hypothesis theorizes that learning occurs when higher level neural units change how they weight different information sources from lower-level neural units. This meshes well with research that suggests that VPL might involve enhancing relevant input from V1 and suppressing irrelevant information (e.g. Astorga et al., 2022; Yan et al., 2014). Furthermore, there is evidence that V1 activation as related to VPL is often inconsistent (Ghose et al., 2002). Instead, an alternative proposed explanation is that higher level areas such as V4 or beyond are reweighting and reselecting inputs from lower-level areas like V1 based on task demands, and enhance their selectivity and weighting over time, which is then expressed as learning on a test measure (Astorga et al., 2022).

Most importantly, the reweighting theory allows for the occurrence of generalization, which has been observed in various forms in VPL research (e.g. Liu & Weinshall, 2000; Xiao et al., 2008; Zhang & Yang, 2014) over the past 2 decades. It is important to note that simply training participants on a typical psychophysical task and observing improvement is unlikely to itself lead to transfer. However, reweighting theory has been used to explain newer research that has been able to demonstrate partial or even complete transfer of learning in VPL. Some examples of paradigms that have had varied success in inducing generalization include more complex tasks, ranging from changing the variation in trained stimuli (e.g. Liu et al., 2023; Xie & Yu, 2020), to combining training with exposure to different stimuli characteristics (e.g. Wang et al., 2016; Xiao et al., 2008; Zhang & Yang, 2014), to manipulating the amount of training participants receive (e.g. Jeter et al., 2010; Liang et al., 2015), to utilizing more complex or realistic training tasks, such as video games (e.g. Green et al., 2010). Although not all such studies argue for reweighting theory to support their results, many reweighting theorists have argued that the wide variety of specificity and transfer results seen in VPL are only explainable with a reweighting theory. A major example of reweighting theories is Dosher et al.'s (2013) integrated reweighting theory (IRT), which proposes multiple layers of neural processors that each reweight connections with lower layers during learning. A more recent modification even accounts for feedback, if present (Liu et al., 2023).

While neural representation and reweighting theories have long been major contenders in VPL literature for explaining VPL mechanistically, there are other hypotheses that have more recently begun to emerge that offer other perspectives. One simple hypothesis that would neatly integrate much of the current body of evidence is that VPL requires both change in neural representations and reweighting (e.g. Gong et al., 2022; Yan et al., 2014). Another perspective of this combined theory is simply that learning involves multiple levels of processing in the brain, all of which speak to each other. It is clear from neural evidence that vision is not a feedforward process alone; information travels both from V1 upward and from higher level processes back down to lower-level cortical areas (e.g. Astorga et al., 2022). Knowing this, it is logical that eventually one might argue that vision is simply a complex process that involves the brain as a whole in a complex interconnected web of processors that all influence each other. Maniglia & Seitz (2018) make this argument, pointing out that behavioral and neural evidence has indicated potential visual learning occurring at multiple levels of visual processing, and at multiple regions of the brain. They propose a global brain hypothesis, such that plasticity during VPL likely occurs throughout the brain.

Another type of VPL theory is removed from the physical loci of learning. Instead, these hypotheses focus on abstract mechanisms of learning, with the likely eventuality of suggesting that learning requires some higher-level and possibly amodal mechanism. For example, Bavelier et al. (2012) have adopted the “learning to learn” hypothesis (originally proposed by Harlow, (1949)), which suggests that perceptual learning in and of itself is a higher-level skill that is enhanced by training. Therefore, rather than specific neural units or circuits that are being changed in perceptual learning, it is a higher-level mechanism that in turn affects decisions made about lower-level information. Another example is Wang et al.'s (2016) hypothesis of abstraction of learning. Specifically, they describe perceptual learning as learning concepts from multiple exemplars, rather than learning specific perceptual properties or discriminations, and this is what allows for generalization. Rather than being controlled by a higher-level mechanism that is separate from the units that process specific properties of the visual stimulus, their hypothesis suggests that visual concepts are learned via reweighting of connections between lower- and higher-level visual cortex. An interesting difference is that Wang et al.'s hypothesis relies on the presence of a variety of stimuli in order for generalization to occur, whether that takes the form of multiple varieties of the stimulus, or exposure to additional stimuli in the training-plus-exposure (TPE) procedure. In contrast, Bavelier et al.'s (2012) theory falls more in line with theories about a general intelligence factor g, that might be affected as much by individual disposition as it is training.

Two other major examples of VPL theories are Watanabe & Sasaki's (2015) inattention theory, and Ahissar & Hochstein's (2004) reverse hierarchy theory. The inattention theory suggests that there is a gating mechanism during VPL that prevents irrelevant information from passing into memory for learning, but only when one is attending to a stimulus. However, if there is other information present during a task that is not attended, perhaps because it is irrelevant in the moment, then that unattended information can make it past the gating mechanism and be learned indirectly, resulting in generalization. On the other hand, the reverse hierarchy theory suggests that learning occurs at higher levels first, and then works downward to lower levels over training. The initial higher-level learning is where learning is more generalizable, but if one continues to train and learning makes it down to lower levels, specificity occurs instead. Reverse hierarchy theory also posits that easier tasks tend to be processed at higher levels and more difficult tasks at lower levels, although more recent research (Le Dantec & Seitz, 2012) suggests that it is in fact precision and not difficulty of the task that causes this effect. While reverse hierarchy theory is considered separately from reweighting theories, one might argue for some compatibility if it is assumed that at the so-called higher levels of processing in reverse hierarchy theory, all neural connections remain potentially engaged, which might lend itself to generalization. In contrast, perhaps as a task becomes more difficult or processed more by lower levels in reverse hierarchy theory, neural connections between high- and low-level processing areas may become more specific in nature, leading to more specificity. However, this is a potential reconciliation between theories that has not yet been explored.

VPL paradigms and transfer of learning

Much of VPL research and the resulting theories stem from the specificity finding that is so ubiquitous to the VPL literature, and a desire to discover what specificity implies for the physical and mechanistic origins of VPL. Increasingly, researchers have moved away from viewing VPL as purely based in neural representations, considering that 1) generalization has been observed consistently, albeit in specific situations/paradigms, and 2) that evidence has accumulated to show that neural representations alone cannot be the sole explanation for how VPL occurs.

Researchers have generally tried to elucidate the source of VPL by manipulating different aspects of the training process in order to see how they affect the amount and specificity of the resulting learning. There is a long list of factors that have been examined, but some of these factors include the amount of training; the presence, frequency, and informativeness of feedback;

the variability of the stimuli used in training; the precision or difficulty of the training task; the amount of overlap between the stimuli, task, and retinal location of training and testing; exposure to untrained stimuli during training; the signal to noise ratio of stimuli; the complexity of learned stimuli; and more.

The result of these manipulations can give insight into which neural representations might be used in VPL, while others give insight into mechanisms, albeit without any specific physical locus. For example, training participants on a specific orientation of grating stimuli and seeing how they perform after training on an untrained orientation of the same stimulus informs us on the specificity of orientation discrimination. If the learning from training does not transfer to an untrained orientation, this implies that learning must be occurring in such a way that it only applies to a specific orientation. Furthermore, this type of result has often been interpreted as evidence that VPL may occur in early visual processing, specifically in V1, where individual neurons are known to represent specific orientations. However, interpretation has generally changed in the past two decades, and this specificity can also now be interpreted as compatible with the reweighting hypothesis. Another example of experimental manipulations that have led to conclusions of VPL occurring in neural representations in visual cortex is research that shows limited transfer between hemifields (e.g. Wilson et al., 2010). Specifically, it is known that visual representations are significantly segregated by visual hemifield in early visual processing, such that all right visual field information is sent to left visual cortex, and vice versa. Therefore, if VPL is unable to transfer between hemifields, it can be interpreted to mean that VPL only occurs in neural representations prior to any communication between hemifields, which occurs in processes primarily beyond visual cortex.

Another aspect of training that has become a focus of interest in recent years is the concept of exposure to stimuli. Xiao et al.'s (2008) research is the most prominent early study regarding this concept – that generalization might require co-activation of neurons corresponding to other stimuli aside from those being actively trained. In addition, it has been suggested that there is a priming effect from exposing learners to additional stimuli, to prime the learning circuits in the brain that whatever is being learned may also apply to other stimuli or locations. Other researchers that have examined variations of this concept include Cong et al. (2016) and Wang et al. (2012), except that the term used more often in recent literature is training-plus-exposure (TPE), rather than double training. Watanabe & Sasaki's (2015) inattention experiments may also fall under this umbrella of manipulating exposure to stimuli, with the exception that they have focused more on sub-threshold exposure rather than explicit exposure. TPE often leads to generalization of a learned task to untrained stimuli and retinal locations. However, there are also some limitations that have been observed – sometimes transfer is partial rather than full, and it does appear that some skills are more likely to transfer via this method than others. For example, directionality may be an issue. Second-order motion transfers to first-order motion stimuli, but not vice versa (Wang et al., 2016). While exposure clearly brings one aspect of generalization to light, it is not the entire explanation.

The variability of stimuli is also a factor that has periodically been revisited as affecting VPL generalization. The work of Kellman (e.g. Kellman, 2002), for example, inherently suggests that variability is a necessity for generalized VPL because VPL involves abstraction of relevant or informative features for a given task. If a learner is repeatedly exposed to one specific stimulus, then the brain inherently focuses on small differences in specific features, leading to specificity. However, if a learner is exposed to a wider range of stimuli in learning a task, the brain abstracts a more general rule from training, leading to more transferable learning. Notably, there is synchrony to varying degrees between this particular aspect of VPL experiments and multiple theories. For instance, it is clear how this synchronizes with a more conceptual view of VPL – one learns more general concepts better with a wider range of exemplars, not unlike category learning. Nor is Kellman's research group is not the only proponent of this theory – Wang et al. (2012) are some recent champions of this concept.

However, the idea of exposure also may synchronize well with the role of increased variability in training paradigms. After all, is not exposure to other stimuli in a way simply increasing the variability of the stimuli presented as potentially relevant during training? Wang et al. (2012) suggested a statistical learning of sorts as a mechanism behind a conceptual view of VPL, and this may also work well to explain how the brain comes to generalize – it needs a good array of exemplars to learn a realistic, generalizable skill, because otherwise the model that the brain is presented with is that a given task only requires one specific discrimination.

Feedback is yet another manipulation in VPL research that has been examined. While there have been mixed results as to whether or not feedback is required for learning to occur, the current consensus seems to fall more toward providing feedback as a necessary component of learning (e.g. Liu et al., 2023). Liu et al. (2023) found that receiving more informative feedback led to increased learning, suggesting that participants learn more given full information about what they did incorrectly. Furthermore, adjacent to feedback is the concept of reward, in terms of given feedback that may motivate participants more. Indeed, Zhang et al. (2018) found that giving participants a frequent high reward led to better learning and generalization. While the question of a reward that appeals to all learners equally is another issue, it does appear that providing the right kind of feedback, whether it pertains to more information or increased motivation, seems to greatly affect learning amount and learning generalizability.

Current evidence from video game training research

VPL research has tended to focus on the characteristics and limitations of specificity, and the resulting implications for the mechanisms and neural circuitry behind VPL. In contrast, the field of video games and visual learning has focused more on the surprising extent to which playing action video games transfers to visual skills. The delineation of what describes an action video game is crucial for the intersection of VPL and video game research, because the characteristics inherent to the genre seem to be crucial for the transfer of learning from video games to vision. Therefore, while the debate over how best to overcome the ambiguity of the "action" genre label is ongoing, some key characteristics of an effective training game have been defined. These three characteristics are 1) pacing, or making decisions under subjective time pressure; 2) load on divided attention, such that the player must both attend to a primary task and attend to other potential stimuli; and 3) a need to switch between processing modes, such that the player might both have moments of focused attention and moments of divided attention (Bavelier & Green, 2019). These factors have been defined with some predominant mechanisms of video game learning in mind, which we can connect to VPL learning hypotheses.

The current hypothesis behind the general effectiveness of video game training predominantly depends on increased attentional control abilities. Namely, that video games may convey their variety of benefits by increasing plasticity in top-down attentional control mechanisms. One example of how this plasticity might be implemented is that it might enhance the brain' decision making units' ability to select task-relevant information, while simultaneously enhancing the ability to suppress task-irrelevant information (Bavelier & Green, 2019). In this example, connections could potentially be drawn between video game manipulation of information discrimination ability, and Watanabe & Sasaki's (2015) theory of subliminal threshold learning. In the context of VPL, it has even been suggested that improvement in perceptual abilities from video game training is in fact still attributable to attentional mechanisms – Bavelier & Green (2019) suggest that top-down attentional control allows learners to better focus on relevant perceptual characteristics, potentially allowing for formation of better perceptual templates. Another mechanistic connection between video games and VPL is that video games themselves are inherently structured around rewarding players, in order to encourage further gameplay. Reward and feedback are known to affect the amount and generalizability of VPL (Liu et al., 2023), and so it is logical to consider that the high reward conditions built into video games could affect the amount and generalizability of learning from playing video games.

Mechanisms aside, the primary motivation to study video game learning from a VPL perspective is that AVGs have been shown to transfer to such a wide range of visual skills. AVGs have been shown to transfer especially to many higher level visual skills, including visual search (Castel et al., 2005; S. Wu & Spence, 2013), multiple object tracking (Boot et al., 2008; Green & Bavelier, 2006; Sungur & Boduroglu, 2012; Trick et al., 2005), visual working memory (Blacker et al., 2014; Blacker & Curby, 2013; Boot et al., 2008; Colzato et al., 2013; R. W. Li et al., 2015; McDermott et al., 2014; Wilms et al., 2013), attentional blink (Green & Bavelier, 2003; Oei & Patterson, 2015), oculomotor capture (Chisholm et al., 2010; Chisholm & Kingstone, 2012, 2015), mental rotation (Feng et al., 2007; Flores-Gallegos & Mayer, 2022), and useful field of view (Dale et al., 2019; Dye et al., 2009; Feng et al., 2007; Green & Bavelier, 2003; S. Wu et al., 2012). Furthermore, some video game studies have found potential low-level visual benefits from video game experience for skills including contrast detection (R. Li et al., 2009), stimulus detection in crowded visual fields (Green & Bavelier, 2007; R. Li et al., 2009), and orientation discrimination under external noise (Bejjanki et al., 2014).

Therefore, there is a preponderance of evidence suggesting that playing AVGs may benefit vision across multiple levels. With such support for the benefits of video game play, it is surprising that there has not been more research on the benefits of video game play for lower-level visual skills. From a theoretical perspective, video games are an intriguing training paradigm that could be used to examine the mechanisms of VPL from an alternative perspective. If video games are so widely transferable, the VPL perspective could potentially learn much about the training characteristics that encourage transferable visual learning from video games. From an applied perspective, it is sensible to study video games and how they might affect visual learning at all levels, given that a more transferable visual learning paradigm could be beneficial for clinical applications such as treating amblyopia (e.g. Jeon et al., 2012) and skill training applications (e.g. training surgeons or pilots (Hart & Battiste, 1992; Rosser et al., 2007)). However, as the literature stands, there are not many studies that have focused on evaluating the efficacy of video game training from a VPL perspective (some exceptions include Bejjanki et al., 2014; Jacques & Seitz, 2020).

Furthermore, despite the overall positive attitude in the literature toward video games as being beneficial for visual learning, there is continuing debate over the existence and the effective magnitude of these benefits. There are studies that have found no benefits or mixed effects from action video game training (Boot et al., 2008; Jacques & Seitz, 2020; Murphy & Spencer, 2009; van Ravenzwaaij et al., 2014). In addition, multiple meta-analyses have been conducted that differentiate the types of visual skills that are affected by video game training, as well as quantifying their effects (Bediou et al., 2018; Chopin et al., 2019; Powers et al., 2013;

Sala et al., 2018; Toril et al., 2014). Of particular interest is what these meta-analyses have to say about the effects of video game play on perceptual learning. Bediou et al. (2018) report a significant effect size for the advantage VGPs have over non-VGPs for perception (Hodges' g = .775). However, they also report a small, non-significant effect size for the effect of AVG training vs non-AVG training when it comes to perception (Hodges' g = .227). Similarly, Powers et al. (2013) report a larger effect size for a VGP advantage in cross-sectional studies for visual processing (Cohen's d = 0.68), but a smaller effect size for AVG training (Cohen's d = 0.36). This implies that either AVGs are not responsible for the advantage that VGPs have demonstrated in perceptual skills, or there are methodological limitations in the training studies that have been enacted which have muddled the actual effect. However, despite claiming generally non-significant effects of AVGs, even the meta-analysis from Sala et al. (2018) acknowledges the presence of some amount of advantage for AVG players. Either way, this difference in effect size implies a need to further examine the potential presence or lack thereof of causation between AVG play and visual perceptual ability.

The current project is therefore focused on addressing the lack of research that has studied the effects of AVG training from a VPL perspective. Not only is such a topic able to contribute meaningfully to an ongoing controversy over the effectiveness of AVG training, but also given the seemingly widely transferable effects of AVG training in the literature, it is sensible to further explore how that transfer might look for VPL skills. We therefore turn our attention to outlining how some of the paradigms of VPL research might be applied meaningfully to video game learning research.

Research questions addressed in the current dissertation

Video games are a logical exploration from the current state of the VPL field. The field of VPL is increasingly moving toward exploring paradigms that are promising for inducing transfer of learning, and with these paradigms come the evolution of concurrent hypotheses. Many of these hypotheses are moving away from pinpointing specific neural representations that are modified during VPL, and instead focusing on neural connections or even wider, higher level, or more global networks that may be responsible for guiding VPL. The logical next step is to examine other paradigms that affect visual learning from an opposite approach – coming from the perspective of maximum variability rather than isolated and lab-controlled stimuli. Video games meet this criteria, while also providing a potential avenue for gamification of a visual training program that could be used in clinical settings.

Therefore, in the current project, we integrate principles of VPL research with video game training through several approaches. First, we aim to explore whether or not AVG training transfers to several visual perceptual tasks. Specifically, we attempt to explicitly compare video game training to classic VPL training methods. This method has several benefits. The results of such a comparison add to the overall body of evidence pertaining to whether or not AVG training transfers to perceptual tasks, specifically lower-level visual tasks. Our more direct comparison also allows for a quantification of the visual learning induced by AVG training relative to the ideal training for a visual task – the task itself. To our knowledge, such a direct quantification of video game training relative to psychophysics training for a visual perceptual skill has not been done previously. This quantification allows for an objective measure of the efficacy of video game training while also providing a measure of the degree of transfer, which has been used in prior VPL research (Study 1).

Another aspect that we explore in the current project is the rate of learning from video game training. The timing of learning over the course of training is an issue that has been explored in VPL, and is especially crucial given that research has shown that a large amount of learning occurs early on in VPL training (e.g. Censor & Sagi, 2008; Hussain et al., 2009; Karni & Sagi, 1993). Part of disentangling the learning effects in a VPL study is that inevitably part of the early learning observed will be due to task learning rather than improvement in the skill itself. That is, a sharp increase in performance earlier in training may simply be due to the participant needing some number of trials to learn how to do the task at hand. On the other hand, excluding any early practice trials from data analysis also runs the risk of removing early learning data. Furthermore, early learning from VPL training can lead to more generalization of learning than further training (Jeter et al., 2010). Other studies have shown that the distribution of training over time can affect the amount of learning that occurs (Larcombe et al., 2017) or the amount of transfer that occurs (Song et al., 2021). The time course of learning clearly can have significant effects on the resulting improvement; therefore, we explore the amount of improvement in visual perceptual skills in Study 1 before, halfway through, and after training. The aim of this experimental paradigm is to compare the time course of any VPL that occurs as a result of action video game training to VPL from typical VPL psychophysics training (Study 1).

Finally, we explore a different type of transfer that has been less often studied in the video game literature: location transfer. The majority of video game learning studies have focused on task and stimulus transfer. Typically, video game researchers have been interested in investigating which visual skills video game training might improve or give an advantage for. Because video games involve stimuli and tasks that are typically not comparable to the tasks that participants complete in the lab, these studies have inherently been focused on transfer of the learning from video game stimuli and tasks to lab stimuli and tasks. We therefore want to focus more on location transfer as a relatively neglected type of transfer in video game research. The most common instance of location transfer being studied in the context of video games is tests of the useful field of view (UFOV). This task involves testing participant ability to identify the presence and general location of a quickly flashed stimulus presented at varying eccentricities from the fovea. Multiple studies have found an advantage for video gamers with this task (e.g. Green & Bavelier, 2003), with the reasoning that AVGs often require visual attention to both the center and the periphery of the screen. However, no studies to date have examined location transfer systematically with methods more comparable to those used in VPL research (Study 2).

Our approach to studying location transfer focuses on transfer of video game training from trained to untrained retinal locations. In terms of visual processing, visual information is expected to be processed by multiple units with overlapping receptive fields, but segregation of information is expected in that ultimately, only a subset of visual neurons will be activated by a given stimulus. Location transfer or specificity can therefore be interpreted in the context of the receptive fields being activated by a given stimulus. If a stimulus is smaller, then it will activate a smaller subset of neurons in visual cortex, which may in turn only activate one specific higher level processing unit. Whereas if a stimulus is larger, it will activate a larger subset of neurons, which might encourage location transfer because there may be activation of multiple higher-level units. Another factor that may affect location transfer is the complexity of the stimulus – the variation in the composite features or the number of types of characteristics involved in perceiving the stimulus. More complex stimuli may encourage location transfer by requiring higher level processing in the visual pathway (Gong et al., 2022). Finally, the location of the stimulus in question may also affect location transfer due to the relatively large receptive fields in the periphery of the visual field (as opposed to the fovea). With all of these factors taken into account, it would suggest that action video game training should encourage location transfer, considering that a video game inherently contains stimuli of varying sizes that are complex and located throughout the visual field.

Many VPL studies have found specificity of retinal location (Ball & Sekuler, 1982; Berardi & Fiorentini, 1987; Schoups et al., 1995; Shiu & Pashler, 1992). This has been taken as evidence that VPL occurs in early neural representations (e.g. V1), as visual information from throughout the visual field is integrated later in visual processing. However, more recent, contradicting results have lent support for other alternative theories that involve higher level processors (e.g. Astorga et al., 2022). Video games therefore stand to provide unique insight into VPL by being a form of visual training that purportedly has generalized widely both across tasks but also across retinal locations. In the current project, we test the level of location transfer that AVGs can induce. Should AVG training prove to successfully transfer to visual perceptual skills, we gain further insight into the levels of processing at which perceptual learning operates. Should AVG training not successfully transfer across locations, we stand to gain further insight into the mechanisms behind video game induced learning. This is especially valuable insight considering that there is little research examining whether the visual learning induced by video games and in VPL are utilizing the same neural mechanisms.

We therefore examine the extent to which action video game training can transfer to visual perceptual skills in two training studies, as follows:

Study 1

In Study 1, we examine the direct quantification of VPL transfer from AVG training in comparison to psychophysical training. Furthermore, we also investigate the comparative rate of visual learning from video game training and psychophysical training by testing participants before, midway through, and after training. The research questions we seek to address with this study are

1) whether AVG training can transfer to low-level visual perceptual skills;
2) whether the extent of transfer from AVG training matches learning from psychophysics training; and
3) whether learning rates for visual perceptual skills are similar between AVG training and psychophysics training.

Study 2

In Study 2, we continue to investigate the extent to which AVG training can transfer to visual perceptual skills. However, we additionally investigate whether AVG training is able to transfer between retinal locations, which we operationalize as trained or untrained pairs of diagonal visual quadrants. The research questions we seek to address with this study are

1) Whether AVG training can transfer to low-level visual perceptual skills;
2) Whether AVG training can transfer to untrained retinal locations.

Chapter 2: A review of the video game and visual learning literature

The growing availability of video games has been accompanied by an increasing interest in researching the effects of this new form of media. Video games only became a form of entertainment for the public in 1971 with the creation of the first commercial video game in arcades, *Computer Space*, followed shortly by the invention of the first home gaming systems. However, video games as a more accessible and popular format of entertainment media as we think of it today only really started in 1985 with Nintendo's NES console, among others, and video games have only taken off in popular awareness in the 21st century (*Video Game History*, n.d.). Nowadays, video games have expanded beyond merely being a niche form of media, to being a form of sport, an artistic and creative modality, and an educational tool.

It is sensible in such an explosively growing form of media to investigate how it might affect human psychology. Vision in particular is very relevant in the field of video games, with games being primarily visual in modality and in implementation of gameplay. The so-called AAA video game studios (larger video game making companies) are notorious for producing games with claims for ever-increasing visual quality and realism. It is telling that one of the key features often promoted in newer video games is ray tracing, a 3D rendering technique that produces much more realistic lighting in games, but at a higher computational cost. Therefore, the visual aspect of games is clearly a priority for the video game industry.

When one typically thinks of video games and vision in the popular consciousness, the connection that likely arises is the potential detriment of extensive video game play on vision, due to excessive screen time. However, another more intriguing avenue was first brought to research prominence with Green & Bavelier;s (2003) study claiming that playing action video games enhanced various visual abilities. Since then, Green & Bavelier's (2003) research has led to a wider body of literature that has examined whether playing video games causes improvement of visual abilities, ranging from visual perception to visual working memory to executive function. The evidence from this research is diverse and complex, and it is the aim of this chapter to provide an overview of the research questions that have been asked in this field, as well as the evidence that has been found at this point in time.

First, we will discuss the primary methodologies that have been used to study the effects of playing action video games on visual learning. For each method, we will cover the evidence that has been accumulated and discuss the balance of evidence for and against a beneficial effect of video game training. Next, we will discuss the research that has examined the potential neural correlates and mechanisms behind video game training's effects on vision. Following that, we will examine various factors that potentially modulate the effect of video games on visual learning. Finally, we will discuss research into the potential applications of video games for clinical settings and skill acquisition, as well as future directions of the field.

For this literature review chapter, we will focus primarily on studies that utilize video games or recruit video game players. We define a study as focusing on visual learning if there are measures of skill level or improvement in visual skills ranging from low-level perception in V1 to visual skills that involve higher level processing such as attention, but we will not be focusing on studies that include visual measures that more accurately represent executive function. For example, studies that measure skills such as task switching will not be our focus, given that our unifying interest in this project is on visual perception.

The current research on the effect of video games on vision

The two paradigms that are typically used in video game learning research, cross-sectional and training studies, can be found in Green & Bavelier (2003), which has served as a prototype for many subsequent studies. A cross-sectional study involves comparison of one or more groups of video game players (VGPs), to non-video game players (NVGPs). An example of a more specific video game playing group that might be defined in these studies is action video game players (AVGPs). These studies typically involve pre-experimental surveys to classify participants by video game experience, followed by having participants complete various measures of interest to detect any potential advantage of video game experience for a given ability. While easier to conduct, cross-sectional studies can only point to correlations between video game experience and a given ability, rather than provide any causal evidence.

Training studies are much more informative in terms of causal relationships between video game experience and visual skills, but they are much more resource-intensive. In training studies, participants typically complete pre-tests, complete a training regime, and complete post-tests. Learning or improvement is assessed by comparing pre- to post-tests, which can be a direct comparison of accuracy or reaction time, or can be modeled by an evidence accumulation model such as the drift diffusion model (Ratcliff, 1978). Typically, researchers aim to recruit NVGPs as participants in training studies in order to assess the effect of video game training on naïve subjects. Participants are divided into multiple training groups depending on the manipulation of interest, with researchers often opting for an action video game (AVG) training group and a control group. The control group often also plays a game selected to avoid characteristics of the AVG genre, such as *Tetris* or *The Sims*. The action game genre has been described as involving high speed processing, continuous high cognitive load, and use of the entire visual field (Green, Pouget, et al., 2010), while these control games are selected to avoid the need for such distributed and quick decision making under time pressure.

It should be noted that given that the Green & Bavelier research group has conducted a significant amount of research in this field, we will present the current evidence with a subdivision between the results originating from their research group, and results originating from other labs. This is a division that has been implemented in meta-analyses as well (e.g. Bediou et al., 2018), so there is precedence for this classification of results.

The evidence: cross-sectional studies

Cross-sectional studies are more present in the literature than training studies due to the relative low cost of conducting these studies. Typically, researchers contrast the extremes of the spectrum of video game experience, recruiting participants with either a minimum level of video game play per week, or participants without any video game experience. The majority of the time, action video games are the genre of interest, and so video game participants are recruited based on time spent playing action games, creating the AVGPs typically examined in published studies. There have also been instances of researchers looking at the effects of other genres of game, including role-playing games (RPGs) (Dale et al., 2019), real-time strategy (RTS) games (Dobrowolski et al., 2015; Gobet et al., 2014; Kim et al., 2015), and *Tetris* (Sims & Mayer, 2002). However, since it was action video games that were noted as the effective and transferable game genre in Green & Bavelier's (2003) study, action games have been the focus of most studies. Meanwhile, those participants recruited for lack of video game experience (NVGPs) are the natural control to compare to AVGPs.

Visuospatial attention. The visual skills that have been compared in cross-sectional studies primarily fall under visual attention or visuospatial ability. Additionally, there has been notable interest in examining whether AVGPs display any advantage for skills related to executive function, which has been tested through visual formats. However, executive function is not the primary focus of this review, and so we will not discuss that evidence in significant detail.

Visuospatial skills have been generally found to be better in AVGPs. One key task that has been used as evidence for improved attention across the wider visual field is the useful field-of-view (UFOV) task, where participants must identify or localize targets that appear randomly at varying locations at various eccentricities (Dale et al., 2019; Feng et al., 2007; Green & Bavelier, 2003, 2006; Sungur & Boduroglu, 2012). These targets may also be accompanied by distractors or a simultaneous central identification task. The majority of studies show enhanced vision across the visual field (but for exceptions, see Boot et al., 2008; Jacques & Seitz, 2020; Murphy & Spencer, 2009). The generally positive results of UFOV tests have been taken to mean that VGPs may have better distribution of spatial attention across the peripheral visual field.

Some other tasks used to test VGP visuospatial abilities include visual search and the multiple object tracking (MOT) tasks. In the visual search paradigm, participants must identify a target among a field of distractors; evidence is mixed for any VGP advantage, with some suggesting that VGPs are faster at visual search (e.g. Li et al., 2022) and other suggesting that there is no VGP advantage (e.g. Unsworth et al., 2015). In the MOT task, participants must keep track of varying numbers of moving target objects. Evidence for VGP advantage on the MOT task is also mixed, with some reporting an advantage (Boot et al., 2008; Green & Bavelier, 2006; Sungur & Boduroglu, 2012; Trick et al., 2005), while other results are sometimes less positive (e.g. Dale et al., 2019; Donohue et al., 2012).

VGPs have also been shown to perform better on visual attention tasks without a spatial component. The attentional blink phenomenon is one such task. When shown a sequence of stimuli and told to look for a specific cue stimulus, and then report on a secondary target stimulus that shows up soon after the cue, viewers will often show a gap in attention that is termed the attentional blink. There is a period of time immediately after attending to the cue stimulus where viewers are often unable to attend to subsequent stimuli, as if the viewer blinks and misses the target stimuli. Some studies show that VGPs are less prone to attentional blink, such that they are more capable of catching target stimuli that appear immediately or almost immediately following a cue stimulus (Green & Bavelier, 2003; Murphy & Spencer, 2009) (but see Boot et al., 2008 for one exception).

Another visual attention task often used in video game studies is variations on the flanker task. Participants must identify a target that is flanked by varying numbers of distractors, which may or may not be relevant to the target itself. The flanker task is useful for testing visual crowding (e.g. Green & Bavelier, 2007), and also is a measure of the viewer's ability to attend to and process multiple visual stimuli. The flanker task is unusual in that often, a VGP advantage is interpreted when VGPs show a greater negative effect of the presence of flankers (Dye et al., 2009; Green & Bavelier, 2003, 2006, 2007). This phenomenon is taken as evidence that VGPs have either greater attentional resources, to distribute to the flankers and to be distracted by them, or that VGPs have more efficient distribution of resources, allowing them to attend to more visual targets at once. At the same time, there is also evidence of no relation between video game experience and performance on the flanker task (Cain et al., 2012; Collins & Freeman, 2014; Irons et al., 2011).

Visual working memory. Visual working memory is another aspect of vision that has often been found to be enhanced in VGPs (Blacker & Curby, 2013; Boot et al., 2008; Clark et al., 2011; Huang et al., 2017; McDermott et al., 2014; Moisala et al., 2017; B. Zhang et al., 2020).

However, some studies do not find a VGP advantage (Collins & Freeman, 2014; Cretenoud et al., 2021; Gobet et al., 2014; Unsworth et al., 2015). Some tasks that are commonly used to test visual working memory in the video game literature include the n-back task, where participants are shown stimuli consecutively, and must determine whether the current stimulus is the same as a stimulus presented n places ago; and the change detection task, where a participant must identify what has changed in a scene or field of stimuli. Some hypotheses for a VGP advantage for visual working memory include faster perceptual processing, such as faster encoding (e.g. Dobrowolski et al., 2015; McDermott et al., 2014) and more efficient use of attention resources (e.g. Dye et al., 2009; Wu et al., 2012).

Visual perception. The vast majority of video game studies have focused on attention-based or executive function skills, rather than lower-level visual perception. However, there have been some studies that have assessed whether VGPs might have an advantage for perceptual skills.

Contrast sensitivity function (CSF) has been examined by Li et al. (2009), who found that VGPs outperformed NVGPs on a contrast discrimination task, especially at higher spatial frequencies. Orientation discrimination was tested in two studies, one that found that VGPs had lower contrast thresholds for discriminating Gabor stimuli embedded in external noise (Bejjanki et al., 2014), and one that found no relationship between VGP skill level and performance on an orientation discrimination task (Cretenoud et al., 2021). Green et al. (2010) examined VGP performance on a motion discrimination task and found that VGPs had faster RTs but identical accuracy relative to NVGPs. Another study examined VGP sensitivity to different types of motion, and found that VGPs only showed enhanced sensitivity to radial contraction (Hutchinson & Stocks, 2013), perhaps because many first-person games involve radial contraction as a player moves backward in the game. Finally, two studies examined the ability of VGPs and NVGPs to learn a texture discrimination task (TDT), where the participant must identify a central target and identify the orientation of a peripheral array within a texture. One study by Kim et al. (2015) found that while VGPs performed better on the TDT at pre-test, after training there was no difference in performance between VGPs and NVGPs. Similarly, Jacques & Seitz (2020) found that the amount of video game experience did not affect pre-test or degree of improvement on the TDT.

Overall, the preponderance of evidence leans toward an advantage for VGPs on visual skills relying on attention, including visual working memory. However, that being said, there is clearly still sufficient contradictory evidence such that the matter of whether or not a large amount of prior video game experience is related to enhanced visual attention is still an open question. The cross-sectional evidence for video game transfer to visual perceptual skills is more mixed, with some positive evidence for contrast sensitivity, and mixed evidence otherwise. Given the small amount of research conducted on the topic, it is difficult to conclude decisively either way, and more research will need to investigate whether or not VGPs truly have a perceptual advantage over NVGPs.

The evidence: Training studies

While cross-sectional studies are easier to conduct, training studies are more informative in terms of establishing a causal link between video game play and visual enhancement. However, this does mean that training studies are less common than cross-sectional studies in the literature, and there is a general need to continue research and replication of the effects of video game training.

In training studies, NVGPs are typically recruited and trained on an AVG, although a few studies have looked at RTS games (Boot et al., 2008; Glass et al., 2013; D. Gong et al., 2019; Kim et al., 2015) and puzzle games (Oei & Patterson, 2013, 2014b, 2015). In most training studies, the action game has taken the form of a FPS game, such as *Unreal Tournament 2004* or *Medal of Honor*. The comparison conditions vary, although the most common alternatives are either a no-contact control group or training another group of NVGPs on a non-action game such as *Tetris* or *The Sims*. Participants typically complete a baseline pre-test for the visual skills of interest, and complete another post-test after training is completed. Training can range anywhere from a few hours to over 50 hours.

Visuospatial attention. Similar to cross-sectional studies, the results from training studies for visual attention are mixed, although the evidence trends more positive. The evidence for visuospatial tasks is generally positive. For the UFOV task, AVG training led to greater improvements (Feng et al., 2007; Green & Bavelier, 2003, 2006). AVG training also seems to improve performance on the MOT task more than control games (Oei & Patterson, 2013, 2015). However, a few studies do suggest that training on an AVG does not provide any benefit for MOT (Boot et al., 2008; Flores-Gallegos & Mayer, 2022).

For other types of attention tasks, evidence varies as well. There is some evidence for AVG training transferring to the attentional blink task (Green & Bavelier, 2003; R. W. Li et al., 2015; Oei & Patterson, 2013, 2015), with some exceptions (Boot et al., 2008; Lee et al., 2012). As for flanker tasks, only one study shows evidence in favor of AVG training transferring by causing greater interference from flankers (Green & Bavelier, 2007). However, one interesting study shows that training on a RTS game increases flanker effects (Glass et al., 2013), while another suggests that only training on a physics puzzle game was able to transfer to a flanker task, not an AVG (Oei & Patterson, 2014b). There is also evidence suggesting no increased flanker effect from AVG training (Lee et al., 2012).

Visual working memory, despite the interest it has received in cross-sectional studies, has not been tested as much in training studies. Of those, two studies found that training on an action game did not cause any increased benefit to performance on visual working memory tasks after AVG training (Boot et al., 2008; Flores-Gallegos & Mayer, 2022). Another found mixed results, with AVG training benefiting some visual working memory tests and not others (Blacker et al., 2014).

Visual perception. As with cross-sectional studies, there are not many training studies that have focused on video game transfer to perceptual skills. For orientation discrimination, Bejjanki et al. (2014) found larger improvements in contrast threshold for orientation discrimination after AVG training. Green et al. (2010) also found improved posterior distributions in participants trained on an AVG for a motion discrimination task, but van Ravenzwaaij et al. (2014) did not find any benefit for AVG training on performance or diffusion model parameters for a motion discrimination task. As for contrast sensitivity, Li et al. (2009) showed that participants trained on an AVG showed greater improvement in their contrast sensitivity function.

For training studies, one major weakness in the evidence is that there simply are not many of these studies in the published evidence relative to the cross-sectional studies. Therefore, it is difficult to conclusively make any claims about AVG transfer to visual skills, let alone the potential effects of any other game genre. However, it is clear that the evidence from training studies is much more mixed between studies claiming evidence of AVG transfer and studies claiming evidence of no transfer at all.

Typically, attention-based skills find more support for AVG transfer in cross-sectional studies, and this holds true to a degree in training studies as well, especially for the UFOV and attentional blink tasks. Beyond attention-based skills, visual perception is once again much less studied. Out of the 4 studies we found, 3 report positive benefits of AVG training to visual perceptual skills. However, with such a small amount of research, undoubtedly more training studies are required in order to settle the question of video game transfer to any visual skills.

Neural correlates and mechanisms behind the effects of video games on vision

Examining the potential effects of playing video games on vision logically leads to the question of how this influence might occur. As a relatively small and growing field, there is not a surplus of research focusing on the mechanistic questions relating to transfer from video games, but there are some interesting insights from studies focusing on neural mechanisms. In addition, some researchers have hypothesized the nature of how video games might be affecting visual skills based on behavioral evidence.

Neural mechanisms

As with the majority of video game studies, there are cross-sectional and training studies that have incorporated various methods to study how video gaming affects the brain. The cross-sectional studies have typically compared VGPs with significant experience to NVGPs. One such study (Tanaka et al., 2013) specifically recruited experts who spent at least 20 hours per week gaming, and had won prizes in competitive gaming. MRI scans were correlated with performance on a visual working memory task, and revealed that the gaming experts had increased volume in the right posterior parietal cortex, which is associated with visuospatial processing. This matches the findings of video game studies that suggest greater visuospatial ability in video gamers in tasks such as the UFOV task. Another study by Schenk et al. (2017)

looked at non-competitive but experienced VGPs, whose VGP participants spent at least 15 hours per week playing AVGs to qualify. MRI scans of participants were compared to their performance on a probabilistic classification task. VGPs both had better categorization performance and greater activation in brain regions associated with visual imagery, attentional control, and semantic memory, suggesting that professional-level expertise is not needed for video game experience to alter the brain – merely significant time spent training.

There are also those who have examined neural activity of VGPs and NVGPs in cross-sectional studies. Moisala et al. (2017) utilized fMRI to observe brain activity of participants with a range of video game experience while completing an n-back task. By focusing on the whole range of video game experience rather than the extremes, they were able to conduct a correlational analysis and found that those with more video game experience showed larger increases in brain activity at higher perceptual loads. The authors theorized that this could be evidence of greater prefrontal recruitment, or generally better recruitment of attention resources for more demanding tasks. A unique study by Kim et al. (2015) observed increased connectivity between higher order cognitive areas and visual areas during a texture discrimination task in VGPs who had significant experience in RTS games. However, they noted that they could not conclude whether this increased neuronal plasticity was caused by video game experience or another factor. Multiple studies have also used EEG to compare VGPs to NVGPs on visual attention tasks (Föcker et al., 2019; Mishra et al., 2011) and observed VGP brain activity suggesting better attentional control. This took the form of reduced ERP amplitude in response to irrelevant distractors compared to NVGPs (Mishra et al., 2011) and increased ERP amplitude during focused attention (Föcker et al., 2019). Of particular interest is the fact that Föcker et al. (2019) did not observe any difference between VGPs and NVGPs in occipital ERPs that correspond to early sensory processing, suggesting that the VGP advantage for visual tasks does not originate from differences in low-level visual perceptual processes.

Training studies that measure neural correlates are particularly interesting given that participants are typically not video game players, and so they are experiencing a relatively short amount of training in the lab compared to a habitual video gamer. Nonetheless, the training studies that have measured neural correlates have in fact reported that the video game training conducted in the lab is sufficient for inducing observable neural changes. In terms of neural activity, Wu et al. (2012) utilized EEG during the testing phases of a training study where participants trained on either an AVG or a control puzzle game for 10 hours. Their test measure was an attention task meant to test attention abilities across the entire visual field. What is interesting about this study is that the higher performing participants in the action game training group showed significantly different EEG activity in the form of increased P2 and P3 amplitude. P2 is associated with attentional control (Potts et al., 1996), while P3 is associated with allocation of visual attention (Polich, 2007). Therefore, these results suggest that AVGs affect later attentional processes rather than earlier perceptual processes (which would have been represented by earlier P1 and N1 ERPs).

In addition, studies have also focused on structural changes induced by video game experience. Momi et al. (2021) trained participants on an AVG for 30 hours and compared their pre- and post-training performance on a battery of cognitive tests to a no-contact control. Their AVG training group demonstrated increased connectivity between brain areas related to navigation and environmental recognition, such as between the cerebellum and other brain regions. This kind of structural change is especially interesting as it implies that video game training alters the brain in a longer lasting manner, as opposed to a temporary change to neural activity. Another study by Kühn et al. (2014) focused on change in size of different brain areas, and found that after training on a platforming video game, participants had increased gray matter in the hippocampus and cerebellum. These changes were associated with increased ability to track orientation of a character on the screen and enhanced motor skills for using the gaming console.

The majority of the research that has looked at neural correlates of video game training effects on vision have focused on attention-based tasks. It is therefore unsurprising that all of the evidence suggests that video game training may increase neural activity and connectivity in brain regions associated with visuospatial processes and visual attention. What is surprising is that only 10-30 hours of video game training is apparently sufficient to induce changes in neural correlates, based on the training studies that currently are available (Kühn et al., 2014; Momi et al., 2021; S. Wu et al., 2012). This is not a significant amount of training compared to what a habitual video gamer might experience, and so the fact that it can induce neural changes suggests that perhaps video games are an effective training tool.

However, it is notable that both a cross-sectional and a training study that used EEG to measure brain activity during a visual task did not note any effect of video game experience on the ERPs associated with early visual processing. This suggests that if video games do have a physical effect on the brain, it is not on early perceptual processes, and therefore video game training may not have a significant effect visual tasks that rely primarily on perceptual ability rather than attention or other cognitive functions. We only found one study that specifically measured brain activity during a perceptual task (Kim et al., 2015). While this one study did note a change in connectivity between brain areas seemingly associated with video game experience, it was between higher order cognitive areas and visual areas. This suggests that if video game experience played a role in perceptual performance, it may be due to changes in higher level cognition such as attentional control rather than any change to lower-level perceptual ability.

Mechanistic hypotheses

The theoretical mechanism behind the effectiveness of AVGs for visual skills is currently unknown, and researchers have only recently begun to explicitly investigate the question of how video games might affect vision, as opposed to what breadth of skills video games can affect. This is where the study of AVGs and vision might benefit from referencing the research paradigms that have long been standard practice in fields such as VPL, where mechanistic questions are a common focus of the current literature. However, there are some studies that have specifically structured their design in order to attempt to answer mechanistic questions in the video game literature, as well as some common threads in the hypothesized potential mechanisms that have been proposed in many a discussion section.

A few studies on the effects of video game training have been conducted with methods that have been previously used in VPL research. One such study (Bejjanki et al., 2014) involved a collaboration between the Green & Bavelier research group, from the video game literature, and the Dosher & Lu research group, from the VPL literature. In their study, both cross-sectional and training data were fit to a perceptual template model (PTM), which distinguishes between perceptual learning that takes the form of reduced internal noise, versus perceptual learning that takes the form of better perceptual templates that both improve the ability to make probabilistic inferences at the task at hand, as well as improving perceptual sensitivity. They conclude that their data supports the hypothesis of video game players having better perceptual templates. This builds on an earlier study by Green et al. (2010), which fit AVGP and NVGP data to a diffusion model. In this previous study, both cross-sectional and training data were fit to the diffusion model, in addition to posterior distributions being calculated. They found that the participants with video game training or experience had better posterior distributions (i.e., were making better use of the evidence in each trial to calculate the probability of different stimuli) and better information integration rate. This is suggested to be evidence of more efficient and faster learning of the statistics of the task stimuli in video gamers. Bejjanki et al. (2014) builds upon this prior study to then suggest a more specific mechanism, better perceptual templates, behind the more efficient information processing that was apparent in Green et al. (2010).

Bavelier & Green (2019) discuss potential mechanisms of learning as caused by AVGs in their review, describing action games as "exemplary learning experiences". Their reasoning is that learning is driven by reward and by attention (as defined as focusing on task-relevant information and suppressing task-irrelevant information) (see Watanabe & Sasaki, 2015). Video games in general are created to be rewarding by nature, as a form of entertainment. Attentional demands vary from game to game, however, and this is why many studies have focused on the action game genre, since action games typically require high attentional load given their speed and constant switching between focused attention on enemies and diffused attention on monitoring surroundings. Therefore, because AVGs meet these two characteristics, they can cause learning.

However, further reading of Bavelier & Green (2019) suggests that they believe that the main mechanism by which video game experience causes enhanced performance is through increased attentional control. This hypothesis has been discussed in various forms in many video game and visual learning articles. One approach, for example, is to argue that VGPs have increased attention resources, allowing them to attend to more items at once (Dye et al., 2009; Green & Bavelier, 2003, 2006; Kowal et al., 2018; Sungur & Boduroglu, 2012; West et al., 2013). This might take the form of tracking larger numbers of objects, or increased ability to attend to the periphery of the visual field along with the center, as opposed to restricting attention to the central visual field.

More recent papers tend to conclude that it is not the attentional capacity that is enhanced in VGPs; rather, VGPs have better allocation of attention (e.g. Föcker et al., 2019; Mack & Ilg, 2014). Typically allocation is used to refer to attending to relevant information and inhibiting irrelevant information or distractors. Specifically, many researchers have attributed enhanced performance in VGPs to better top-down control of attention. There is some debate over how to interpret video game study results, however, in this context. This is because increased attentional control would suggest that VGPs should show a greater ability to ignore distractor stimuli such as flankers. However, researchers like Green & Bavelier (2003) have previously instead argued that VGPs should be expected to show greater flanker effects. Their interpretation of such data is that VGPs have increased attentional resources, allowing them to attend to stimuli beyond the target stimulus, leading to their attention being "caught" by the flanker stimuli. Therefore, it would appear that most researchers agree that there is an attentional enhancement that is caused by AVG training. However, the exact form this enhancement takes has yet to be clarified and requires further investigation.

Furthermore, it is unclear how exactly this attentional enhancement occurs. AVGs seem to have multiple components that require a significant attentional load, which theoretically could form ideal training for attentional skills. Bavelier & Green (2019) propose three primary components of action games that contribute to enhancing attentional control: pacing, or the need to make decisions under time pressure; divided attentional load over a significant period of time; and switching between attentional modes, such as between divided and focused attention. They argue that these three characteristics are combined with three tenets of a good training paradigm to make the action video game so successful at inducing learning: 1) keeping the player in the zone of proximal development, such that the player is always challenged but within achievable parameters; 2) providing a rich environment for training, avoiding automatization; and 3) providing rewards. However, it is unknown what specific brain mechanisms are affected by this attentional training, and it is unknown how exactly this leads to the generalization of attentional skills beyond video games and to the various visual skills that have been reported as benefiting from AVG training or experience. The previous section on neural correlates of video game experience does suggest that playing video games can cause structural change in the brain, and some of the regions implicated are linked to attention and cognitive control. However, some of the studies of neural correlates also contradict each other, with evidence both for and against sensorimotor enhancement from video games. The evidence on low-level sensory enhancement is mixed in the literature, as previously discussed. Beyond the research that has directly targeted low-level visual processes, others have hypothesized that video game experience may cause enhanced perceptual processing (e.g. McDermott et al., 2014; Oei & Patterson, 2014), but this hypothesis has not garnered much support.

Instead, two hypotheses appear to have some presence in the field. These hypotheses are not necessarily exclusive of the other hypotheses discussed previously, but perhaps are slightly better defined. First, there is the common demands hypothesis, which finds support in the likes of Oei & Patterson. On the other hand, there is the learning to learn hypothesis, which has been adopted more by the Green & Bavelier research group.

The common demands hypothesis suggests that video game training enhances performance on tasks that share common demands with the video game being trained on. There is a simple logic to this hypothesis; after all, video games are primarily visual, and so there are undoubtedly visual tasks that use the same underlying skills as every video game. Oei & Patterson have published multiple articles where their participants have trained on action and non-action games alike, and have reported that different genres of games appear to enhance skills on distinct visual skills (Oei & Patterson, 2013, 2014b, 2015). For example, in one study they found that AVG training enhanced attentional blink, MOT, cognitive control, and complex span task performance. However, training on a hidden-object game, memory matrix game, or match-3 game improved performance on a visual search task, and the match-3 group also improved on the complex span task, while the hidden-object game and memory-matrix game groups also improved on a spatial working memory task (Oei & Patterson, 2013). The researchers suggested that this is evidence of near transfer – the video games were training skills that could be generalized to visual tasks that shared similar requirements. One other study that has come to this conclusion compared FPS VGPs to RTS VGPs and NVGPs on task switching and a MOT task, and found that RTS VGPs either outperformed the FPS VGPs or performed comparably, while both groups outperformed NVGPs (Dobrowolski et al., 2015). These results are sensible in the context of the demands of a typical RTS game – attending to a wider visual field of stimuli, constantly switching between tasks, responding as quickly as possible in order to make the best gaming move possible. One study has even attempted to extend the common demands hypothesis to education – participants were trained on a non-spatial word game or a spatial shooter game and tested on a visuospatial task and learning about plate tectonics (Sanchez, 2012). Remarkably, the spatial game training group showed improved performance on both the visuospatial task and in learning tectonics, which the author attributed to the relevance of the spatial game both to the test task and to understanding tectonics, such as by understanding how plates move against each other in three dimensions.

In contrast, the learning to learn hypothesis supports the notion of wide generalizability of video game training. This hypothesis has seen published support primarily from the Bavelier research group, which published an outline of how this hypothesis might apply to AVGs and learning (Bavelier et al., 2012). According to the learning to learn hypothesis, the wide generalizability of AVG training is due to this genre of games training learners to more quickly and accurately learn the statistics of a new task. Bavelier et al. (2012) argue that AVGs facilitate better learning through improving resources, knowledge, and learning rules. In their explanation, AVGs increase attentional resources, which in turn increases the capacity for learning. Knowledge refers to the ability to create structured and complex representations of a given task, allowing for abstraction of information at higher levels of these representations. Finally, learning rules refer to the ability to modify representations to better complete the task at hand. Bavelier et al. (2012) acknowledge that there was much more evidence for AVGs benefiting attentional resources, and lacking evidence for AVG benefits to knowledge or learning rules. They argue, however, that there are studies that point to AVG improvement for tasks that do not require large attentional resources or do not rely on attention (e.g Li et al., 2009 and contrast sensitivity). They also suggest that AVGs are generally structured in a way that encourage improved learning rules, such as balancing distracting stimuli and the primary task in a game, or managing short-term versus long-term goals during gameplay. However, in both Bavelier et al.'s (2012) review and in the published evidence since, there is not much direct evidence for AVG training affecting knowledge or learning rules.

In summary, the mechanistic basis for AVG training benefits on vision is still in the early stages of exploration. There are various hypotheses that have been proposed and discussed, primarily differing in whether the researcher believes that AVGs are fundamentally capable of wide generalizability or believes that AVGs are limited to near transfer to visual skills with similar requirements. However, both types of theories are still very much open questions and topics of current research. Furthermore, the connection between potential mechanisms of learning and neural correlates is still in early stages as well. The main point that AVG researchers agree on is that the AVG genre contains characteristics that facilitate improvement in attentional control.

Factors of interest in video game research

In addition to the wider question of mechanism, video game research also must take into account many other variables that are inevitable in a field that focuses on a non-laboratory training paradigm. Commercial video games are not designed for highly controlled lab settings. Furthermore, video games are commonly available and easily engaged with in day-to-day life, introducing many other factors into individual video game experience.

Extremes of gaming experience

A notable exclusion from many video game studies is the population of video game players who play games for an intermediate amount of time, or those who play games for a significant amount of time but do not play AVGs. Given that most video game studies focus on the extremes of video game experience, this intermediate population is often neglected in these studies. However, it is increasingly important to consider how this population might be affected by video game experience for several reasons. First, when video game research began in the 1980s, video gamers were a somewhat distinct set of the population, and it was not unusual to find participants with no video game experience. In the 21st century, however, video games are increasingly available to the general population, given the spread of games to smartphones and personal computers. Furthermore, free games are much more available, and players no longer need to visit a physical location or purchase a specialized device for playing games. With the invention of smartphones, video game players can also play games in many more locations and situations than they could previously. This means that the research participants of 2024 are significantly different perhaps even from the research participants that originally took part in the original Green & Bavelier (2003) study that kickstarted much of the modern field of video game and vision research. Modern participants tend to have more video game experience, and experience in a more diverse set of genres of video game, compared to participants of the past. This constant evolution of video game experience requires the research into video games to evolve as well, an issue that the Green & Bavelier research group has acknowledged (e.g. Bavelier & Green, 2019; Dale et al., 2019).

Video game genre

Video games are no longer as defined by a single genre as they were 2 decades ago (see Dale et al., 2020 for a more detailed discussion). Formerly, an AVG might be defined purely by one primary game mechanic (e.g. navigating through levels and shooting targets), without much focus on storyline or any additional gameplay mechanics. This is no longer the case, with AVG mechanics present in many genres of game. The simple mechanic of identifying and shooting targets might be combined with puzzles, life simulation games, RPGs, RTS games, and more. This muddles the ability for researchers to use the "action" label to truly identify either how a game might affect participants visually, or what kind of visual stimuli a participant might have previously experienced in their gaming experiences.

Furthermore, in older video game studies (e.g. Green & Bavelier, 2003), AVGs might include first-person shooter games, third-person shooters, racing games, and more. These games might share some overlap in characteristics, but they are considered distinct genres and do have some important differences. For example, a first-person game will always involve a narrower field of view than a third-person game, necessitating more attention devoted to scanning surroundings and faster movement of stimuli through the visual field. Therefore, there is both a constant issue of defining what exactly an "action" game comprises, combined with a more recent issue of genre ambiguity in modern video games. In fact, in their article, Dale et al. (2020) acknowledges these issues and calls for a move away from defining video games by genre, and instead focusing on characteristics in games that facilitate visual learning. While classifying games by variables relevant to the research is a logical next step, doing so would be a significant endeavor in and of itself, given that video game researchers do not yet know which characteristics would be the most useful or meaningful, not to mention the sheer number of exiting games.

Finally, it may be the case that limiting the transferability of video games to one genre was not a useful delimiter even previously, considering the research that suggests that other genres of video game might be able to induce visual learning. This evidence ranges from *Tetris* transferring to mental rotation (Boot et al., 2008; Okagaki & Frensch, 1994; Sims & Mayer, 2002), to RTS games transferring to MOT (Dobrowolski et al., 2015) and cognitive flexibility (Glass et al., 2013), to puzzle games transferring to attentional control and visual search (Oei & Patterson, 2013, 2014b). This suggests that while AVGs might contain multiple characteristics that can benefit vision, it is far from the only genre with potential benefit – it may merely be the best suited for a certain type of visual task.

Gender

There has long been a secondary question in video game research pertaining to whether or not there is a gender difference in benefits from video game training. The issue originates from a longstanding gender imbalance in the population of video gamers that persists even to the current day. For example, one study by Quaiser-Pohl et al. (2006) reported that not only did boys play more computer games than girls, but boys also played more AVGs than girls. The question, then, is whether there is an inherent difference between genders in terms of various visual and cognitive abilities, or whether the increased experience with video games in boys causes increased visual ability. It has been reported that gender differences in mental rotation ability are mediated by level of experience with spatial video games (Terlecki & Newcombe, 2005). Furthermore, multiple studies have reported that training on a spatial game like *Tetris* (De Lisi & Wolford, 2002) or an AVG (Feng et al., 2007) reduces gender differences in mental rotation, suggesting that video games may in fact improve spatial cognitive abilities, but more so for those who are less skilled pre-training.

At the same time, it is difficult to conclude from the existing evidence whether or not a gender difference in video game training exists. As it stands, gender differences in cognitive abilities are controversial – mental rotation is one of the few cognitive abilities that has consistent evidence of a gender difference (e.g. Hyde, 2016; Terlecki & Newcombe, 2005), while many other claims of cognitive differences have not held up over time. In the context of video game training, any gender differences in the context of improvement after training must be interpreted in the wider social context of socialized differences in experience in education and elsewhere. For example, women are stereotyped as being worse at math, and so they may feel discouraged from engaging more in math classes and math-based extracurriculars. This in turn reduces their experience compared to men, leading to gender differences that are perhaps more accurately based on average differences in math training rather than differences in ability between genders.

The question of gender differences is further complicated by the tendency of video game studies to account for gender differences in prior video game experience by restricting participants to one gender or another. For example, many cross-sectional studies restrict their participant recruitment to male participants alone for both VGP and NVGP groups, citing the difficulty in recruiting female VGPs (e.g. Chisholm & Kingstone, 2015; Green & Bavelier, 2006; Sungur & Boduroglu, 2012). This is sensible in a practical sense, but prevents the collection of evidence to indicate the nature of any correlational relationship between female VGPs' gaming experience and visual ability. Training studies, on the other hand, recruit both male and female participants, although only a few studies explicitly report any statistical comparison between female and male participants (and report no difference) (e.g. Appelbaum et al., 2013; Dale et al., 2019; Okagaki & Frensch, 1994; Unsworth et al., 2015).

Finally, considering that the majority of video game studies are cross-sectional in design, gender becomes an issue when it comes to considering the causal effectiveness of video game experience. With any cross-sectional design, causality cannot be inferred. On top of that, with video game studies, there are multiple possible explanations for any VGP advantage observed. One possibility, of course, is that the video game experience of the VGP group causes improvement in their visual abilities. However, another commonly acknowledged possibility is that video gamers may self-select – in other words, those who innately possess better visual, spatial, and attentional abilities may find video games easier to play and more rewarding when they first try playing them. This in turn may lead them to become more habitual video gamers.

Conversely, those who may be less skilled in visual and attentional abilities earlier in life may find video games less rewarding and more difficult initially, and may be deterred from playing games later in life. Therefore the differences observed in cross-sectional studies may be due to innate differences in ability that led to differences in gaming behavior, rather than due to the gaming behavior itself. Gender further complicates the tangled question of causality in this case because gender also plays a role in whether a child might be encouraged to play video games, especially in genres considered more violent. Video games are stereotypically considered a more masculine extracurricular activity in youth, and so early formation of video game behavior may also be attributed to gender roles and expectations rather than differences in video game ability or interest.

Training time

Habitual video game players can easily play 5 hours a week or more. Even one year of this level of gaming adds up to 260 hours of gaming experience. In contrast, video game training studies typically have participants train for as little as 10 hours (e.g. Green & Bavelier, 2003), with longer training times still only reaching around 50 hours (e.g. Li et al., 2009). While many training studies have produced results that suggest that this amount of video game training is sufficient to induce visual learning, others have not, and therefore it is possible that a relatively low amount of training compared to naturalistic conditions may contribute to the mixed results of training studies. This is only reinforced by the fact that cross-sectional studies typically report results with larger effect sizes than training studies (see Bediou et al., 2018).

Bavelier & Green (2019) also argue that video game training is subject to the same rules as any other learning experience, and therefore the distribution of training time is also important for effective learning. Namely, they suggest that massing video game training may be less effective than distributed training, a common finding in the learning literature (e.g. Cepeda et al., 2006; Kornell & Bjork, 2008). In this sense, perhaps training studies may benefit from caution regarding rushing video game training, such as restricting participants from playing more than 2 hours per day, and enforcing a weekly maximum training time. However, the specific effects of massed vs distributed practice in the context of video games and vision has not been explicitly studied in the literature.

Dependent variable of interest: Reaction time vs accuracy

Many video game studies investigate both reaction time and accuracy when testing the results of video game experience or training. VGPs having faster RTs for a range of tasks is a robust finding across a plethora of studies, and in fact many cross-sectional studies report an advantage for VGPs in reaction time, and not necessarily in accuracy (e.g. Castel et al., 2005; Green et al., 2012; Li et al., 2022; Moisala et al., 2017; Pohl et al., 2014; Strobach et al., 2012). This is perhaps to be expected, as AVGs in particular emphasize operating under constant time pressure in terms of gameplay, and so habitual AVG players would be expected to become faster and more efficient in executing tasks. Training studies, on the other hand, report reaction time changes much less frequently, although there are a few that suggest that AVG training does benefit reaction time (Hutchinson et al., 2016; Nelson & Strachan, 2009; Okagaki & Frensch, 1994). It is uncertain why exactly VGPs so consistently produce faster RTs than NVGPs, and the effect of video game experience on reaction time specifically has not been well-investigated (one exception is Dye et al., 2009). One possible implication is that VGPs, with hundreds to thousands of hours of gaming experience, may have developed a more efficient speed-accuracy trade-off, such that they are able to complete tasks faster while maintaining a high level of accuracy, which has been previously noted (Bavelier et al., 2012). Another possibility is that

VGPs simply have developed faster execution of motor commands, but one meta-analysis by Dye et al. (2009) suggests that there was a multiplicative component to VGP vs NVGP RT data at the time that ruled out a motor component alone as the explanation for the VGP advantage in RT.

The question of why VGPs are consistently better at RT than NVGPs remains unanswered at present, but likely is part of the same general theoretical question pertaining to the mechanisms by which video games affect visual skills. However, another interesting comparison can be made between the methodological choices of the video game research field and the VPL research field, which overlap to some degree. Both fields are interested in enhancement of visual skills, although VPL tends to focus more on low-level vision and mechanistic questions, comparatively. Another difference is that VPL researchers tend to focus on accuracy as the measure of choice for gauging learning in visual tasks, whether that takes the form of mean accuracy, accuracy-based staircasing, or conversion of accuracy data into another statistic or model parameter. That being said, both accuracy and reaction time are commonly used measures in vision research. It is known that the psychological characteristic being measured and the demands of the task can affect reaction time and accuracy data differently (e.g. Wood & Jennings, 1976). Therefore, it may be of interest to video game researchers to further investigate their unique pattern of results in comparison to typical findings in other related fields such as VPL.

Replication

As seen in the previous section reviewing the evidence regarding the effects of video games on vision, there is mixed evidence for a variety of cognitive and visual tasks. However, beyond the studies listed, there are a miscellaneous collection of studies that have also examined the effects of video games on various other skills and tasks, such as enumeration (Green & Bavelier, 2003, 2006), multisensory simultaneity judgment (Donohue et al., 2010), or inattentional blindness (Murphy & Spencer, 2009; Vallett et al., 2013), among many others. The field of video game effects on vision is still a developing one, but it is clear that many studies from the first two decades of the 21st century would benefit from replications. It can be said that attention is a common factor that is easily identified among the positive results reported, but the number of contradictory or mixed results suggests that further investigation is warranted. The many other visual and cognitive skills that have been investigated in one or two studies would benefit even more from further research, even if only to confirm the existence or absence of video game benefits to various skills. Identifying the breadth and limitations of video game benefits on vision will be informative to future researchers, and potentially provide a foundation for more deeply investigating the causal mechanisms by which video games affect cognition.

There is also a need for replication independently of the Green & Bavelier research group. As one might expect, Green, Bavelier, and colleagues have continued to research the effects of video games over the years since their initial 2003 publication. However, one meta-analysis suggests that for both cross-sectional and intervention studies, the Bavelier lab group reports significantly larger effect sizes (Bediou et al., 2018). It is suggested that this difference may be due to stricter VGP recruitment criteria and longer video game training duration (30 hours or more). Another meta-analysis, however, responds to the Bediou et al. (2018) publication, arguing that they did not properly control for publication bias (Hilgard et al., 2019). After conducting their own correction for publication bias, they claim that controlling for publication bias results in small or no effect of action video game training on various measured outcomes. Furthermore, Hilgard et al. (2019) also point out that many of the Bavelier studies in fact recruited from potentially overlapping participant groups. In other words, it is possible that many of their participants were used in multiple research studies, although this is never addressed in the resulting publications. As a result, the validity of the effects reported in the Bavelier group's publications is muddled, given the inflating effect of publication bias and the uncertainty about which participants were involved with which experiments. Ideally, other research groups would take these differences into consideration and attempt to replicate their results, in order to address the validity of the Bavelier lab group results.

Potential applications of video games for vision

The concept of using video games for skill training is not a new one. In the late 20th century, prior to the sharp increase in interest in studying the effects of video games on vision in the 2000s, there was already some interest in using video games for education (Driskell & Dwyer, 1984) and for training military pilots (Hart & Battiste, 1992; Lintern & Kennedy, 1984). In the decades since, the evidence shows that despite the uncertainty regarding the evidence for visual enhancement from action video game training, there is undoubtedly some benefit for attention-based vision from video games. As a result, researchers have capitalized on these results and begun to investigate the use of video games as a treatment for various vision-related impairments. There also continues to be research into video games as an educational tool (e.g. Sanchez, 2012), but we will focus on two areas of interest for video game treatment: amblyopia and dyslexia.

Amblyopia

Amblyopia is a visual disorder wherein one or both eyes did not receive normal visual input during the critical period after birth, resulting in reduced acuity. Another key characteristic is that the visual impairment can not be attributed to an eye abnormality, such as is the case in common causes of nearsightedness like myopia. The most common type of amblyopia is anisometropic amblyopia, where differences in refractive errors in the two eyes prevent simultaneous focusing of images on both retinas, resulting in the brain relying more on one eye's visual input. The least common type is deprivation amblyopia, where some physical obstruction causes severely reduced visual input into the eye. Regardless of the cause, one of the factors that makes amblyopia more difficult to treat is that the lack of normal visual input in the critical period causes abnormal or lack of development in the brain regions corresponding to visual processing.

Typically, amblyopia has been treated with physical correction of issues (e.g. removing a cataract that prevented visual input into the eye). If only one eye was affected, a common follow-up treatment is patching, where the stronger eye is covered to encourage usage of the deprived eye. Although this treatment is typically considered sufficient, there is some interest in investigating whether further improvements to visual acuity can be made in amblyopic adults.

Video games are therefore a potential treatment of interest for amblyopia given that some research suggests that playing AVGs may benefit low-level vision (e.g. Li et al., 2009; Green & Bavelier, 2006), and more research suggests that video games may benefit visual attention across the entire visual field (e.g. Green & Bavelier, 2003). This is particularly promising for amblyopia, which stems from cortical issues caused by prior physical issues in the eyes. A visual task like a video game that also engages higher level cortical circuits involving attention has the potential to be able to beneficially modify the visual circuits in the brain that may not have had the chance to properly develop in amblyopic individuals.

To that end, there has been research into the potential use of video games to improve visual skills in amblyopic adults. One such study trained amblyopic adults on a FPS video game, and found that the participants improved on measures of letter acuity, spatial contrast sensitivity, and global motion sensitivity, although they did not improve on binocular fusion (Jeon et al., 2012). Another research group has similarly investigated the effects of training on an AVG on attentional blink in monocular amblyopic adults, such that the participants did not train their non-amblyopic eye on the video game. They found that not only did these participants show reduced attentional blink in the trained eye, they also showed improvement in the untrained eye as well, suggesting that there was modification of higher level attentional mechanisms during training that transferred throughout the visual system (R. W. Li et al., 2015). Finally, there is evidence that playing an AVG may both increase visual acuity and reduce suppression of the amblyopic eye by the stronger eye (Vedamurthy et al., 2015).

Interestingly, there is also evidence that amblyopic individuals may benefit from playing video games other than action FPS games. Amblyopic adults trained on a city-building simulation game showed improvement comparable to those trained on a FPS game in visual acuity and enumeration (R. W. Li et al., 2011). It is unclear why exactly both types of video games were able to induce visual improvement, although the authors do suggest that the simulation game used was still structured such that it trained spatial vision, given that the game requires players to navigate and complete tasks within a larger city space. It is also interesting to consider these results in the context of the larger question of video game transfer to vision. Do amblyopic adults benefit from multiple types of games because the visual skills they lack are similar to the visual skills utilized in many genres of video game? Or do they benefit because the particular games used both target higher level spatial attention? Or, is this a result of video games providing a highly visual task that is rewarding and rich in visual variety, encouraging the players to spend more time deliberately using their amblyopic eye than they would otherwise?

The number of studies that have investigated video game training as a treatment for amblyopia is still small, but the evidence is encouraging. As research into using video games to train amblyopic adults continues, more evidence of the mechanism by which video games benefit amblyopic individuals may emerge.

Dyslexia

Dyslexia is a neurodevelopmental disorder characterized by difficulty reading that cannot be attributed to other potential causes such as lower intelligence (Gabrieli, 2009). The specific cause of dyslexia is unknown, and treatment is resource-intensive and constantly under development. However, one major facet of dyslexia is attention dysfunction (Stein & Walsh, 1997; Vidyasagar & Pammer, 2010), such that individuals with dyslexia struggle to orient attention efficiently in order to learn to pair speech sounds with letters.

The combination of attention deficit and visual stimuli has led some researchers to train children with dyslexia using AVGs. Theoretically, the fairly robust finding of AVGs benefiting visual attention could counteract the attention deficit in children with dyslexia. And in fact, there has been some evidence that training on AVGs specifically improves reading ability and speed, as well as correlating with improvements in measures of attention (Bertoni et al., 2021; Franceschini et al., 2013, 2017; Peters et al., 2021). These findings align with the hypothesis in the video game training research that AVGs specifically are able to improve attentional abilities. One research group (Franceschini et al., 2013) selected child-friendly minigames from a larger game title based on AVG criteria from Green et al. (2010): that AVGs share 1) speed of gameplay and stimuli motion; 2) high perceptual, cognitive, and motor load; 3) unpredictability; 4) and emphasis on peripheral processing. Therefore, the evidence from these training studies also supports the validity of these criteria in defining a type of video game that effectively trains visual attention.

Conclusion

The current pattern of evidence indicates that video games do in fact affect vision, but the specific mechanism by which they do so is still unclear. However, there appears to be some consensus that video games affect attentional control mechanisms, which in turn improves performance on visual tasks based on attention. The video games themselves are also an ideal training paradigm due to their general construction as a series of tasks of achievable but gradually increasing difficulty, combined with consistent reinforcement. This benefit appears to even extend to potential medical treatment in areas such as dyslexia (e.g. Franceschini et al., 2013). However, there is still noticeable controversy in the literature, with most measures of visual skill seeing significant evidence both for and against video game transfer. This controversy is furthered by the fact that there are still many more cross-sectional studies suggesting benefits of video game transfer, as opposed to training studies that are much more useful for inferring true causality. Therefore, there is a need for more training studies to confirm or replicate evidence of video game transfer to visual skills.

The study of the effect of video games, particularly AVGs, upon visual learning is still a relatively young field, having only been growing in its current form for about two decades. There is the potential for interesting and practically applicable research into video games in the future, which has already been investigated for medical purposes such as treating amblyopia and dyslexia. However, this also means that there are many unanswered questions about the exact nature of video game transfer to vision, as well as many additional factors that must be considered moving forward in this research. The constantly evolving nature of video games means that studying their effect is an ongoing process. There is an increasing need for researchers in this field to adapt to these changes, particularly in relation to expectations of average video game experience in the modern participant, as well as classification of video games by genre. The leading researchers in the field have already published on these changes (e.g. Dale et al., 2020), and the field is making moves to adapt accordingly. Whether these changes will have any significant effect on the pattern of evidence currently present in this research field remains to be seen.

Chapter 3: Comparing conventional and action video game training in visual perceptual learning

Abstract

Action video game (AVG) playing has been found to transfer to a variety of laboratory tasks in visual cognition. More recently, it has even been found to transfer to low-level visual psychophysical tasks. This is unexpected since such low-level tasks have traditionally been found to be largely “immune” to transfer from another task, or even from the same task but a different attribute, e.g., motion direction. In this study, we set out to directly quantify transfer efficiency from AVG training to motion discrimination. Participants (*n* = 65) trained for 20 hours on either a first-person active shooting video game, or a motion direction discrimination task with random dots. They were tested before, midway, and after training with the same motion task and an orientation discrimination task that had been shown to receive transfer from AVG training, but not from motion training. A subsequent control group (*n* = 18) was recruited to rule out any test-retest effect, by taking the same tests with the same time intervals, but without training. We found that improvement in motion discrimination performance was comparable between the AVG training and control groups, and less than the motion discrimination training group. We could not replicate the AVG transfer to orientation discrimination, but this was likely due to the fact that our participants (*n* = 65) were practically at chance for this task at all test points. Our study found no evidence, in either accuracy or reaction time, that AVG training transferred to motion discrimination.

Introduction

Visual learning is essential for interacting with and interpreting an individual's environment. The ability to improve visual skills plays a role in various forms of skill acquisition in fields such as sports, education, and medicine. From a scientific perspective, visual learning is a mechanism that provides externally observable improved behaviors that can in turn be utilized to infer further understanding of the workings of the brain. It is therefore advantageous to identify and understand potential training methods for vision, such as video games.

What is formally known as visual perceptual learning (VPL) refers to improvement of visual perceptual skills after some visual training. There is extensive literature studying perceptual learning of fundamental visual dimensions such as orientation (Dosher & Lu, 2007; Fahle, 1997; Fiorentini & Berardi, 1980) and motion direction (Ball & Sekuler, 1982; Z. Liu & Vaina, 1998).

Traditional VPL research has found that perceptual training tends to result in specific learning. That is, the improvement observed after traditional VPL training is specific to stimulus attributes used in that training, but does not transfer to other values of a trained attribute (Ahissar & Hochstein, 1996; Karni & Sagi, 1991; Yu et al., 2004). For example, participants trained to identify the target grating from two vertically oriented gratings dropped to pretraining performance when the same gratings were rotated and presented horizontally (Fiorentini & Berardi, 1980). These participants attained a level of mastery of the discrimination task, but only with the originally trained stimuli. The exact mechanism behind VPL remains under active debate in the VPL field, but this specificity is often interpreted to suggest that VPL is occurring at low-level of processing in the brain, e.g., in the primary visual cortex (V1), where neurons respond to specific visual characteristics. In other words, specificity would suggest that VPL is a kind of template learning, that is unable to generalize beyond the learned exemplars.

However, it is unlikely that VPL only occurs in V1, given that there are exceptions to the trend of specific learning in VPL in the form of studies that have added specific manipulations to their training paradigm that result in transferable learning. One well-known study (Xiao et al., 2008) introduced the concept of "training plus exposure", where training one feature at location 1 and exposure to an irrelevant second feature at location 2 resulted in transfer of learning of the first feature to the second location (but see contrasting evidence Huang et al., 2017; Liang et al., 2015a, 2015b). In other words, training plus exposure was able to overcome location specificity (see other examples Jeter et al., 2010; Liu & Weinshall, 2000). Other, earlier, studies have also explored factors that may influence transfer, such as the role of task difficulty (Ahissar & Hochstein, 1997; Z. Liu, n.d.; Liu, Zili, 1995; Rubin et al., 1997). These studies have led to various theories regarding the mechanisms of VPL involving factors such as when activation of different visual areas occurs, or how connections between different levels of visual processing might be modified (Ahissar & Hochstein, 2004; Dosher & Lu, 2009; Sagi, 2011; Watanabe & Sasaki, 2015; Xie & Yu, 2020). Other researchers have instead focused on the functional mechanisms of visual learning rather than the physical mechanisms, using such models as signal-detection theory (Z. Liu & Weinshall, 2000).

In comparison, studies of the effect of action video game (AVG) training on visual learning have commonly reported generalization of AVG-induced learning to untrained stimuli (Blacker & Curby, 2013; Dale et al., 2020; Oei & Patterson, 2013) although there are some notable studies that have failed to replicate AVG-induced learning (Boot et al., 2008; van Ravenzwaaij et al., 2014) and articles that have pointed out methodological issues with AVG learning results (Boot et al., 2011; Hilgard et al., 2019; Unsworth et al., 2015). AVG is a training paradigm where participants play AVGs and are tested for improvement in visual skills. The games used in this training typically are first-person shooter (FPS) games, where the player views the screen from a first-person perspective, and must identify and shoot various targets that possess their own unique movements and behaviors. For example, one early study trained participants with an FPS game and found generalization to flanker compatibility, enumeration, and attentional blink tasks (Green & Bavelier, 2003). These tasks used stimuli that differed significantly from the video game graphics that participants trained on, suggesting that AVG generalized to a wider range of visual stimuli. Furthermore, the tasks did not precisely replicate any sub-tasks that made up the gameplay of the FPS game, suggesting that AVG generalizes to a variety of visual skills. The generalizability of AVG suggests that it induces some form of general rule learning, regardless of whether participants were aware of such rules.

Despite the promising extent of transfer reported in AVG studies, the vast majority of AVG research has focused on attention-based visual skills such as visual search (Chisholm & Kingstone, 2015; Strobach et al., 2012) and visual working memory (Blacker & Curby, 2013; Dale et al., 2019; Moisala et al., 2017). In contrast, VPL typically focuses on learning basic dimensions of visual features, such as orientation and motion direction. Overall, only a few studies have examined whether generalizability of AVG extends to the stimuli and tasks typically used in VPL research. These include a study that assessed video game-induced improvement in acuity, spatial and temporal contrast sensitivity, contrast threshold in noise, global motion perception, and useful field of view (Jeon et al., 2012); another that tested the effect of video game training on the contrast sensitivity function (R. Li et al., 2009); and a third that tested participants on an orientation discrimination task with variable external noise (Bejjanki et al., 2014). That is, there is still, relatively speaking, a lack of studies testing the effects of AVG on visual skills utilizing low-level fundamental visual characteristics, and we would like to verify and extend the results of those studies that have done so. There is also the fact that the results of existing AVG learning studies remain controversial (e.g. Hilgard et al., 2019), and so we wish to examine the claim of AVG transfer to vision using more traditionally rigorous methodology from VPL literature.

AVG may induce some form of rule learning that traditional VPL training does not do. As a possible explanation for this difference between AVG and traditional VPL training, we hypothesize that AVG is a form of varied training. Varied training involves varying the stimuli or tasks used for training (Kerr & Booth, 1978). The reported effects of varied training include better performance on a novel stimulus that was actually used for training the comparison group – the constant training group -- which suggests that varied training is beneficial for generalization of learning. The reason for the effectiveness of varied training may be that the variety of stimuli presented in varied training enables learning of a broader and more abstract concept, rather than focusing on the specific attributes that might be more useful in a narrower training. For example, traditional VPL training may train participants to discriminate between 43 and 47 degrees in directions. Whereas in AVG, a range of stimuli such as 43 and 47 degrees, 83 and 87 degrees, or 133 and 137 degrees may be also presented in training, such that discriminating two directions that differ by 4 degrees may be better learned no matter what the average of the two orientations is (Z. Liu & Vaina, 1998; Xiong et al., 2016). A participant trained with AVG may therefore be better able to learn underlying rules of direction discrimination from such variety of stimuli, while a traditional VPL-trained participant may struggle to learn such a rule due to the lack of various examples provided.

The varied training hypothesis may also potentially explain some of the VPL studies that have been able to find transfer of learning. One suggested explanation for how methods such as "training plus exposure" may encourage transfer is that the secondary training location serves as a prime for that location (Xiao et al., 2008). In other words, exposure to a higher variety of locations allows for transfer of feature learning to multiple locations. Varied training may serve as an expansion of that priming effect, where the trainee is exposed to a wide variety of locations and features, thus allowing for generalized visual learning. This had been termed "rooting" in an earlier study (Z. Liu & Weinshall, 2000).

In order to better understand AVG's generalized learning, directly compared AVG with traditional psychophysics VPL training. This comparison provides not only insight into the differences between the two training methods, but also additional evidence of whether AVG can generalize beyond attention-based tasks. In addition, the proposed hypothesis of varied training would also suggest that the characteristics of AVG-induced learning may differ from the characteristics of traditional VPL.

One way of comparing AVG and VPL training is to compare their rates of learning. Our reasoning is that AVG may demonstrate a slower rate of learning, because learning an abstract rule from a more complex video game may take longer than learning a specific instance from a more concrete VPL training task. There is also evidence that suggests that varied training does in fact require more training in order to reach the same criterion of learning comparable to constant training (Sabah et al., 2019). In the AVG literature, one review suggests that 20 hours of training is the minimum required in order to observe significant learning43, although the literature has seen a range of training times ranging from 10 (Feng et al., 2007; Green & Bavelier, 2003; Hutchinson et al., 2016) to 50 hours (Green et al., 2012). In contrast, VPL literature typically does not quantify training in terms of hours, but rather in terms of number of sessions completed, and research on minimum training required is scarce. One study suggests that as few as five trials per condition per day is sufficient to obtain significant learning on a texture discrimination task (Hussain et al., 2009). Another suggests that a minimum of 400 trials per session is required for learning a Chevron discrimination task (Aberg et al., 2009). However, it is not unusual to see VPL studies that require participants to complete weeks of training sessions (Chung et al., 2006; Liang et al., 2015a). The learning rates of AVG and traditional VPL training have not previously been compared, but doing so provides evidence of potential mechanistic similarities and differences between the two methods.

Therefore, we tested our hypotheses by having participants train either on AVG or psychophysics tasks. The psychophysics tasks we used have been tried and tested in prior VPL studies in the literature, so we already know what the expected amount of learning should be. This allowed us to assess whether the amount of transfer to the psychophysics tasks from AVG training was comparable to that from traditional psychophysics training of the same task (we already expected minimal transfer from the trained psychophysical task to the untrained psychophysics task).

All participants completed a pre-test and post-test consisting of two psychophysics tasks to assess performance before and after training. The psychophysics task used for training was identical to one of the tasks used in pre- and post-tests. This was the matched task, while the other task used in testing served as an unmatched task. This allowed us to test whether the AVG training was able to induce learning in the two psychophysics task, and if this transfer was more than that from the matched to the nonmatched psychophysics task. There is also the question of potential differences in rate of transfer. Therefore, participants also completed a middle test after

9.75 hours of training, in addition to the pre- and post-training tests with 19.5 hours training total.

In sum, we tested four potential hypotheses. First, after completing the entirety of training, we predicted that those trained with AVG would demonstrate comparable levels of learning (in the form of improved test performance) on a matched psychophysics test as compared to participants trained on a psychophysics task.

Second, for the unmatched psychophysics test, we predicted that participants trained with AVG would demonstrate more learning post-training than the participants trained with psychophysics. In other words, the AVG participants would show transfer from AVG to both psychophysics tasks after completing all training. This would have taken the form of an interaction between training type and time, comparing pre-test to post-test.

Third, for the matched test, we predicted that those trained with AVG would demonstrate an overall slower rate of learning than the psychophysics training group. This would have taken the form of two interactions. The first interaction is between training type and time, comparing learning from pre-test to mid-test (9.75 hours into training). We expected the psychophysics training group to show more transfer than the AVG group at this point. The second interaction is identical to the first but compares learning from mid-test to post-test. We expected at this time point for AVG to show more transfer than the psychophysics training group - this would indicate slow down or even a plateau for the psychophysics training group after the first half of training while the AVG group continued to improve.

Fourth, for the nonmatched test, we predicted that those trained with AVG would show more transfer than those trained with psychophysics. This would have taken the form of one main effect and one interaction. The main effect was predicted to be of time, because we expected both training groups to transfer relatively little from pre-test to mid-test. The predicted interaction was between training type and time, comparing transfer from mid-test to post-test. We expected that, similar to the matched test, AVG would show more transfer than the psychophysics training group. However, unlike the matched test, we expected that the psychophysics training would simply transfer minimally, whereas AVG would transfer significantly.

Methods

Ethics information

Our research complied with all relevant ethical regulations. Our study protocol was approved by Hebei Normal University (Protocol ID: 2020LLSC050) and the University of California, Los Angeles (UCLA) General IRB (Protocol ID: 21-000928). Informed consent was obtained from all participants. Participants were compensated with credit to a school account (Hebei Normal University), or course credit (UCLA). Compensation occurred when participants completed their final experimental session, or voluntary early termination of participation, whichever occurred earlier.

Design

Survey. All participants completed a survey prior to participating in the experiment. The survey included demographic questions regarding gender and age. Participants were also asked about motion sickness, normal vision, and prior experience with psychophysics tasks. The bulk of the rest of the survey consisted of questions regarding the participant's video game experience in the past year, and asked participants for estimates of time spent playing games and examples of commonly played games.

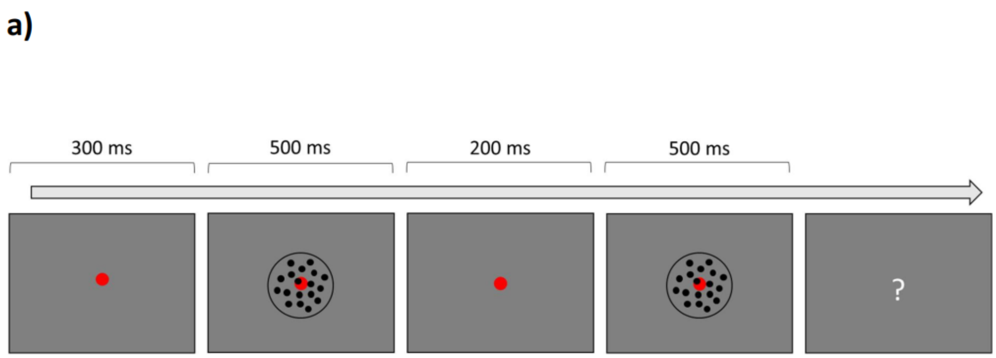
Experimental Design. This study consisted of a 2 x 3 design, containing one between-subjects variable, and 1 within-subjects variable. For the between-subjects variable, participants were assigned to one of two training conditions, AVG or psychophysics training. Note that we separated participants by gender and randomly assigned to the two training conditions within each gender group such that the gender ratio of the two training groups was as similar as possible. This is because prior video game studies have often found that recruiting participants who have no prior video game experience tends to result in primarily female participants. Whether this is due to cultural factors or self-selection resulting from perceptual differences is unclear, and so we attempted to ensure that there was the same gender ratio in all training conditions.

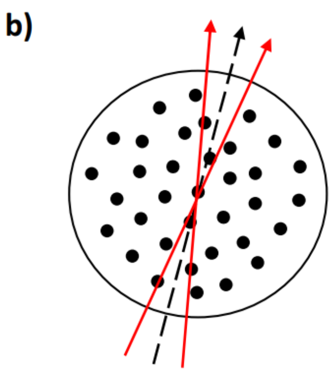
There was also one within-subjects condition. Namely, the duration of training before a given test: 0, 9.75, or 19.5 hours. There were two measures at each time point: an orientation discrimination task and a motion direction discrimination task. All participants took a test consisting of these two psychophysics tasks at 0th, 9.75th, and 19.5th training hours. Data collection and analysis were not performed blind to the conditions of the experiment.

Psychophysics Tasks. There were two psychophysics tasks used for this study, coded using PsychoPy (Peirce et al., 2019). The tasks consisted of a motion direction discrimination task and an orientation discrimination task. These tasks were selected because they cover two low-level visual characteristics that have been previously studied in the VPL literature. Furthermore, replicating tasks used in prior publications allowed us to utilize the results from these publications as set expectation points for our own study. The motion task originated from a VPL study (Liang et al., 2015a), providing an estimate of expected optimal transfer (i.e., testing and training are identical). The orientation task originated from a video game learning study

(Bejjanki et al., 2014) and provided an estimate of expected AVG transfer. Each participant completed the two tasks in a randomized order that was reused for every subsequent test that specific participant took.

Figure 3: Motion direction discrimination task

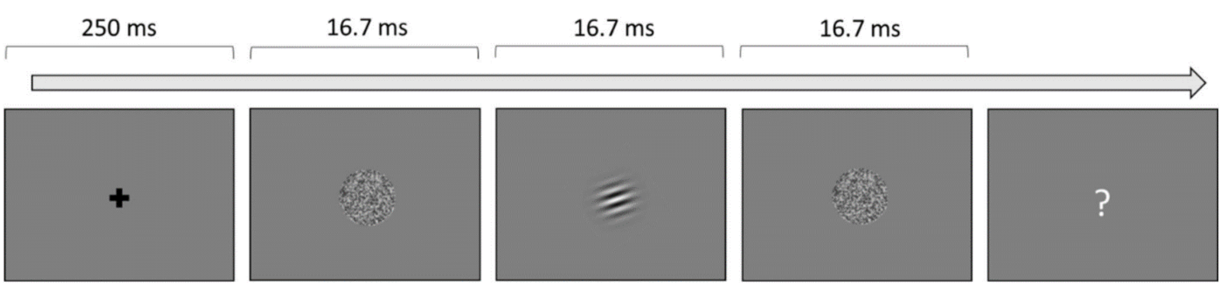




Note. (A) Example trial procedure for motion direction discrimination task. (B) Each trial's stimuli will contain the same pair of motion directions (solid red arrows): one with a positive offset from the implicit reference angle (75˚, dotted black arrow) and one with a negative offset (not to scale in figure). The order of presentation will randomly vary from trial to trial.

The motion discrimination task (Figure 3) replicated the 2AFC task used in Liang et al. (2015). Each stimulus was a motion dot stimulus consisting of a borderless circular aperture (8˚ visual angle in diameter) containing 400 randomly placed dots (0.09˚ in diameter) that were all moving in the same direction at the same speed of 10˚/sec, with a full life time. Each stimulus was presented for 500 ms, with an inter-stimulus interval of 200 ms. The average motion direction of each trial was 75˚, with the two stimuli always separated by +3˚ or -3˚. That is, the pair of stimuli always had motion directions of either 73.5˚ and 76.5˚, or 76.5˚ and 73.5˚. There was a central red fixation dot throughout each trial, 0.5˚ in diameter. Participants were asked to indicate which stimulus contained a more clockwise motion direction. Feedback for every trial was provided in the form of a beep if correct.

Figure 4: Orientation Task



Note. Example trial procedure for the orientation discrimination task. After stimulus presentation, participants have unlimited time to respond. Once a participant responds, they will receive auditory feedback if they were correct.

The orientation discrimination task (Figure 4) replicated the yes-no task used in Bejjanki et al. (2014), using Gabors (sine wave grating with a Gaussian filter) viewed through a circular aperture (1.5˚ visual angle in diameter) as stimuli. We replicated all of their stimuli and conditions used. All Gabors were identical in spatial frequency (2 cpd), and only differed in orientation. Namely, the target stimulus was tilted 2˚ clockwise or counterclockwise from horizontal. In addition, every Gabor was presented simultaneously with external noise. External noise images were the same size and shape as the Gabors, consisting of pixels drawn independently from a Gaussian distribution. Noise energy was increased in task-relevant spatial frequency channels by filtering the external noise images through a band-pass filter with spatial frequencies ranging from one octave below to one octave above the Gabor frequency.

For each trial of the orientation discrimination task, a central fixation cross was presented for 250 ms. A Gabor stimulus with external noise added was then presented sandwiched between two external noise images, with each of the three images being presented for 16.7 ms. Participants responded with a keypress to indicate whether the Gabor was tilted more clockwise or counterclockwise from horizontal, and received auditory feedback for a correct answer. There were eight external noise contrast levels for the Gabor stimulus (0.0, 2.1, 4.1, 8.3, 12.4, 16.5, 24.8, and 33.0%), presented in an interleaved fashion. In addition, there were two interleaved staircase procedures used for each level of contrast, one targeting a 79.37% threshold (3-down-1-up) and the other targeting a 70.71% threshold (2-down-1-up). Step size was 10% of the current contrast. Contrast threshold was calculated as the mean of all reversals, barring the first four. There were 100 trials for each 3-down-1-up staircase, and 80 for each 2-down-1-up staircase, totaling 1440 trials.

Both tasks were also preceded by 12 practice trials identical to experimental trials, but with larger offsets that were easier to perceive. The practice trials used three offsets that were presented from largest to smallest. For example, the motion discrimination practice consisted of four trials with ±10˚ offset, four with ±7˚ offset, and finally four with ±4˚ offset.

Video Game. The AVG that participants were trained on is *Medal of Honor: Pacific Assault* (Electronic Arts Inc., 2004). This game is a commercial first-person shooting (FPS) game, selected because it and other games from the Medal of Honor series have been used in prior video game learning studies (Green & Bavelier, 2003; R. W. Li et al., 2015; S. Wu &

Spence, 2013). The game allows the player to progress through a series of levels of increasing difficulty, while navigating in a 3D environment and shooting of various targets.

The selection of an older video game raises the question of whether it is truly relevant to utilize a video game that is no longer comparable to modern video games in terms of gameplay and graphics. However, similar games from the 2000s have commonly been used as training games in most prior video game studies (Boot et al., 2008; Green & Bavelier, 2003; S. Wu et al., 2012), including the study whose orientation discrimination task we attempted to replicate. Given that the claims of AVG transfer from these prior studies is controversial, it is important to first verify the results of these previous studies before moving on to more modern games.

Training procedure. Participants assigned to the video game training played through the video game starting from the beginning, which was a tutorial level designed to introduce players to the controls of the game. In subsequent sessions, participants proceeded through the levels of the game. For participants assigned to the psychophysics training, they trained on a motion direction discrimination task identical to the one used in the pre- and post-test.

Participants completed training and testing over the course of 24.5 hours. All tests were conducted as two 45-minute sessions that took place on two consecutive days, one task per day. The pre-test was conducted before training began, the first post-test after 9.75 hours of training, and the second post-test after 19.5 hours training total. Training was conducted as 26 45-minute sessions, each conducted on a separate day (Figure 5). Participants trained on their assigned task for the entirety of each 45-minute session.

Figure 5: Training and testing procedure

Note. Timeline of training and testing. There will be 19.5 hours total of training. There are also 2 45-minute sessions per test, spread over 2 days. The pre-test occurs before training begins, the first post-test after 9.75 hours of training, and the second post-test after 19.5 hours of training.

We opted for a compromise training session length of 45 minutes. While AVG studies typically use training sessions of at least one hour in duration, VPL studies rely more commonly on a given number of trials. Furthermore, research into the length of VPL training sessions indicates that a session duration of 30-60 minutes does not encounter performance decrements over time, while longer sessions of 90-150 minutes do (Censor & Sagi, 2008). We therefore chose a training session duration that falls within that shorter range to prevent potential performance decreases in the psychophysics training condition due to overtraining.

Sampling plan

Participants. Participants in China were recruited using flyers and received monetary compensation. The flyers used to recruit participants indicated criteria for participation, including normal or corrected-to-normal vision and lack of video game experience. Interested participants were asked to complete an online survey before continuing to the experiment itself, in order to verify that they qualified for the experiment and to gather some video game history and demographic information from participants. If a participant was selected, normal or corrected-to-normal vision was confirmed in the laboratory using a Snellen visual acuity chart.

Participants at UCLA were recruited from the lab's research assistants, and received course credit. These participants were screened by an experimenter for the same criteria for participation as the Chinese participants.

Exclusions. Participants were excluded from further analyses if they did not complete more than one test session.

Sample size. Ideal sample size can be typically calculated based on a priori analysis using effect sizes from the literature. However, for this study, it was difficult to determine which field to draw effect sizes from, as this proposed study combined two groups of literature: video game learning studies, and VPL. Furthermore, this study was planning to apply AVG training to truly low-level psychophysics tasks, which previous studies have not done. Therefore, it was difficult to find existing effect sizes from the literature.

There was no clear effect size to rely on from prior literature because our study combines two separate fields of research. However, our study is structured similarly to many psychophysics studies, which tend to use a small number of participants, each of which completes a high number of trials. Sample size can be as small as three (Lu et al., 2009) and as large as 34 (Cong et al., 2016). The use of high numbers of trials has the effect of increasing reliability of a measurement, which in turn increases the effect size (Brysbaert, 2019). One can also expect a larger effect size for the psychophysics training condition of our study, as the best training for a given test is that test itself. Indeed, in the VPL literature, effect sizes for the learning observed on a task after training on said task range from Cohen's $d = 1.109$ (Tan et al., 2019) to $d = 2.74$ (D. Wu et al., 2020).

It was reasonable to assume, however, that we did not expect such large effect sizes from our study. Not only do we not have prior effect sizes to draw from within the literature, but also our study compares what is essentially the ideal training for a test to AVG, and so it was unlikely that there would be such a large effect size for AVG. Therefore, we chose to use a more conservative estimate. We chose to use an effect size of Cohen's $d = 0.227$, based on the effect size for studies targeting "perception" learning from AVG obtained from a meta-analysis of AVG learning studies (Bediou et al., 2018).

We calculated a priori power using the online power calculator WebPower (Z. Zhang & Yuan, n.d.). Specifically, we chose to focus on the interaction effect between training type and time - that is, will one type of training show more transfer than the other on a given test task? Therefore, we calculated the n required for a repeated-measures ANOVA, and found that a total n of 64 participants was required in order to achieve a power of 0.9, or 32 participants per training group.

Analysis Plan

Pre-processing. As indicated previously in the Sampling Plan, participant data was excluded if participants did not complete more than one test session. All data was included in the analyses otherwise.

Computing thresholds. For each participant, we calculated their threshold for each condition of the orientation discrimination task, as well as an overall mean threshold, at each stage of testing: pre-test and both post-tests. Because the orientation discrimination task used a staircase procedure, we were able to calculate thresholds by averaging all reversal values except the first four. There were two thresholds calculated due to the use of two different staircases to achieve different thresholds. Specifically, these thresholds represented the contrast value at which the participant was able to accurately discriminate the presented orientation 79.37% or 70.71% of the time.

Computing sensitivity. For each participant, we calculated their d' for the motion discrimination task at each stage of testing: pre-test and both post-tests. d' is a measure of sensitivity used in Signal Detection Theory, and is calculated by subtracting the Z value of the false alarm rate (i.e., when the participant incorrectly identifies that the two stimuli are different) from the Z value of the hit-rate (i.e., when the participant correctly identifies that the two stimuli are different). A higher d' indicates that the participant is better at detecting the signal – in this case, the trials where the two stimuli were different. An increase in d' over the course of the experiment would therefore indicate that a participant had experienced learning.

Training scores. Performance values for each participant's training were also calculated. For participants training with a psychophysics task, this was calculated by finding their sensitivity for each training session. For participants that trained with a video game, the time taken to get through the first level was compared at each testing point. Training scores were used to verify participant effort, and to check that participants did experience learning on their specific training task.

We also used training scores for a corollary hypothesis tying together improvement on training and improvement on our visual tests. Namely, we predicted that participants who experienced more AVG learning would experience more visual learning. Therefore, we predicted that the correlation coefficient between AVG improvement (difference score between post- and pre-tests) and mean percentage improvement (MPI) for both tests would be positive. In contrast, we predicted that participants who underwent psychophysics training would experience the same amount of visual learning on the nonmatched test regardless of how much improvement they showed on their training task. Therefore, we predicted that the correlation coefficient between psychophysics training and MPI for the nonmatched test would be 0. Note that a positive correlation between improvement on the psychophysics training and improvement on the matched test was expected, as the best training for a task is the task itself. Therefore, we did not plan to calculate correlation for psychophysics training and matched test improvement.

Hypothesis Testing

We looked at changes in participant performance on each of the psychophysics tasks by examining the changes in their sensitivity (motion task) or threshold (orientation task). For testing our hypotheses, three ANOVAs were conducted per test task, with six ANOVAs total. For each test task, one ANOVA compared the pre- and mid-test data, while the second ANOVA compared the mid- and post–test data. The third ANOVA compared the pre- and post-test data. We believe that these specific ANOVAs each tests a specific hypothesis (the first two test the learning rate hypothesis, whereas the third tests the overall amount of transfer), and is more specific and informative than an overall 2 x 3 ANOVA.

Our experiment was designed to test the effect of training type and training duration on low-level visual skills: motion direction and orientation discrimination. For all of our ANOVAs, there was one between-subjects variable: type of training. There was also one within-subjects variable: hours of training completed before testing. Our effect of interest was an interaction: if AVG did not transfer as much as psychophysics training, then we would expect a significant interaction. On the other hand, if both training conditions transferred equally, then we would not expect an interaction. We did expect a main effect of time, because at the very least, the psychophysics training should yield better performance post-training. We also expected a main effect of training condition if psychophysics training proved to be superior to AVG. This main effect, however, would not be expected if AVG and psychophysics training proved to be similar in transfer.

Note that for our matched test task, we predicted two interactions and one non-interaction. This is because we expected that psychophysics training would transfer more than AVG from pre- to mid-test, but AVG would transfer more than psychophysics training from mid- to post-test. Overall, however, we expected that both training conditions would transfer similar amounts from pre- to post-test.

In contrast, for our non-matched test task, we predicted no interaction for the pre-test/mid-test comparison, but we did predict interactions for the mid-test/post-test comparison and the pre-test/post-test comparison. This is because we expected that neither training condition would transfer much from pre- to mid-test, but AVG would transfer more than psychophysics training from mid- to post-test. Overall, we therefore expected that AVG would transfer more than psychophysics training from pre- to post-test.

Results

Participants

Sixty-seven participants were recruited from the University of California, Los Angeles (UCLA) (n = 9, seven female, M_{age} = 20.78 years) and Hebei Normal University, China (n = 58, 43 female, M_{age} = 20.18 years). Participants were first divided into male and female categories, and then within each category randomly assigned to either the video game or motion discrimination training group. This resulted in seven males and 21 females in the Hebei video game group (plus two excluded female participants), and eight males and 20 females in the Hebei motion training group. In the UCLA cohort, one male and four females were in the video game training group, and one male and three females in the motion training group.

In a subsequent control condition, an additional 35 participants were recruited at Hebei Normal University, but 11 dropped out, leaving 24 remaining (22 female, M_{age} = 22 years).

Exclusions. 11 control participants and two video game participants, all from the Chinese site, did not complete the study and were excluded from the final data set. One left the study due to extreme cybersickness. Out of the remaining 12 participants, six left the study for academic reasons and six for personal reasons.

Orientation discrimination

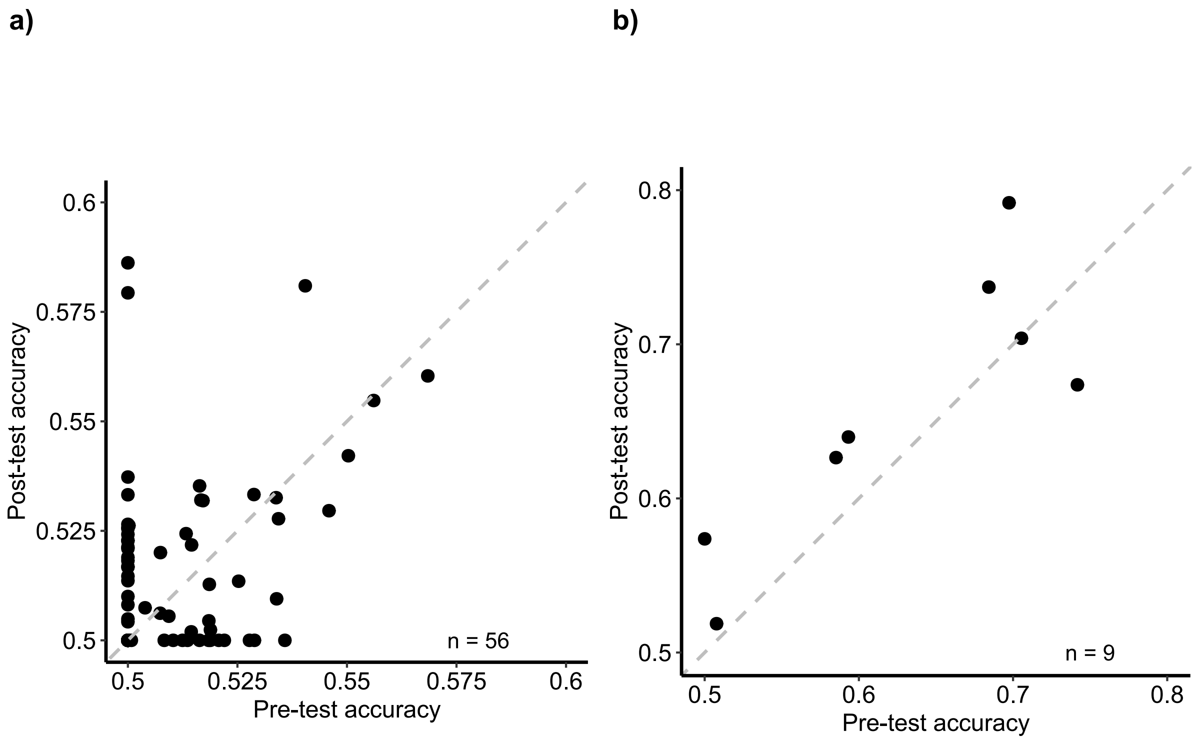
After scrutinizing the staircase data, we realized that most subjects' staircases did not converge, but oscillated near the maximal stimulus contrast of 1.0, suggesting that the task was too difficult. Consequently, rather than computing an average from the reversals, as was done in Bejjanki et al. (2014), we used logistic regression in MATLAB (Mathworks) to fit a psychometric function for each participant at each external noise level, with x = stimulus contrast and y = behavioral response (0 or 1), using the following function:

$$y = 0.5 * e^{-(x/a)^{b^2}}$$

To assess whether a participant was able to do the task at all, we estimated the accuracy from such curve fitting at each external noise level when the stimulus contrast was 1 (Figure 6). None of such accuracies from our Chinese participants (n = 52) exceeded 55%, at stimulus contrast = 1. Therefore, it seemed that these participants were nearly at chance in all conditions.

Of the nine UCLA participants, seven exceeded 55% at stimulus contrast of 1. We hence compared these accuracy values between pre- and post-training, for each of the eight external noise levels. For each participant, we counted the number of external noise conditions when this accuracy increased. If more than half of the conditions showed increases, this participant would be labeled as a learner. Five of the seven participants were learners. However, this result could not reject the null hypothesis that the probability for a participant to improve was 0.5 (p = 0.16). We concluded therefore that the UCLA group did not improve. That is, irrespective of their training condition, the participants did not improve their orientation discrimination, but we could not rule out the possibility that this was simply due to the participants' near chance performance.

Figure 6: Pre-test vs. post-test accuracy on the orientation discrimination task

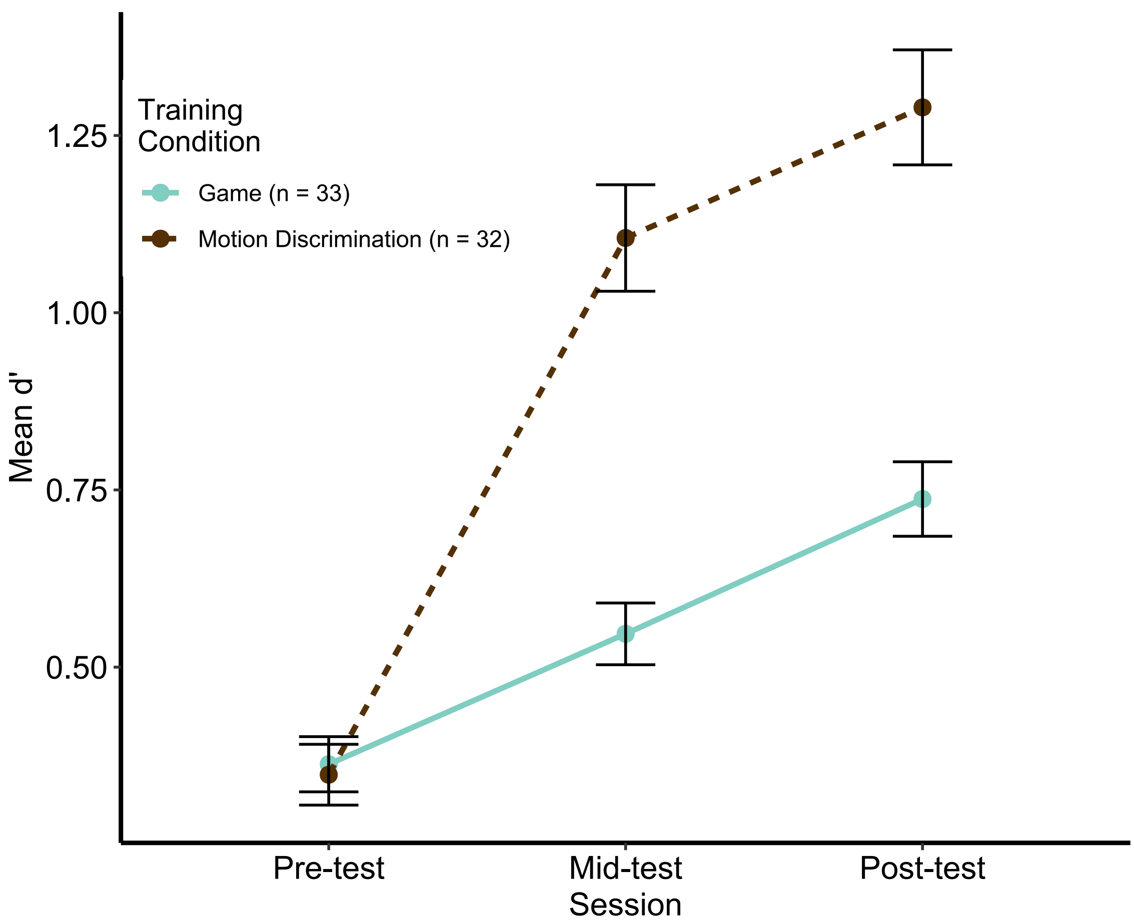


Note. Each participant's pre-test and post-test data from the orientation discrimination task was fit to a psychometric function, which was used to calculate predicted accuracy when the stimulus contrast = 1: A) from the Chinese participants, B) from the UCLA participants.

Motion direction discrimination

Discrimination sensitivity (d') was calculated from 720 experimental trials at each test point (pre-, mid-, and post-test) for each participant. Two type III mixed-subjects ANOVAs were conducted on these data, with training condition (video game vs. motion training) as the between-subjects factor and test session as the within-subjects factor. Comparing pre- to mid-test, we found statistically significant main effects of test session ($F(1, 63) = 149.35$, $p < .001$) and training condition ($F(1, 63) = 18.92$, $p < .001$). There was also a significant interaction ($F(1, 63) = 55.41$, $p < .001$). For the ANOVA comparing mid- to post-test, we found statistically significant main effects of test ($F(1, 63) = 52.92$, $p < .001$) and training ($F(1, 63) = 40.24$, $p < .001$). However, the interaction was non-significant ($F(1, 63) = 0.013$, $p = .91$).

Figure 7: Mean sensitivity over the course of training



Note. Participants trained on an FPS video game or a motion discrimination task for 20 hours, and were tested on a motion discrimination task before, midway, and after training. Mean group d' (sensitivity) on motion discrimination is plotted at each test point. Error bars represent ±1 standard error, as error bars in subsequent figures.

These results suggested that, after 10 hours of training, the motion discrimination group (*M* = 1.11, *SD* = 0.43) outperformed the video game group (*M* = 0.55, *SD* = 0.25), and such advantage persisted after another 10 hours of training (motion: *M* = 1.29, *SD* = 0.46; video game: *M* = 0.74, *SD* = 0.30) (Figure 7). It is also important to note that, although there was statistically significant improvement from pre- to mid- and to the post-test for both groups, it remained unclear how much such improvements were due to test-retest difference. Apparently, for the psychophysics group, the improvements could not possibly be due to test-retest only, given their greater improvement. Nevertheless, without a test-retest control comparison, it would be unclear whether or not video gaming could transfer to motion discrimination at all.

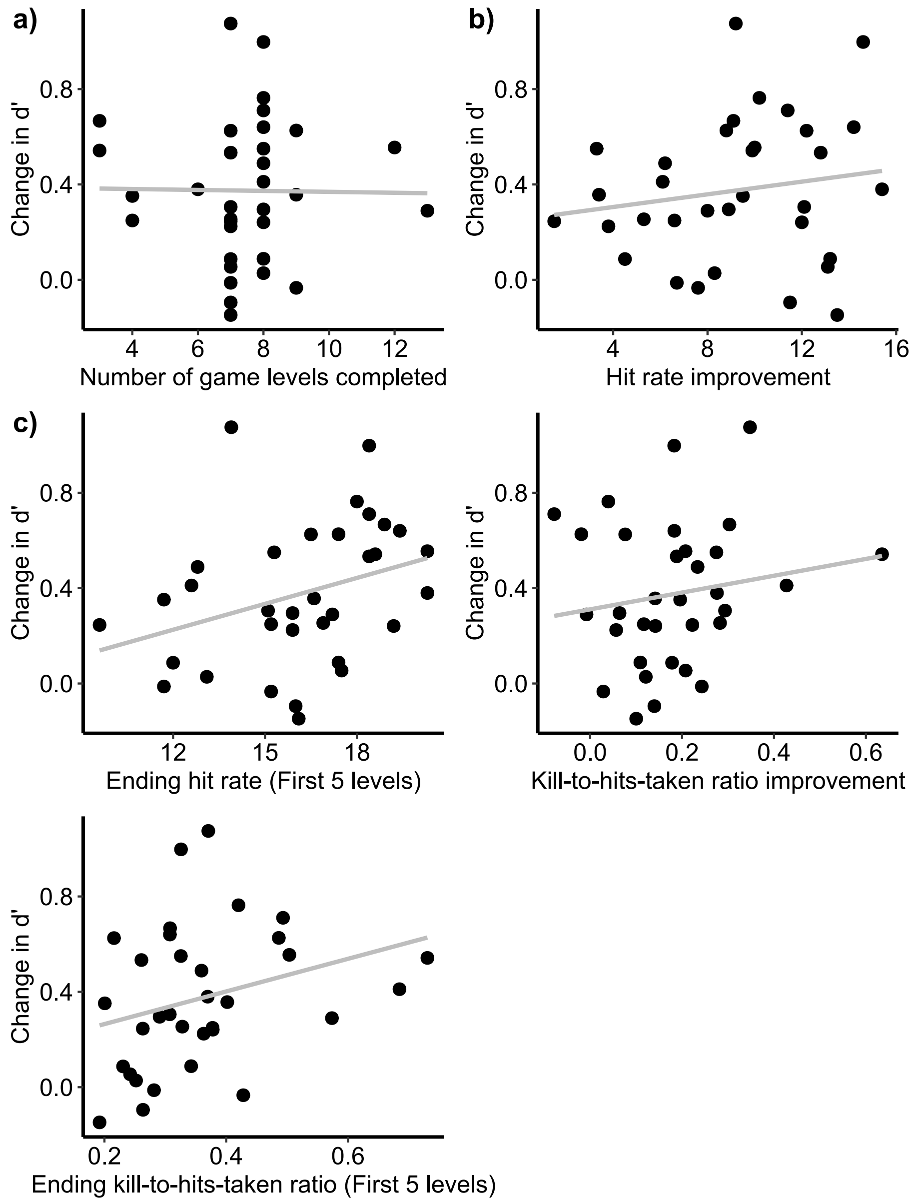
Correlation between video game training and motion discrimination tests

As an additional check on any possible transfer from video game training to motion discrimination, we calculated a number of indexes for video game improvements, and then correlated each with improvement in d' in motion discrimination, from pre- to post-test (Figure 8).

The first metric was the number of game levels completed. A one-sample t-test was conducted on the number of levels completed and confirmed that the video game training group completed a significant number of levels ($t(32) = 21.1$, $p < .001$). The correlation coefficient between this number and improvement in motion d' was -0.013, however, and was not significant ($t(31) = -0.074$, $p = .94$).

The second metric was improvement in hit rate within the first five levels, which constituted the first stage of the game. We only used these five levels because not all participants progressed beyond them in training. This hit rate improvement was quantified as a participant's hit rate after completing the first two levels (in order to avoid unreasonably high hit rate after the

Figure 8: Correlation between training measures and sensitivity



Note. All correlations are between a training measure and individual improvement in d' (sensitivity). Training measures depicted are A) Number of game levels completed; B) Improvement in hit rate (calculated from the ratio of the number of hits landed on enemy targets to the number of shots fired) over the course of playing the first five levels; C) Ending hit rate after the first five levels; D) improvement in ratio of kills to hits taken (the number of enemies successfully killed versus the number of times the player was hit by enemy fire) over the first five levels; and E) Ending ratio of kills to hits taken after the first five levels. All correlations were small and not statistically significant.

introductory level), subtracted from the participant's hit rate at the end of training or the completion of these five levels, whichever came first. A paired-sample t-test confirmed that the participants significantly improved this hit rate ($t(32) = 14.5$, $p < .001$). The relevant correlation coefficient, however, was 0.16 and not statistically significant ($t(31) = 0.91$, $p = .37$).

The third metric used was the hit rate upon completion of training or the first five levels of the game, whichever came first. This was the same as the second measure used in the last paragraph. The reasoning was that even if participants improved little over training, this may not reflect some other skills of the participant independent of training. The corresponding correlation coefficient was 0.29, but was still not significant ($t(31) = 1.94$, $p = .062$).

The fourth metric used was a modification of a common measure of performance in competitive first-person shooter video games: kill-death ratio (KDR). This measure had also been used in prior studies (Green & Bavelier, 2006, 2007). We modified this measure slightly given that the game used did not record player deaths. Instead, we substituted the death number by the number of hits taken by the player. We looked at the improvement over the first five levels, or over the course of training, whichever was shorter. A t-test confirmed that participants demonstrated significant improvement in ($t(32) = 7.45$, $p < .001$). The correlation was .16, but was not significant ($t(31) = 0.92$, $p = .37$).

The fifth and final metric was a variation of the fourth above. Whereas the fourth considered the rate achieved initially, the fifth considered the same rate achieved at the end. (This rate was necessarily the same if a participant could not complete the first five levels.) The correlation was .29, but was not significant ($t(31) = 1.70$, $p = .099$).

Exploratory analyses

Control group. We conducted a follow-up control condition (*n* = 18) with participants from Hebei Normal University, China. In this control, participants simply completed the pre-, mid- and post-tests at the same time intervals as trained participants, but did nothing otherwise.

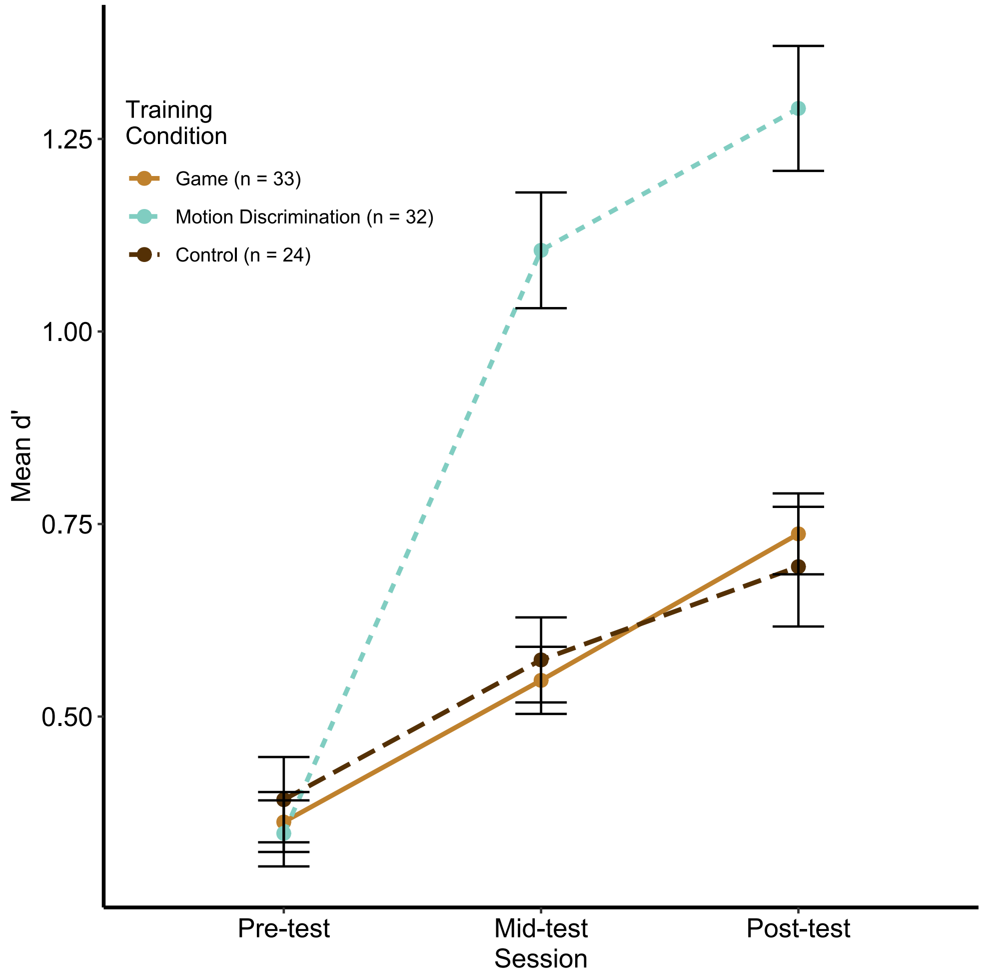
A mixed-subjects ANOVA was conducted on data from all participants. Statistically significant main effects of test ($F(1.49, 113.08) = 138.80, p < .001$) and group ($F(2, 76) = 14.30, p < .001$) were found. A statistically significant interaction was also found ($F(2.98, 113.08) = 25.24, p < .001$). Figure 9 shows the results.

Follow-up t-tests were conducted, particularly in comparisons between the video game training and control groups. At pre-test, the control group (M = 0.39, SD = 0.23) was comparable to each of the two trained groups ($t(35.1) = 0.48, p = .63$; $t(32.9) = 1.13, p = .27$). At mid-test, no significant difference was found between the control (M = 0.57, SD = 0.23) and video game training group ($t(38.4) = .31, p = .76$), but the motion group showed greater sensitivity than the control group ($t(45.7) = 5.32, p < .001$, Cohen's d = 1). This pattern persisted at post-test: between controls (M = 0.69, SD = 0.33) and gamers ($t(33.2) = -0.64, p = .53$), between motion and controls ($t(44.4) = 4.95, p < .001$, Cohen's d = 1.49).

Importantly, the addition of the control group indicated that there was no evidence that video game training transferred at all to the motion discrimination task.

Reaction time. Green et al. (2010) reported that active video game training reduced a participant's reaction time, whereas a control participant's reaction time was not reduced, even though no difference was found between them when accuracy was measured (see also Wu & Spence, 2013). We accordingly looked into our participants' reaction times (RT), both in the mean RT and median RT since the latter better addresses outliers.

Figure 9. Mean sensitivity over the course of training, including control

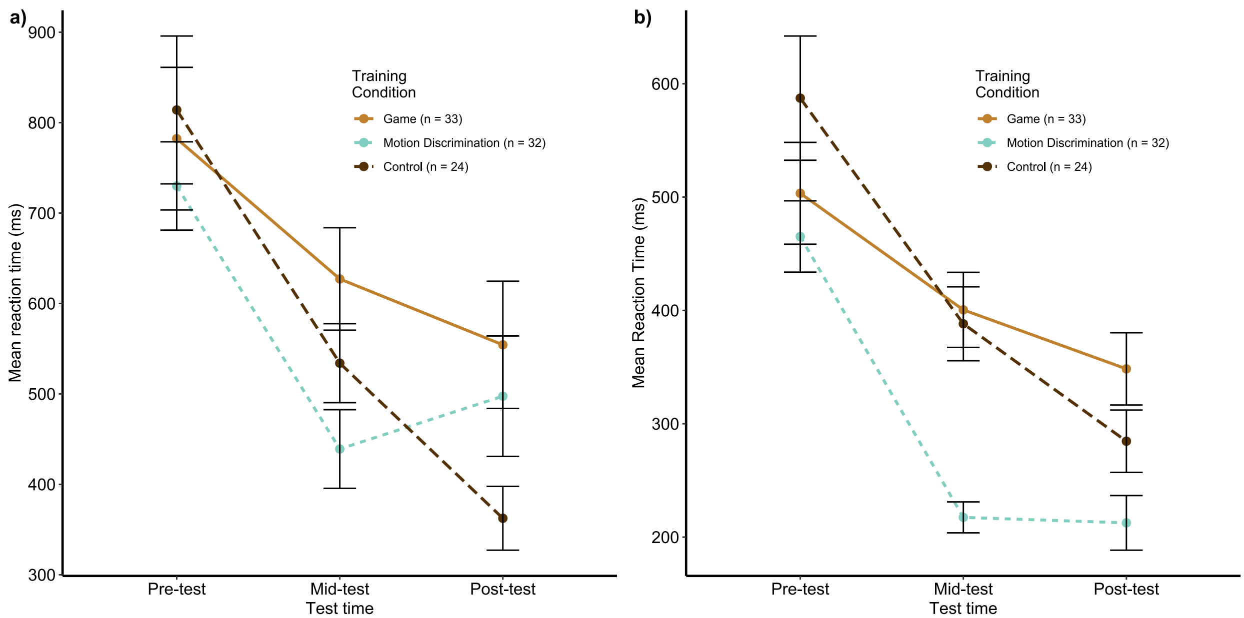


Note. Mean d' (sensitivity) for both training groups and the control group is plotted at each test point. The data from the video game and motion discrimination training groups are identical to those in Figure 5. The control participants did not train, but were simply tested at the three time points matched to the training schedule. No difference was found between the control and video game training group.

A mixed-subjects ANOVA conducted on mean RT data from all three training groups revealed only a significant main effect for test time (F(1.76, 141) = 29.94, p < .001). However, the main effect for training group and the interaction were not significant (F(2, 80) = 1.31, I = .28; F(3.53, 141) = 2.13, p = .089).

A mixed-subjects ANOVA was also conducted on median RT data from all three training groups. Significant main effects were found for test (F(1.4, 111.85) = 78.92, p < .001) and for group ($F(2, 80) = 6.56$, $p < .01$). A significant interaction was also found ($F(2.8, 111.85) = 4.22$, $p < .01$). As seen in Figure 10, unlike in Green et al. (2010), all training groups improved in reaction time over the course of training, but the psychophysics training group consistently had faster improvement.

Figure 10. Reaction time over the course of training



Note. Mean reaction time (RT) data for each training group and the control group at each testing point, calculated from individual median RT data at each time point. All groups decreased reaction time significantly over time, but the motion discrimination training group experienced the largest overall decrease. The video game training group and control group did not have statistically significantly different reaction times at any time point.

Discussion

Prior research has suggested that playing AVGs has beneficial effects for a wide variety of visual tasks (Bediou et al., 2018; Green & Bavelier, 2003; Oei & Patterson, 2014b), which implies that playing AVGs transfers broadly and effectively to vision. Therefore, we investigated whether playing an AVG would transfer to lower-level visual tasks such as orientation discrimination and motion direction discrimination. Participants with no significant AVG experience were recruited and trained on either an AVG or a motion discrimination task. Motion and orientation discrimination performance was assessed before, in the middle of, and after training. We hypothesized that based on prior literature, those participants trained on the video game would demonstrate transfer of learning to low-level visual tasks. We asked how effective transfer would be from video game training as compared to from training on motion discrimination, to motion and orientation discrimination.

While all our participants demonstrated significant improvement in d' on motion discrimination from pre- to post-test, the psychophysics training group yielded a significantly larger improvement than the video game training group, indicating that playing a video game did not transfer as much to motion discrimination as training on motion discrimination itself. In fact, data collected from a control group demonstrated that this group's improvement from pre- to post-test was comparable to the video game group. This indicated that such an improvement was likely due to test and retest, since the controls merely completed the same visual tests as the two training groups with the same time intervals between tests.

We also analyzed reaction time data, since Green et al. (2010) had found that video game training reduced reaction times in motion discrimination. Our analysis was consistent with the d' analysis above; namely, that reaction times were reduced with statistical significance for all participants, but more so for the motion training group. The video game training group and the controls showed comparable reduction in reaction times, indicating that such reduction was due to test retest and little evidence for transfer from video game training to motion discrimination.

Correlational analysis of the video game training group provided further support that video game training did not transfer to motion discrimination. Among all the metrics that we could think of that measured video game improvement, none correlated with the participant's motion discrimination improvement. Note that all the metrics above improved with statistical significance, meaning they were sensible measures of improvement in video game playing. The lack of correlations between improvements in video games and in motion discrimination was consistent with our conclusion above that video game training did not transfer to motion discrimination.

Our orientation discrimination task was intended to replicate the task used in Bejjanki et al. (2014), which was one of only a few studies demonstrating transfer from video gaming to a low-level psychophysical task. Unfortunately, this task proved to be too difficult for our participants. Experimenter error was the cause for not detecting this difficulty earlier, in part because the upper bound of stimulus contrast made the staircases often appear to be converging. Our best explanation is that we did not pre-train our participants enough. Our overall results in orientation discrimination, therefore, may completely be due to our participants' failure to do the task in pre-test, leaving the question unanswered of whether or not video gaming could transfer to orientation discrimination.

Our hypothesis for potential broad transfer to a variety of laboratory cognitive and perceptual tasks from video game learning was varied training - that exposure to a diverse range of stimuli and demands would facilitate general rule learning that subsequently enables transfer to any specific stimulus and task (Garrigan & Kellman, 2008; Z. Liu & Vaina, 1998; Xie & Yu, 2020). However, our current results did not support such a hypothesis. What might be the explanation?

1. One possibility is that 20 hours of video game training was insufficient. Although one meta-analysis found that 20 hours was within the effective range albeit at the lower

bound (Chopin et al., 2019), it could be that, for transfer to low-level psychophysics tasks such as motion discrimination, longer training was necessary. Indeed, video gamers can easily spend 15 hours or more per week playing video games, which would within two weeks surpass the amount of our participants' training. This possibility is consistent with results from cross-sectional studies that directly compared video game and non-video game players, and training studies that investigated effects of video game training in the laboratory (Bediou et al., 2018; Chopin et al., 2019). That said, we note that multiple studies that did report improvement in visual skills trained with AVGs for only about 10 hours, although the visual skills addressed were not at the same low-level as motion discrimination (Gozli et al., 2014; Green & Bavelier, 2003, 2006). One study that did address motion discrimination did not find any improvement in discrimination sensitivity d'; they instead found greater reduction in reaction time than controls (Green, Pouget, et al., 2010). However, in the current study, we could not find a similarly large reduction in reaction times for our video game training group, compared to the controls. We do not have an explanation regarding this discrepancy.

2. The second possibility is that AVG training could not transfer to low-level VPL, no matter how long training took. After all, the varied learning remains a theory that may or may not apply to visual perceptual or other kinds of learning (Willey & Liu, 2018). It remains possible that motion perceptual learning, as studied currently, was primarily template learning and untransferable from higher-level, rule-based learning. Similar lack of transfer had been found in prior studies that compared AVG training with various control conditions, although none of the prior research has tested motion direction discrimination (Basak et al., 2008; Boot et al., 2008; Lee et al., 2012).

Finally, the current study was set out to quantify the relative amount of transfer to low-level visual perceptual tasks from AVG training, under the assumption that AVG training could indeed transfer. Such an assumption was made as a result of numerous studies claiming transfer from AVG training, particularly to psychophysics tasks (Bejjanki et al., 2014; R. Li et al., 2009). Nevertheless, such an assumption remained an assumption until verified empirically in our specific case. Ideally, therefore, three groups of participants, including controls in addition to game and psychophysics groups, could be tested simultaneously. In practice, however, doing so would have been cost prohibitive, particularly since active controls were requested, i.e., controls trained with non-AVGs such as *Tetris*.

Ultimately, due to ambiguous results from the AVG training group, controls were added to verify whether the improved performance from the group above was simply due to test retest, and unrelated to any transfer. Due to the same cost constraint, the controls could only be no-contact, namely no training, and was a smaller sample size than the other two groups. Here we address two objections against this use of the control.

1. One objection was that such controls were below standards in AVG literature, in demand characteristics, and placebo/expectation effects. This objection appeared to suggest that no-contact controls could only give rise to minimal change in performance from pre- to post-test, thereby underestimating the “true” control effect. However, our experimental evidence indicated that such test-retest measurement already matched the full effect the active experimental group of action video gamers could offer. Therefore, any possible effects due to demand characteristics and placebo/expectation must be negligible, in our case.

2. Another objection was that, should a group (here, the controls) be selected after, rather than simultaneously, other groups, random selection would be compromised. We had already found10, however, whether a group was selected simultaneously (e.g., in the fall semester) with another group such that random assignment was enable, or a group was selected (e.g., in the spring semester) after another group made little difference, when everything else was held unchanged. It appeared that, at least in the study's context with visual psychophysical perceptual learning, high-level factors such as demand characteristics and placebo/expectation effects played a minimal role.

After 20 hours of playing a first-person shooter video game, participants transferred little of this learning to a motion discrimination task. It remains to be seen whether playing video games may benefit other low-level visual skills. This study added to the body of evidence suggesting that despite their broad benefits to other visual skills, video games may be limited in expanding to benefiting low-level visual perception.

Some studies have already used prior research expanding on the many benefits of playing video games to explore the use of video games therapeutically, for treating conditions with visual aspects such as amblyopia (Jeon et al., 2012; R. W. Li et al., 2011, 2015) or dyslexia (Franceschini et al., 2013, 2017). These studies have generally found promising results, such that video game training improved visual skills that are impaired in these conditions. Thus, video games have the potential to significantly affect vision, but the mechanism by which they do so does not affect low-level vision. Therefore, while our results suggest video games are limited in the extent to which they transfer, they also provide further evidence to narrow down the mechanism by which video games are able to affect visual learning.

Chapter 4: Testing location transfer of visual learning from action video games

Abstract

Video games have been found to be beneficial not only for a wide range of visual skills, but also across both peripheral and central vision. This is surprising, given that the typical video game screen subtends only around 15 degrees from the center of the player's visual field (Green & Bavelier, 2007), suggesting that video games may transfer to untrained regions of the visual field. Given that such location transfer is not typical of visual perceptual learning studies, we investigated whether playing an action video game (AVG) would transfer to untrained regions of the visual field. Furthermore, we aimed to replicate AVG transfer to a visual crowding task used in prior video game research. We found that AVG training did not transfer to either of the visual tasks used, suggesting that AVGs may in fact be limited in their ability to transfer to lower-level vision.

Introduction

Since the publication of the seminal study by Green & Bavelier (2003), action video games (AVGs) have become one of the most promising tools to induce generalized or transferable learning (for reviews see Bavelier & Green, 2019; Green et al., 2010; Oei & Patterson, 2014). This first study reported that video game players (VGPs) performed better on a variety of visual tasks than non-video game players (NVGPs). Furthermore, they also reported that training naive participants (specifically NVGPs) with 10 hours of an AVG was sufficient for significant improvement in their visual skills. This field has only become more relevant as video games have become much more accessible and popular as a form of entertainment in the two decades since Green & Bavelier's publication. Research has shown that action video games transfer to attentional, cognitive, and, remarkably, perceptual tasks.

That laboratory perceptual tasks can benefit from AVGs is remarkable because, perhaps more than any tasks in attention and cognition, perceptual learning has been shown for decades to be highly stimulus specific (Ball & Sekuler, 1982; Fahle, 1997; Shiu & Pashler, 1992). That is to say, classic visual perceptual learning (VPL) studies have found that learning was highly specific, and did not transfer from a trained stimulus attribute (e.g., vertical orientation) to an untrained attribute (e.g., horizontal orientation). However, AVG training has been found to facilitate orientation discrimination (Bejjanki et al., 2014), and to enhance contrast sensitivity function (Li et al., 2009) (see also commentary in Caplovitz & Kastner, 2009). These two basic perceptual functions, namely orientation discrimination and contrast sensitivity function, have been traditionally considered as "low-level" vision with little chance of receiving transfer of learning from any other stimuli or tasks. In this sense, the findings that AVGs transferred to these two perceptual tasks were highly remarkable.

Another highly specific aspect of perceptual learning is retinal location specificity. Similar to stimulus specificity, classic VPL studies have found that learning does not transfer from a trained retinal location to an untrained retinal location (Ball & Sekuler, 1987; Karni & Sagi, 1991; Shiu & Pashler, 1992). For example, learning from an orientation discrimination task where the stimuli are located in the upper left visual field does not transfer to the same orientation discrimination task where the stimuli are located in the lower right visual field. However, multiple studies have found that AVG training improves visual skills across the visual field, including peripheral eccentricities that surpass the typical visual field area typically used in video game play. Green & Bavelier (2007) reports, for example, that the typical video game player in their study played games on screens that occupies up to 15 degrees eccentricity from the center of their visual field. In contrast, video game training has been reported to improve vision at eccentricities up to 30 degrees (Green & Bavelier, 2003; Sungur & Boduroglu, 2012; S. Wu et al., 2012). Video game training may therefore be enhancing vision in untrained peripheral visual fields; in other words, demonstrating retinal location transfer from central to peripheral vision.

However, there are also findings contrary to the above claims, including some from the same research group. For example, Green et al. (2010) found in a random dot motion discrimination task that VGPs and NVGPs shared comparable discrimination accuracies, although the VGPs were faster in their responses. Yet, in motion perception and learning research, discrimination sensitivities or accuracies have been more often used as the behavioral measure of choice rather than response latencies (Ball & Sekuler, 1980). While Li et al. (2011) found improvements for amblyopic adults trained with video games, no difference was found between AVG and non-AVG training. This finding differs from studies with dyslexic children

(Franceschini et al., 2013, 2017), which found that AVG training led to more improvement in reading speed (with comparable accuracy) than non-AVG training. More recently, Hilgard et al. (2019) suggested that the effect of facilitation from AVGs to cognitive tasks may be overestimated, in that publication bias causes only positive results to get published whereas negative ones do not.

It is clear that there is still debate over the extent to which video games can transfer to vision. Many video game studies have compared VGPs to NVGPs, and found an advantage for the VGPs in a variety of skills, including attentional blink (R. W. Li et al., 2015), visual search (Bavelier et al., 2012) , visual short term memory (Blacker & Curby, 2013; Huang et al., 2017; Sungur & Boduroglu, 2012), useful field of vision (UFOV) (Blacker et al., 2014; Dale et al., 2019), object tracking (Dale et al., 2019; Trick et al., 2005), and mental rotation (Basak et al., 2008; Terlecki & Newcombe, 2005). However, these studies are limited to correlational conclusions, which is why training studies are so important, where NVGP participants are trained on a video game and tested pre- and post-training to assess the causal effect of video games on visual skills. The results of these training studies is mixed, with some studies reporting successful transfer of video game training to a variety of visual skills (e.g. Dye et al., 2009; Green & Bavelier, 2003; Hutchinson et al., 2016), while others report no significant transfer of video game training (Boot et al., 2008; van Ravenzwaaij et al., 2014). Furthermore, while the phenomenon of video game transfer to lower-level perceptual skills is remarkable, it has only been reported in a few studies that we described earlier.

Therefore, the current study was motivated to address this controversy over the extent to which AVGs can be identified as a causal factor for widely generalizable visual learning, specifically for perceptual skills. In particular, we focused on the issue of retinal positional specificity that has been found in the literature by traditional methods (e.g. Shiu & Pashler, 1992) but was found to be overcome by AVG training (Green & Bavelier, 2003). Accordingly, we selected two psychophysical tasks.

The first task we used is a visual crowding task based on the task used in Green & Bavelier (2007). Visual crowding is a measure of spatial resolution of vision, and refers to the phenomenon wherein a stimulus is more difficult to discriminate when distractor stimuli are present in the same visual region as the target stimulus. There is debate over the neural mechanisms behind visual crowding, ranging from lateral interactions between neurons in the visual cortex (e.g. Polat & Sagi, 1994) to limits of resolution in visual attention (Tripathy & Cavanagh, 2002). Therefore, visual crowding provides a representative mid-level visual task for our study. The previous study that we based our task on (Green & Bavelier, 2007) also reported an increase in visuospatial resolution after AVG training, and we aimed to replicate that effect in our study.

The second task selected for our study is an orientation discrimination task based on the paradigm used in Bejjanki et al. (2014) with precedent from Lu & Dosher (2004). As one of the only low-level perceptual tasks with published evidence of video game training transfer, their version of the orientation discrimination task is ideal for use in our study. Orientation discrimination is also a representative low-level perceptual skill that has long been studied in VPL research, and has been reported to be stimulus-specific (Fahle, 1997; Fiorentini & Berardi, 1981; Schoups et al., 1995). We therefore opted to test this skill given that it has both previously been used to show specificity of learning and it has been shown to benefit from video game training.

Our participants were tested on these two tasks before and after training on an AVG; specifically, a first-person shooter (FPS) game. In order to test transferability of video game training across retinal position, diagonal quadrants of the screen were covered during training, to create both trained and untrained quadrants of the visual field. Psychophysical tasks were modified in order to distinguish performance between trained and untrained regions of the visual field. We hypothesized that video game training would transfer to both psychophysical tasks, in both trained and untrained quadrants of the visual field, resulting in significant improvement in all test tasks and locations after training.

Methods

Tasks

Two psychophysical tasks were used in the current study. They served to measure behavioral performance before and after video game training. Training was on two diagonal quadrants of the visual field, whereas the remaining quadrants served as the transfer condition. In a given task, identical stimuli were presented in two diagonal quadrants, with one pair of quadrants serving as the trained region of the visual field, and the other pair serving as the transfer region.

1. Crowding: discriminating whether a target T was upright or inverted, which was flanked by a distractor T above and a distractor T below.
2. Orientation discrimination: a Gabor was shown in two possible orientations for the participant to discriminate.

Stimuli

T-flanker crowding. The stimuli and task were adopted from Green & Bavelier (2007). The participant was presented with a target T and two distractor T's directly above and below the target, respectively. One difference from the original study was that two identical sets of triplet T's were presented in two diagonal quadrants, one set in each quadrant. In a given trial, both distractor T's and the target T were randomly oriented to be upright or inverted. The target T was 10° away from the fixation. The color of the T stimulus was black, and the line width was 2 pixels (3.72 min in visual angle). A red 1.5° fixation cross was present at the center of the screen in each trial.

Orientation discrimination. The stimuli and task were adopted from Bejjanki et al. (2014). The target stimulus was a Gabor, 2° in diameter rather than the original 1.5°, presented 5° away from the fixation. The same stimulus was presented in two diagonal quadrants simultaneously in each trial. The central frequency of the Gabor was 1.34 c/deg. In each trial, the Gabor was randomly tilted 2° clockwise or counterclockwise from horizontal. The Gabor was presented sandwiched temporally between visual noise stimuli. The visual noise stimuli were generated with pixel contrasts drawn from a Gaussian distribution. The noise was filtered with a band-pass from one octave below to one octave above the central frequency of the Gabors. Each element of the noise stimulus measured 2 x 2 pixels. The final noise stimulus was viewed through a circular mask measuring the same size as the Gabor stimulus in order to prevent explicit angle cues. The visual noise was set at the average value of the contrast levels used in Bejjanki et al. (2014), i.e., average of 0.083 and 0.124 = 0.104. In each trial, a red 0.5° fixation cross was presented at the center of the screen.

Procedure

The order of the two tasks was randomized between participants, but remained unchanged from pre- to post-test for each participant. Each participant went through pre-tests, training, and post-tests. During both pre- and post-test, behavioral performance in the T-flanker crowding and orientation discrimination tasks was measured.

T-flanker crowding. The distance between each of the two distractors and their target was staircased in order to identify the participant's threshold for discriminating the orientation of the target T, upright or inverted. There were three phases to tailor stimulus parameters for each participant.

Practice. A researcher guided each participant through the practice phase, explaining the task to the participant and checking the participant's understanding of the task. In each trial, a central fixation cross was presented for 150 ms. Then a target T and its two distractor Ts were shown in one quadrant for 300 ms, and at the same time an identical copy of the three Ts were also shown in the opposite quadrant. Each T was 1° in visual angle. Whether the quadrants were I & III or II & IV was randomized. The participant was given unlimited time to indicate the perceived orientation of the target T by a key press. Feedback lasting 200 ms was provided in the form of text and a tone for a correct response, or text only for an incorrect response.

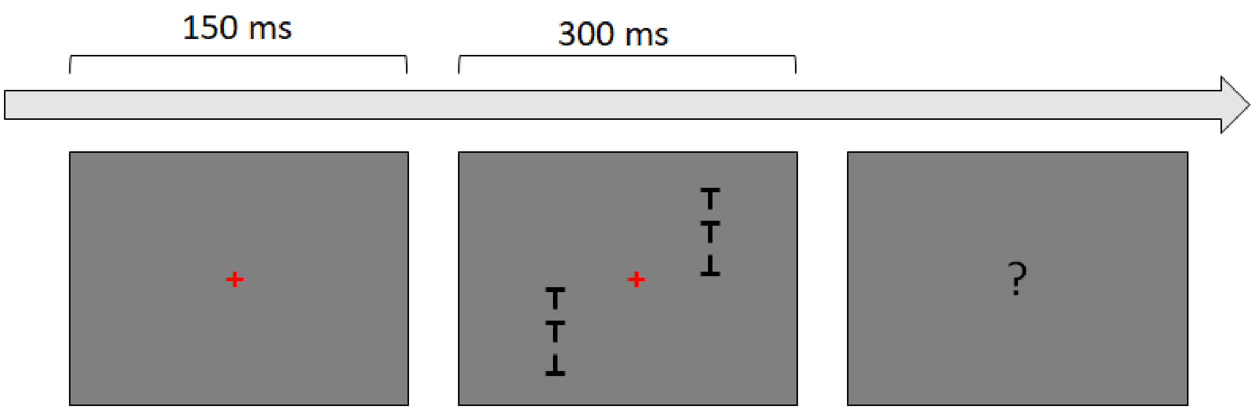
Practice started with a 3° inter-T distance, in 20 trial blocks. If 80% accuracy was not achievable after three blocks, then practice stopped when at least 70% accuracy was obtained. No participant failed to reach this 70% accuracy.

Otherwise, if at least 80% accuracy was achieved within three blocks for 3°, the inter-T distance was reduced to 2°. If the accuracy was below 70% after three blocks, practice stopped. If at least 80% accuracy was achieved within three blocks with 2°, the inter-T distance was further reduced to 1.5°, and three more blocks were run.

T size adjustment. Only the two target Ts, without their distractors, were presented in two opposing quadrants and their size adjusted in staircases to find a threshold that gave rise to 70.71% correct discrimination. The step size for each staircase was 5%. There were four staircases, two for each pair of quadrants. Each staircase consisted of 50 trials. The targets were presented for 100 ms in each trial.

The average threshold from these four staircases (after excluding the first four reversals in each staircase) was then multiplied by 1.5, and the resultant size was used for all Ts in the subsequent phase.

Figure 11: A typical trial in the T-flanker crowding task



Note. In every trial of the practice and staircase phases, a fixation cross was presented, followed by three vertically stacked T stimuli in two diagonal quadrants. The center T was the target, and the top and bottom Ts were distractors. All three Ts were randomly oriented upright or inverted. The T stimuli were identical between the two quadrants. After stimuli presentation, the participant responded with the perceived orientation of the target T, and received feedback before the next trial.

Inter-T distance adjustment. Everything was similar to the above, except the following. The distractor Ts were now added back. Each of the four staircases followed a one up, three down procedure to give rise to a 79.37% correct discrimination. Each staircase consisted of 200 trials. An example of a typical trial used in practice and in this staircase phase is depicted in Figure 11.

Orientation discrimination. This task was adopted from Bejjanki et al. (2014). In the original task, a Gabor was presented centrally, sandwiched temporally between visual noise of varying levels of contrast. The contrast of the Gabor was then staircased to establish a threshold for discriminating between orientations of ±2° from horizontal.

The primary difference between the original version and ours was that we presented two identical Gabors in two diagonal quadrants every trial. This allowed us to compare visual ability in either trained or untrained quadrants of the visual field. Whether stimuli appeared in Quadrants I & III or II & IV was randomized every trial.

There were three phases to this task: practice, one to tailor stimulus parameters for each participant, and the primary experimental measure, as follows.

Practice. Practice trials were conducted with active guidance from a researcher, who explained the task to the participant and checked for participant understanding of the task by asking the participant to explain the task to them. Twenty practice trials were used, with a high Gabor contrast of 0.8 in order to ensure that stimuli were highly visible to the participants while learning the task. In each trial, a fixation cross was presented centrally for 300 ms. Then, with the fixation remaining on the screen, a noise stimulus appeared in two diagonal quadrants for 100 ms, followed by a target Gabor oriented tilted from horizontal for 100 ms, followed by another noise stimulus for 100 ms. Participants were given unlimited time to indicate the perceived orientation of the Gabor with a keypress. Feedback was provided in the form of text and a tone for correct responses, and text only for incorrect responses for 200 ms.

The participant started practice with a Gabor tilted ±5° from horizontal, in blocks of 20 trials. If the participant took more than three blocks to achieve at least 70% accuracy, then practice was continued until they achieved 70% accuracy, and then practice was stopped and 5° would be used in the next phase. Note that all participants were able to achieve 70% accuracy or higher within one test session on the 5° condition.

On the other hand, if the participant was able to achieve 80% accuracy within three blocks of 5° practice, then the Gabor tilt was reduced to 3°. With this 3°, if the participant was able to reach 80% accuracy within three blocks, the Gabor tilt was reduced to 2°. Otherwise, if the participant was able to reach 70% accuracy or higher within three blocks, they would not continue practice, but would use 3° as their degree tilt condition in subsequent experimental phases. If the participant was unable to reach 70% or higher with 3°, then practice stopped after 3 runs and 5° was used as the degree tilt condition in subsequent phases of the experiment.

Finally, if the participant was able to achieve 70% accuracy within 3 blocks of running the 2° tilt condition, practice stopped upon achieving this accuracy and 2° was used as the degree tilt condition in subsequent phases of the experiment. Otherwise, if the participant was unable to reach 70% accuracy within 3 blocks of the 2° condition, practice stopped, and 3° was used as the degree tilt condition in subsequent phases of the experiment.

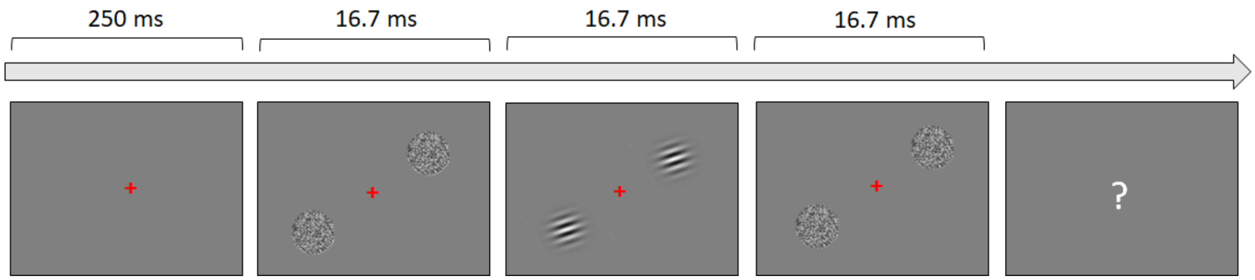
The degrees of tilt used in the test trials of the orientation discrimination task were based on how far participants were able to get in practice trials. If a participant was able to achieve 70% accuracy or higher on the last tilt condition they practiced, that value was used as their test value. However, if the participant was unable to achieve that threshold, then the tilt condition that was one level of difficulty easier than their last practiced tilt condition was used. For example, a participant who could not achieve above 70% accuracy for the 3° tilt condition would be assigned 5° as their test value, whereas a participant who achieved between 70% and 80% accuracy for the same 3°condition in 3 runs (e.g. did not move on to the next difficulty level of 2°) would be assigned 3° as their test value.

Calibration. The contrast of the Gabor itself was staircased for 70.71% accuracy (1 up 2 down). We used four interleaved staircases, two for quadrants I & III and two for quadrants II & IV, with 50 trials per staircase.

In each trial, a central fixation cross was presented for 250 ms, followed by the two Gabors, each of which was temporally sandwiched by visual noise. Each of the three target stimuli was presented for 1/60 sec. The orientation of the Gabor could be ±2°, ±3°, or ±5° from orientation, depending on the results of the calibration phase. The participant responded with the perceived direction of the orientation shown via a keypress, and was given unlimited time to respond. Feedback was provided in the same format as in the practice phase. The mean contrast threshold from the four staircases (excluding the first four reversals for each staircase) was used in all subsequent trials.

Main experiment. The participant completed 720 trials of the same task used in the calibration phase. Quadrant pair and Gabor orientation were randomly selected in each trial. An example sequence of events for a practice or experimental phase trial can be seen in Figure 12. Proportion correct in orientation discrimination was the measure of performance in Quadrants I & III and II & IV, respectively.

Figure 12: Example trial for the orientation discrimination task



Note. Participants saw a Gabor stimulus sandwiched between two noise stimuli to create a temporally integrated stimulus of a Gabor in external noise. The stimuli were presented randomly in one of two possible diagonal quadrant pairs. The stimuli presented in the two quadrants were always identical. Participants were asked to identify the orientation of the Gabor stimulus. Feedback was provided every trial.

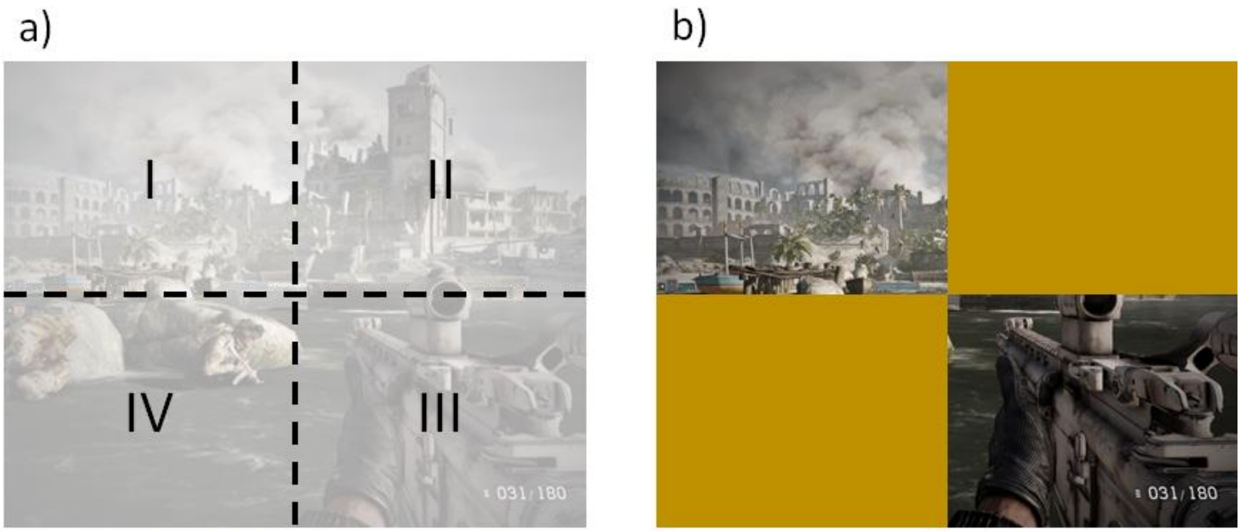
Training

The video game used for training was *Medal of Honor: Warfighter* (Electronic Arts Inc., 2012). It was chosen as a more recent version of a game from the same series used in prior video games and visual learning research (Feng et al., 2007, p. 20; R. W. Li et al., 2011, 2015; S. Wu et al., 2012, p. 20; S. Wu & Spence, 2013), *Medal of Honor: Pacific Assault* (Electronic Arts Inc., 2004). The more recent version was used for OS compatibility reasons with our computers and eyetracker in the laboratory.

The most important aspect of this game series, nevertheless, remained unchanged. Namely, this was a FPS game. In other words, the field of view in the game was meant to simulate the view as if the game player were inhabiting the game character. Thus, a game player was only viewing the character's hands and whatever they were holding at any given moment. The field of view in the game was relatively narrow, requiring frequent movement of the computer mouse to move the character's "head" in order to properly survey the game environment. Furthermore, as a shooter game, the player must frequently move their field of view in order to properly identify, aim at, and hit targets, such as enemies.

During training, in order to ensure participants only trained their assigned visual field quadrants, the two untrained diagonal quadrants were blocked with a cardboard cover, as shown in Figure 13. It took about eight weeks for a participant to complete the entire experiment. Training took place in the lab. On average, training sessions occurred three times per week, one hour per session.

Figure 13. Example video game screenshots



Note. a) The computer monitor used to play the video game was divided into four quadrants. Participants were randomly assigned a pair of diagonal quadrants to train on (I & III or II & IV). b) The quadrant pair designated as untrained were covered during the entirety of training.

Post-test

The main experiment of each of the two tasks in pre-test was repeated in post-test, with the order of tasks preserved for each participant. The tasks were identical to pre-test, with one major difference. Participants completed the post-test without the same intensive guided practice from the pre-test. Instead, participants merely completed a short practice phase for each task to ensure they recalled the task.

For the crowding task, practice trials were identical to those used in the practice phase in pre-test, but there were 24 trials. The distance between distractor and target stimuli was gradually decreased every 8 trials in these practice trials in order to gradually re-introduce participants to the difficulty of the task. The distances used were 1°, 0.5°, and 0.3°.

For the orientation discrimination task, practice trials were identical to those in the practice phase from pre-test, but only 12 trials were used. The degrees of orientation tilt used in these practice trials was identical to the degree of tilt used in pre-test for each participant.

In these post-tests, calibration phases were repeated as in the pre-tests. This was a direct replication of the procedure used in Green & Bavelier (2007), but may confound any learning results, because visual learning may take the form of an improved calibration (e.g. a smaller T stimulus size or lower Gabor contrast) rather than improvement in the target measure (e.g. decreased distance threshold between target and distractor stimuli, or higher orientation discrimination accuracy). Therefore, a second round of post-tests were conducted in order to disentangle these effects. This additional round of post-tests were identical to the previous post-tests, except that the calibration phase was removed. Instead, each participant's pre-test calibration values were used to conduct the additional tests.

Eye tracking

Eye tracking was carried out throughout the experiment for each participant. Namely, in each session, the participant would undergo eye tracker calibration, by using the iViewRED software (SensoMotoric Instruments) as follows. The participant was asked to track a moving dot on the screen without moving their head. After calibration, tracking a moving dot on the screen was done once more as a validation process. If there were any issues with calibration or validation, as indicated by the program, the steps above would be repeated.

During pre- and post-test tasks, eye tracking was used to ensure consistent and proper fixation. The eye tracking code was integrated into the test programs in PsychoPy. For the orientation discrimination task specifically, if participant gaze left a central fixation square of size 5°, the program required them to redo that same trial. Any repeated trials, and not the trials with faulty fixation, were used in data analysis for this task. We were unable to utilize this paradigm with the T flanker task due to the staircase paradigm preventing the same coding method used with the orientation discrimination task.

During video game training, a custom program in Python was used to track eye movement. If the player's gaze moved away from a central fixation square of size 5°, the video game would pause and only resume when the participant's gaze returned to this fixation square.

Apparatus

The eyetracker used in this study was the SMI iViewRed (SensoriMotor Instruments). A Sony CPD-E540 Trinitron CRT display was also used with a resolution of 1280 x 1024 pixels. The diagonal length of the display was 20 inches; therefore a pixel extended 1.86 min in visual angle. The refresh rate was 60 Hz. The viewing distance was 57 cm.

Participants

Ten undergraduate students, six female and four male (M_{age} = 20.7 years), participated as partial fulfillment of research credits. They had a variety of video game playing backgrounds, with 3 participants having no video game experience in the past year, one participant who played games but reported less than 20 hours gaming in the past year, and six participants who reported significant hours spent gaming in the past year (>50 hours). Of the six gamer participants, three did not report having played FPS games in the past year. For the three remaining participants, some examples of games that were considered FPS games included *Valorant*, *Apex Legends*, and

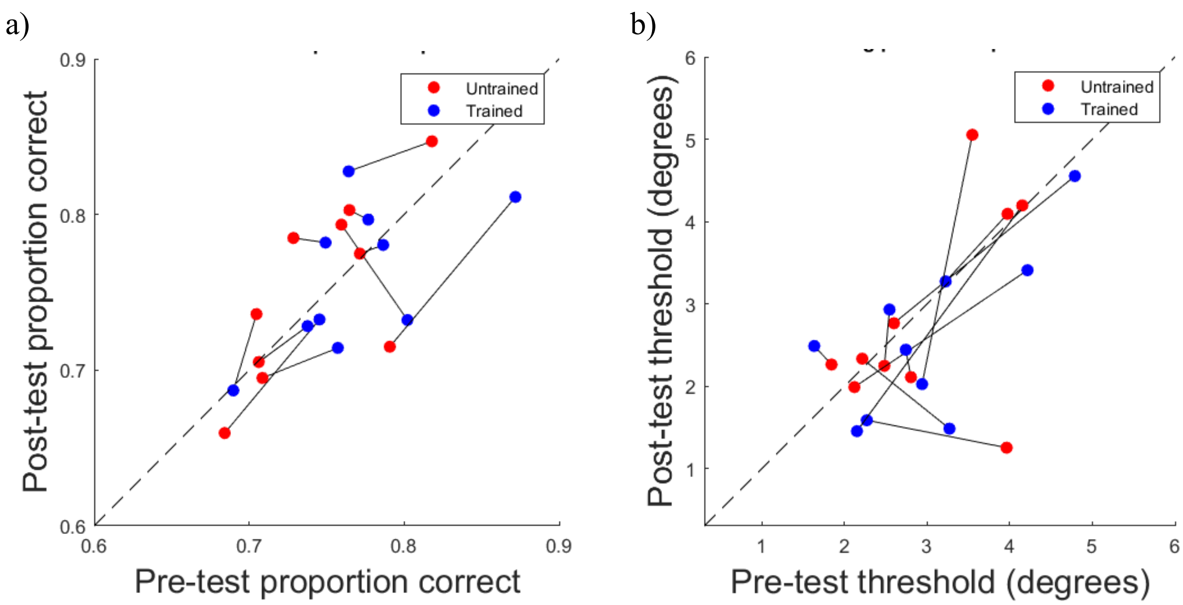
Starfield. Note that some participants reported games that are considered to have action components but do not contain the same rapid changes in field of view or need for rapid and accurate responses in the same way as FPS games. Some examples of this category include *Legend of Zelda: Breath of the Wild* and *Minecraft*.

Video game experience was determined based on a survey administered to all participants prior to beginning the study. Participants were asked to describe any video game experience from the past year on five video game platforms of interest: consoles typically used with a monitor (e.g. a Playstation); handheld consoles (e.g. a Nintendo Switch); personal computers; smartphones or tablets; and virtual reality devices. For each platform, participants reported frequency of playing games per week, number of hours per gaming session, and up to five games typically played.

Results

Figure 14 shows the primary results from both tests, comparing the pre-test to the first round of post-tests. Unexpectedly, there was no transfer from video gaming to the two psychophysical tasks in the trained quadrants. Subsequently, it is unsurprising that no transfer was observed to the untrained quadrants either. A 2 x 2 ANOVA (type III) with time (pre, post) and visual quadrants (trained, untrained) as within-subjects variables confirmed these observations. There were no main effects or interaction effects for the orientation discrimination task ($F(1, 9) = 0.003$, $p = 0.96$; $F(1, 9) = 1.64$, $p = 0.23$; $F(1, 9) = 1.95$, $p = 0.20$). Similarly, for the T-flanker crowding task, both main effects and the interaction were non-significant ($F(1, 9) = 1.76$, $p = .22$; $F(1, 9) = 0.088$, $p = 0.77$, $F(1, 9) = 0.46$, $p = 0.52$). Figure 15 depicts the interaction between test time and quadrant conditions. Note that the post-test data used in this analysis was from the first post-tests conducted, which included an additional calibration.

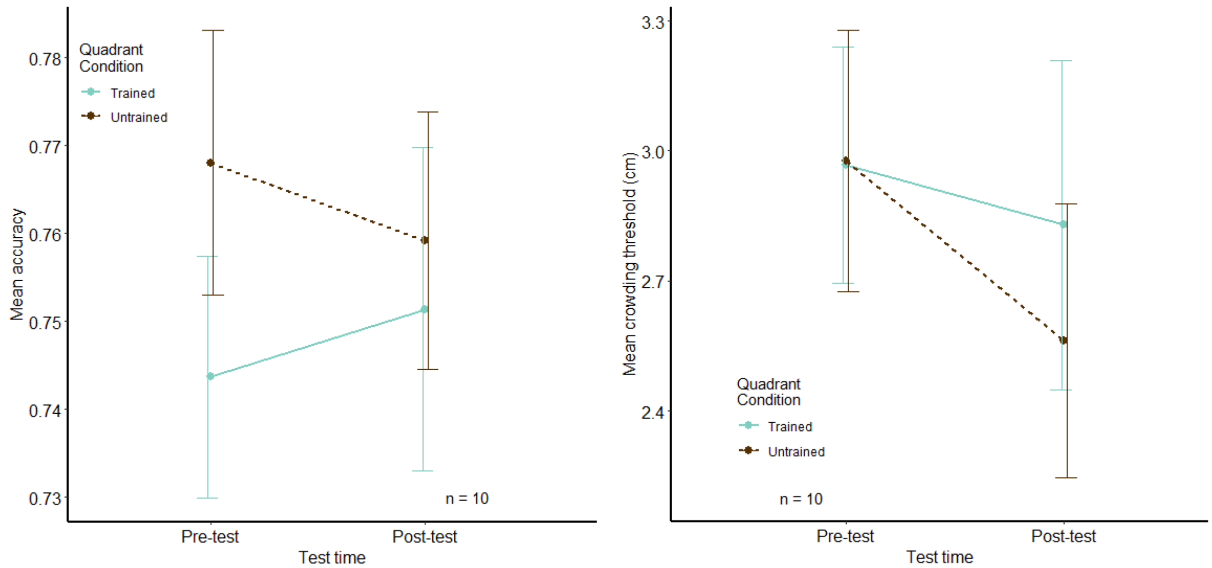
Figure 14: Pre-test vs post-test performance



Note. Performance before and after 20 hours of action video game training by 10 participants with a range of gaming experience. The stimuli were exactly the same pre- and post-test, for a given participant. A) Orientation discrimination accuracies for the trained (blue) and untrained quadrants (red). These two data points from each participant were connected by a solid line. The dashed line represents equal pre- and post-training performance. B) Upright or inverted T orientation discrimination thresholds in the T-flanker crowding test.

Figure 15: Task performance by test time and trained quadrant

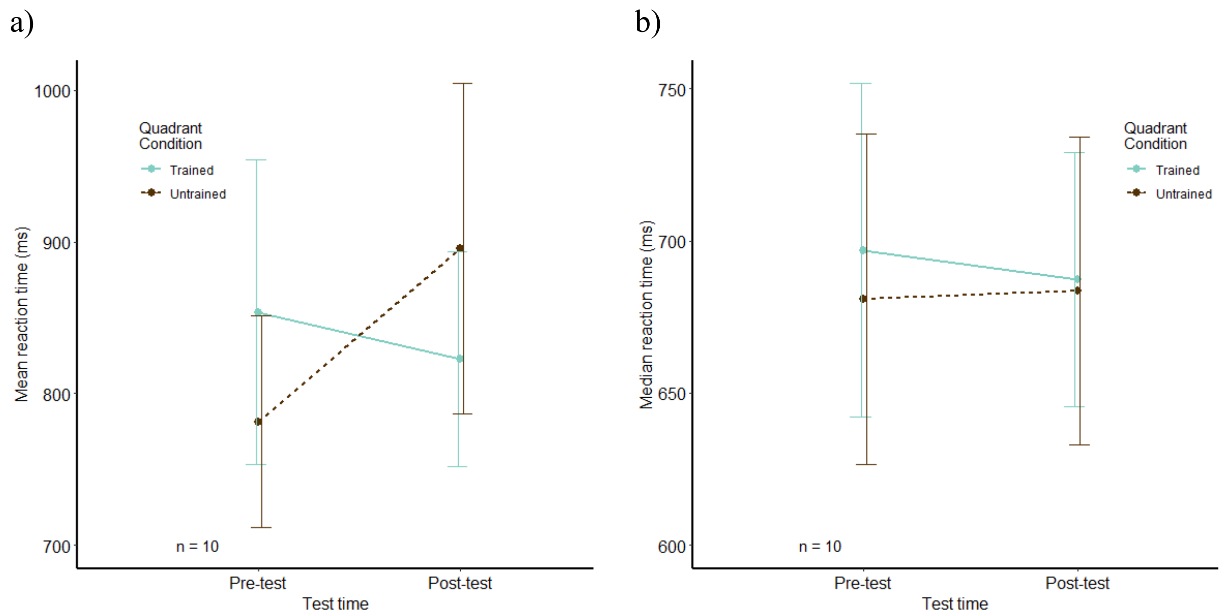
a) b)



Note. Results of the two psychophysics tasks are shown, separated by trained vs untrained quadrants at each test point. Error bars represent ±1 standard error. A) Mean accuracy on the orientation discrimination task are shown. There was no significant difference between quadrant conditions at either test point, nor was there significant improvement in accuracy from pre- to post-test. B) Crowding thresholds from the T-flanker crowding task are shown. The only significant change was overall reduction of thresholds from pre- to post-test. Thresholds in trained quadrants were not significantly different from those in untrained quadrants at either testing point.

We also considered the possibility for the orientation discrimination task that our participants may have experienced learning that is only observable as faster reaction time, rather than increased accuracy. Many video game studies have reported the advantage of playing action games as taking the form of reaction time rather than accuracy (e.g. Green et al., 2010, 2012; Mack & Ilg, 2014; Wu & Spence, 2013). Therefore, we conducted a repeated-measures ANOVA on mean reaction time data for the orientation discrimination task. We did not find any statistically significant effects ($F(1, 9) = 0.43$, $p = .53$; $F(1, 9) = 0.00008$, $p = .99$; $F(1, 9) = 3.59$, $p = .09$). We also conducted a repeated-measures ANOVA on median reaction time data, as it better accounts for outliers. We found a statistically significant main effect of time, suggesting that our participants did in fact experience some improvement in task speed after training ($F(1,9) = 15.09, p < .01$), as seen in Figure 16. However, we did not find a significant main effect of trained quadrant or an interaction between trained quadrant and time ($F(1,9) = 2.53, p = .15$; $F(1,9) = 1.69, p = .23$).

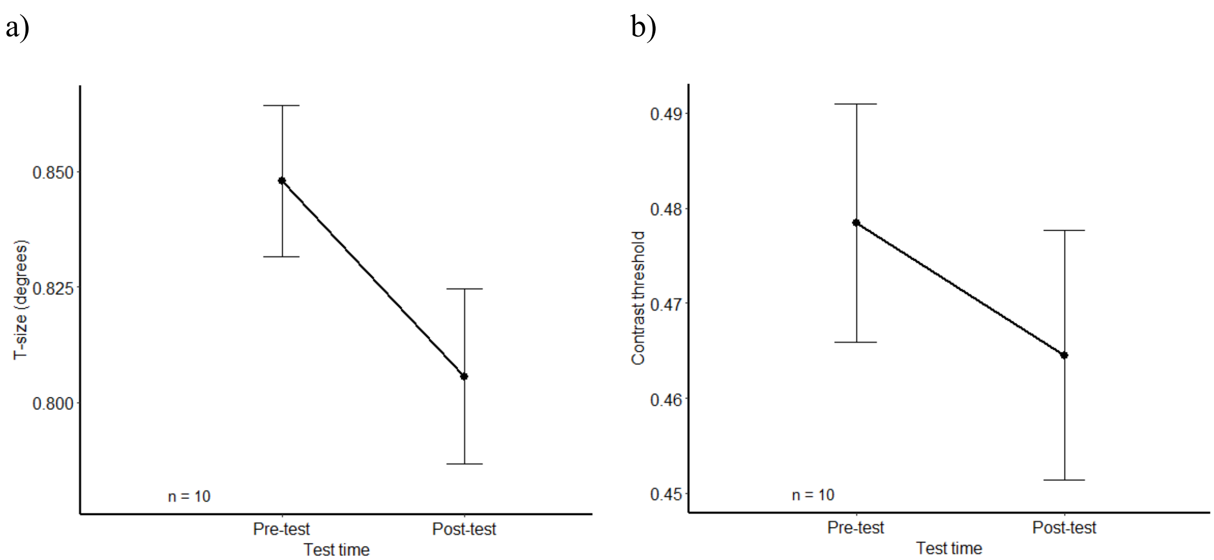
Figure 16: Improvement in reaction time for orientation discrimination



Note. Participants showed no significant change in reaction time from pre- to post-test, regardless of quadrant condition tested or data aggregation method used. A) Mean reaction time data. B) Median reaction time data.

An additional analysis compared change in T-size from the calibration phase of the crowding task, pre- to post-training, utilizing data from the first set of post-tests. This comparison was motivated by those done in Green & Bavelier (2007), where the calibration phase was replicated in both pre- and post-tests. While we did not observe a change in thresholds in our participants, some learning may have occurred that could be captured in this measure. A paired-sample t-test showed that there was no significant change in T-size from pre- to post-training ($t(9) = 1.82$, $p = 0.10$), although participants did generally reduce T-size after video game training. Similarly, the 70.71% contrast threshold from the calibration phase of the orientation discrimination task was compared from pre-test to the first set of post-tests. A paired-sample t-test reveals that there was no significant change in contrast threshold from pre- to post-training ($t(9) = 0.90$, $p = .39$) in the orientation discrimination task either (see Figure 17).

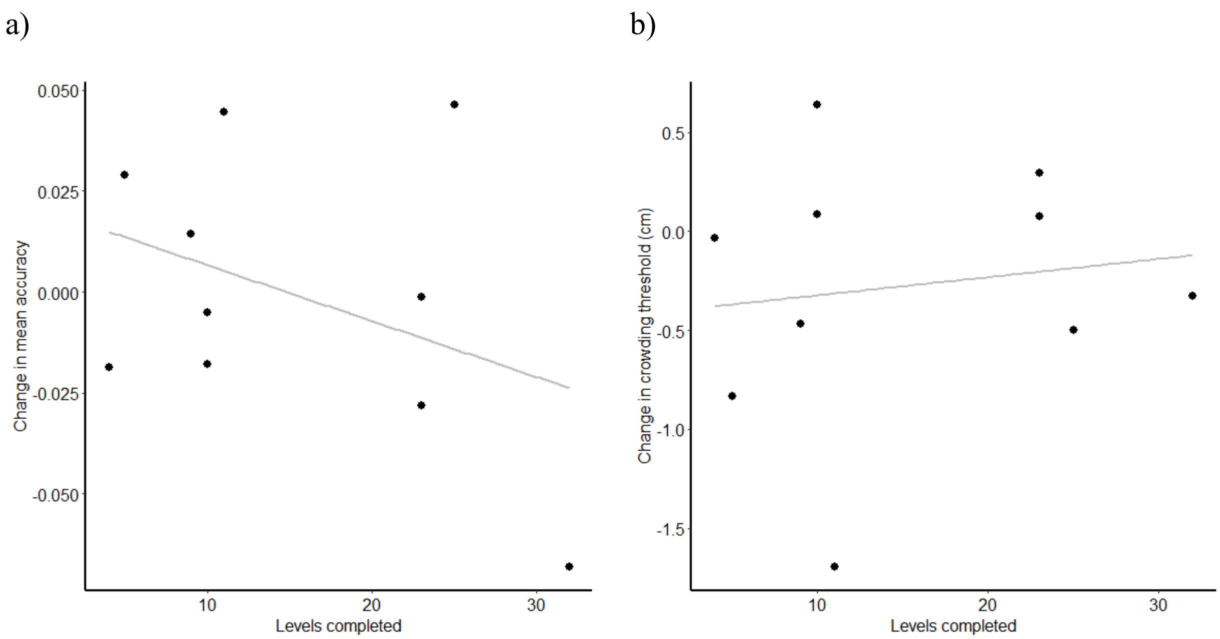
Figure 17: Change in calibration values from pre- to post-test



Note. Participants completed calibration of T size (for the crowding task) or contrast threshold (for the orientation discrimination task) in diagonal quadrants in pre-tests and the first round of post-tests with a 70% staircase. a) T size decreased from pre- to post-training, but the difference was not statistically significant. b) Contrast threshold did not significantly change from pre- to post-training.

Finally, we were interested in observing whether there was any relationship between video game training performance and level of improvement in either of the psychophysical tasks used. The measure of video game performance used was the number of game levels completed by each participant over the course of training. Game progress was compared to change in psychophysical performance in trained and untrained quadrants. No correlations were statistically significant for either the T-flanker crowding task ($t(8) = 0.31$, $p = .76$; $t(8) = 0.23$, $p = .82$) or the orientation discrimination task ($t(8) = -1.76$, $p = .12$; $t(8) = -0.43$, $p = .68$) (Figure 18).

Figure 18: Correlation between video game training and test improvement



Note. Correlation plots comparing levels completed in the video game over the course of training to change in psychophysics task performance. Neither correlation was statistically significant. A) Number of levels completed compared to change in mean accuracy for the orientation task. B) Number of levels completed compared to change in crowding threshold for the T flanker crowding task.

Additional post-test data

As previously described, we collected a second set of post-test data in order to investigate participant learning that may have been obscured by the calibration process that was repeated in the first set of post-tests. Therefore, in this second set of post-tests we used calibration values from the pre-tests instead. However, due to the nature of our data collection, the results of the second post-tests cannot be completely disentangled from potential test-retest effect, given that our participants had already experienced additional practice with the test tasks in the first post-test.

For the orientation discrimination task, a 2x2 repeated-measures ANOVA comparing pre-test data to the second set of post-test data once again did not produce any significant results ($F(1, 9) = 0.52$, $p = .49$; $F(1, 9) = 2.12$, $p = .18$; $F(1, 9) = 2.70$, $p = .14$). An additional ANOVA comparing median reaction time data from pre-test to the second set of post-tests only revealed a statistically significant main effect of test session ($F(1, 9) = 15.09$, $p = .004$). However, the other main effect of trained quadrant and the interaction were not significant ($F(1, 9) = 2.54$, $p = .15$; $F(1, 9) = 1.69$, $p = .23$).

As for the T flanker crowding task, a 2x2 repeated-measures ANOVA comparing pre-test to the second post-test crowding thresholds revealed a significant main effect of test session ($F(1, 9) = 7.18$, $p = .025$), but no significant main effect of trained quadrant or interaction ($F(1, 9) = 0.12$, $p = .74$; $F(1, 9) = 0.94$, $p = .36$).

Eyetracker fixation

A key part of this study was participant fixation on a central point in order to ensure that specific regions of the visual field were being trained or tested. We examined eyetracker data from psychophysics testing in order to determine adherence to fixation. For the T flanker crowding task, participants deviated from fixation on average 37% of the time, $SD = 34\%$. However, we noted that our participants could be separated into those who deviated from fixation about 25% of the time or less ($n = 6$) and those who deviated from fixation 67% of the time or more ($n = 4$). A comparison of the two groups clearly shows that on average, those who looked away from fixation the majority of the time in fact did not benefit from this. To further ensure that this variation in fixation did not change our conclusions, we calculated the correlation between percent deviation from fixation for this task, and change in crowding thresholds, and did not find a significant correlation ($t(8) = -0.87$, $p = .41$).

For the orientation discrimination task, a similar comparison was made for our participants, and once again, dividing participants into binary fixation categories reveals that large deviations from fixation did not benefit those participants. A correlation test between the percent deviation from fixation for the orientation discrimination task and change in accuracy once again did not produce a significant correlation ($t(8) = 0.11$, $p = .92$).

Video game experience

We conducted an exploratory analysis to examine any potential effect of prior video game experience on performance in our study. Our participants had a wide range of hours spent playing video games over the past year (ranging from 0 to 1170 hours), so a log conversion was applied to these values. A correlation analysis of the log gaming hours and change in crowding thresholds for the T flanker task was not significant ($t(8) = 1.38$, $p = .20$). Similarly, the correlation between log gaming hours and change in accuracy for the orientation discrimination task was not statistically significant ($t(8) = -1.07$, $p = .32$).

Discussion

Video games have been a promising training tool for visual learning based on research in the past two decades (Bediou et al., 2018). However, at the same time, there has been controversy over this claim due to continuous competing evidence over the existence of transfer of learning from video game training. This study therefore aimed to add to the body of evidence on the existence of a video game learning effect for vision, while also extending the investigation to lower-level visual perception, which has rarely been examined in the video game literature. In addition, we also aimed to explicitly investigate the limitations of video game visual learning in terms of location transfer, in addition to task or stimulus transfer.

We investigated our hypotheses by training participants on a FPS video game with two diagonal quadrants of the monitor obscured. Combined with eyetracker-enforced fixation during training, we ensured training of only specific regions of the visual field. Participants were tested before and after training on two low-level visual perceptual tasks: visual crowding and orientation discrimination. Surprisingly, our results suggest that participants did not experience any significant visual learning from pre- to post-test on either perceptual test. The one exception to this general result was a significant reduction of median reaction time from pre- to post-test for the orientation discrimination task.

In particular, our T flanker crowding task was designed to replicate the task used in Green & Bavelier (2007), where participants trained on an action video game demonstrated significantly more improvement in crowding thresholds at varying eccentricities from 0 to 25 degrees. However, our results contradict theirs, given that we did not find any such improvement despite our participants viewing stimuli within the eccentricity range used in Green & Bavelier's (2007) study. It is possible that our participants did not experience sufficient training to replicate previous findings, as our participants trained for 20 hours while Green & Bavelier's trained for 30. However, it seems unlikely that our participants would demonstrate no significant improvement after 20 hours of training, even if it might not match the extent reported in Green & Bavelier's (2007) publication. Interestingly, Green & Bavelier (2007) also reported that in a cross-sectional study, VGPs demonstrated smaller T-alone acuity thresholds, but that their participants trained on action games did not show any significant decrease in T-alone acuity after training. Our participants similarly did not demonstrate any significant decrease in T-alone acuity either.

There was a concern that, while the decrease in our participants' T-alone acuity was not significant, it was an observable trend. Therefore, this decrease might have obscured any learning that had occurred in the T-flanker crowding task because it might have divided improvement in the task between the T-alone size and the crowding thresholds that were the primary intended measure. A second round of post-tests was conducted to attempt to discern whether any such obscuring effect had occurred. However, the second set of post-tests primarily produced similar results to the original analyses, with the exception of one statistically significant main effect of time for the crowding task. However, given that we conducted the second set of post-tests after a first set had already occurred, we cannot determine whether test-retest effect accounts for this main effect. Future controls will need to be conducted to clarify this result. Similarly, one statistically significant main effect of time was observed from analyzing median RT data from the second round of post-tests, but once again, test-retest effect cannot be eliminated as a potential explanation for this data.

Our study was designed such that participants would serve as their own controls, such that the untrained quadrant performance could serve as comparison for the trained quadrants. Because the participants did not show any significant improvement overall, we cannot conclude whether any learning occurred due to the video game or simply due to test-retest effects. Overall, our data supports a lack of transfer from video game training to low-level visual skills.

Our results join a minority of studies that report small amounts of or no transfer from AVGs to visual skills. Only one such also looked at the effect of video game training on a perceptual skill, testing perceptual discrimination of random dot kinematograms (van Ravenzwaaij et al., 2014). Participants trained on an AVG did not show any benefit in improvement on this perceptual discrimination task, nor did they show any benefit in model parameters after data was fit to a diffusion model. Only one other cross-sectional study did not find a benefit for VGPs on a texture discrimination task (Jacques & Seitz, 2020). In the attention and executive function realm of visual task, there are only a few more studies that have reported no advantage of video game training (Basak et al., 2008; Oei & Patterson, 2014b; Sims & Mayer, 2002) or video game experience (Gobet et al., 2014; Irons et al., 2011; Unsworth et al., 2015). Such results are crucial to investigate to determine why these results are contradictory to the majority of video game research.

In the case of our particular study, it seems that AVG training may simply be limited to higher level skills, and does not affect low-level perception. This conclusion is supported by prior research, as there are not too many studies that have focused on video game transfer to visual perception rather than visual attention tasks (Bejjanki et al., 2014; Berard et al., 2015; Cretenoud et al., 2021; Green, Pouget, et al., 2010; Hutchinson & Stocks, 2013; Kim et al., 2015; R. Li et al., 2009), which leaves the overall evidence for video game transfer to visual perception as mixed. From our research, participant performance on psychophysical tasks did not support video game transfer, but we also examined correlation between participant progress in the action video game used for training, and performance on both psychophysical tasks. We did not find any relationship between video game performance and psychophysical test performance, further reinforcing that playing an AVG did not affect low-level vision.

Our study was also unusual in that this is the only study that we are aware of that has trained both NVGP and VGP participants on an action game. Typically, video game training studies recruit NVGPs, specifically to avoid any prior video game experience affecting the conclusions that can be drawn from the video game training conducted in the lab. However, we argue that the amount of prior video game experience should not affect whether a conclusion can be drawn about the transferability of action video game training. Indeed, we conducted correlational analyses to check for any relationship between prior video game experience and task performance, and did not find any significant correlations. Given that we conduct pre-tests prior to training, any significant improvement from that baseline, regardless of the amount of prior game experience, would suggest that our video game training had transferred to some extent to perceptual skills. We did not observe any such improvement, and therefore, it is possible that video game training did not transfer even in those participants with more extensive gaming experience. Furthermore, correlational analyses between our participants' video game experience and change in performance on psychophysical tasks only revealed a significant correlation for one of our tasks - the orientation discrimination task.

The limitations of this study should be acknowledged. The sample size of 10 participants is small by the standards of video game training studies, and is generally considered underpowered. While limited by resources, we acknowledge that the results of the study therefore should be considered as part of a larger body of evidence given such small sample size. Indeed, we continue to collect data for a follow-up study to this one as part of addressing the limitations of sample size (Appendix A).

Another major limitation is the difficulty ensuring eyetracker fixation. Correlational analyses indicate that there was no relationship between participant fixation quality and performance on psychophysical tasks; however, it cannot be denied that there is the possibility of participants struggling to fixate properly and therefore not truly training or testing the intended quadrants of the visual field. Anecdotally, participants indicated some difficulty playing the video game with half the screen obscured, and while all participants progressed through the game to some extent, it is uncertain how well they were truly able to play the game and therefore experience the typical visual training of FPS-style games.

Finally, it is clear that the lack of a control condition prevented more conclusive inferences, given that we had expected the video game training to result in transfer based on prior literature. With the current data, we are unable to separate what is already noisy data from the effects of test-retest. However, given that any effect of video game training that might have existed was not large enough to emerge in our noisy data, this study's data is suggestive of a need to investigate and clarify a lack of video game transfer to perceptual vision.

In summary, this study tested the transferability of AVG training to perceptual tasks and did not find support for any significant transfer. While many studies suggest that AVG players have enhanced visual abilities, the evidence increasingly points toward a limit of what AVGs can enhance - specifically attention and visuospatial abilities. Indeed, this difference in category of visual skill that is affected by video games has been noted previously in meta-analyses (Bediou et al., 2018), and existing literature increasingly focuses on attentional enhancement as the mechanism by which video games might affect vision (see Bavelier et al., 2019). Thus, our results serve as part of the movement toward further specifying how video games might benefit or not benefit vision.

Chapter 5: General Discussion

In this dissertation, we reviewed two studies that further investigated the extent to which AVGs are able to transfer to visual perceptual skills. In doing so, we attempted to replicate findings that previously reported transfer from AVG training to various visual tasks (Study 1 and 2), as well as specifically investigating transfer of AVG training across the visual field (Study 2). However, overall, we did not find any evidence of significant transfer, with surprising results that suggest that video games are not as widely transferable as we had thought.

In our first study, participants trained on an action video game, a psychophysics task, or nothing, and were tested on two psychophysics tasks at pre-, mid- and post-training. The two psychophysics tasks used were intended to replicate previously used perceptual tasks that had proven to be reliable and learnable. However, we found that our participants were unable to perform one of our tasks, an orientation discrimination task. On the other hand, the motion discrimination task used provided interesting data that suggested that any improvement in motion discrimination ability observed was attributable to test-retest effects, rather than any unique transfer from playing an AVG. Furthermore, analysis of reaction time data followed the same pattern, with AVG training and no-contact control data showing similar trajectories over the course of the study.

We followed up the first study with our second study, where participants were trained on an action video game with two diagonal quadrants of the screen obscured. They were tested on two psychophysics tasks at pre- and post-training in both trained and untrained pairs of diagonal quadrants. This was intended to assess transfer of AVG training to untrained regions of the visual field. The psychophysics tasks used as tests were again selected to replicate in part tasks used in studies that had reported AVG transfer (Bejjanki et al., 2014; Green & Bavelier, 2007). Similar to

Study 1, participants did not demonstrate any significant improvement from pre- to post-test. Furthermore, there was no difference between trained and untrained quadrants of the visual field, reinforcing that our results do not support transfer of AVG training to these visual perceptual tasks. Reaction time analyses further supported our results, with no statistically significant improvement post-training.

Both studies did not find significant transfer from AVG training to multiple visual perceptual tasks covering motion discrimination, orientation discrimination, and visual crowding. This was surprising given that we selected two tasks that were previously reported to benefit from AVG training – the orientation discrimination task (Bejjanki et al., 2014) and the visual crowding task (Green & Bavelier, 2007). At the same time, the results of these studies have not been replicated in the video game literature, to our knowledge.

In the video game literature, one of the predominant hypotheses about the mechanism by which AVGs might affect visual skills is that AVGs primarily benefit attentional control mechanisms (e.g. Bavelier & Green, 2019). This improvement of attention would explain results reporting transfer of AVGs to a variety of visuospatial tasks such as UFOV (Feng et al., 2007; Green & Bavelier, 2003, 2006) or MOT (Sungur & Boduroglu, 2012; Trick et al., 2005). While arguments have been made for an AVG benefit to attention transferring to perceptual benefits as well (see Bavelier & Green, 2019), our results support the opposite effect. That is, that AVGs may transfer to attention and thus to tasks that may have similar attentional demands, but that this attention benefit does not necessarily extend beyond immediately similar task demands. This hypothesis also matches conclusions drawn by the research of Oei & Patterson, who have conducted multiple studies on the effects of different genres of video game on a variety of visual tasks (Oei & Patterson, 2013, 2014b, 2015). Their results led them to conclude that action games benefit tasks that share similar attentional demands, but other genres such as puzzle games were capable of benefiting tasks with similar demands to them as well. Oei & Patterson (2013) term this the common demands hypothesis, which is similar to the VPL concept of near transfer – when training is able to transfer to similar tasks or stimuli.

Therefore, the results discussed in this dissertation suggest that AVGs may not transfer to low-level perceptual tasks. One possible explanation for this lack of transfer is discussed above. However, we also acknowledge the limitations of the current research. Relatively short video game training hours (our 20 hours versus 30 hours in Green & Bavelier, 2007, for example) may have resulted in too little learning to be observed. As mentioned, in Study 1, there were also difficulties with participant ability to do one of the two test tasks, which resulted in loss of data and limiting our conclusions. It must also be acknowledged that our participants in Study 1 were recruited for a lack of action video game experience, but several of them had experience with video games that could be classified as containing characteristics from multiple genres, which may have served as sufficient experience to give them prior video game experience comparable to an AVGP. Video game researchers are increasingly aware of the issue in using genre to classify video games (see Dale et al., 2020), but an efficient solution for classifying individual video game experience in the modern video game landscape has not yet been created.

Despite the limitations, this research serves as the first, to our knowledge, to directly compare AVG training to psychophysics training used in VPL. Furthermore, we have attempted to replicate results that have not been previously replicated, to our knowledge, from significant AVG visual learning research. The AVG literature has often tested transfer of AVGs to various visual skills, but without much replication to reinforce these findings. This lack of replication is especially notable in lower-level visual skills, such as visual crowding (Green & Bavelier, 2007);

orientation discrimination (Bejjanki et al., 2014); or motion discrimination (Green et al., 2010). Given that these prior studies reported transfer of AVG training, while ours did not, this may be evidence that at minimum, the effect of AVGs on visual perceptual skills is more variable than previously suggested.

Video games have been viewed as potential vehicles for skill training for decades (e.g. Hart & Battiste, 1992). Meanwhile, recent research has suggested that AVGs might be useful for treating dyslexia (Franceschini et al., 2013, 2017) and amblyopia (Jeon et al., 2012), and might even be useful for training surgeons (Rosser et al., 2007). Our research does not necessarily contradict these findings, despite the lack of transfer in our results. Instead, our data suggests that AVGs may simply benefit any skill that would benefit from improved attentional control, but not necessarily skills that rely purely on perceptual ability. For example, Franceschini et al. (2013) first tested AVGs as treatment for dyslexia based on the hypothesis that dyslexia is partially caused by impairment in attentional allocation to written language. Similarly, while amblyopic individuals might suffer impairment in perceptual ability in the affected eyes, the treatment for amblyopia has often involved forcing usage of the impaired eye to stimulate the neural circuits in the brain that had previously been unused. By this reasoning, it is not so surprising that AVGs might be beneficial for these types of treatment while also not benefiting the low-level perceptual skills tested in our research.

The exact mechanism by which AVGs can affect vision and the corresponding neural modifications are a current area of research in the AVG research field. Our project contributes to this larger research question by approaching AVGs from the perspective of the VPL field, which has rarely been done before (exceptions include Bejjanki et al., 2014; Jacques & Seitz, 2020). VPL is a field where the question of how visual learning occurs in the brain has been central for decades, and therefore provides an established and different approach to studying visual transfer that the AVG research field can take advantage of. Our results show that combining the two fields can produce interesting and informative results that should be further explored, especially given that the exact limitations of AVG transfer have yet to be firmly established. As previously discussed, finding the extent of AVG's ability to improve visual skills can inform the mechanism by which AVG affects the brain, making results like ours important for establishing both the boundaries of what AVGs can affect and the mechanistic implications of those boundaries. Further exploration into what VPL methodology can do to inform AVG research is therefore a promising future direction for establishing what video games can do and how those benefits might be best utilized for medical and skill training purposes.

Appendix A: Follow-up control data

Control group data is in the process of being collected to reinforce the findings of this dissertation. Participants (n = 11) were assigned either to a video game training group (n = 7) or a no-contact control group (n = 4). All participants were UCLA undergraduate students who participated in this study for research course credit. The intent of this data collection is to test the effects of training participants on a video game without any additional intervention such as manipulating trained regions of the visual field (Study 2). The no-contact control was assigned in order to provide another control for Study 2 to demonstrate potential test-retest effect.

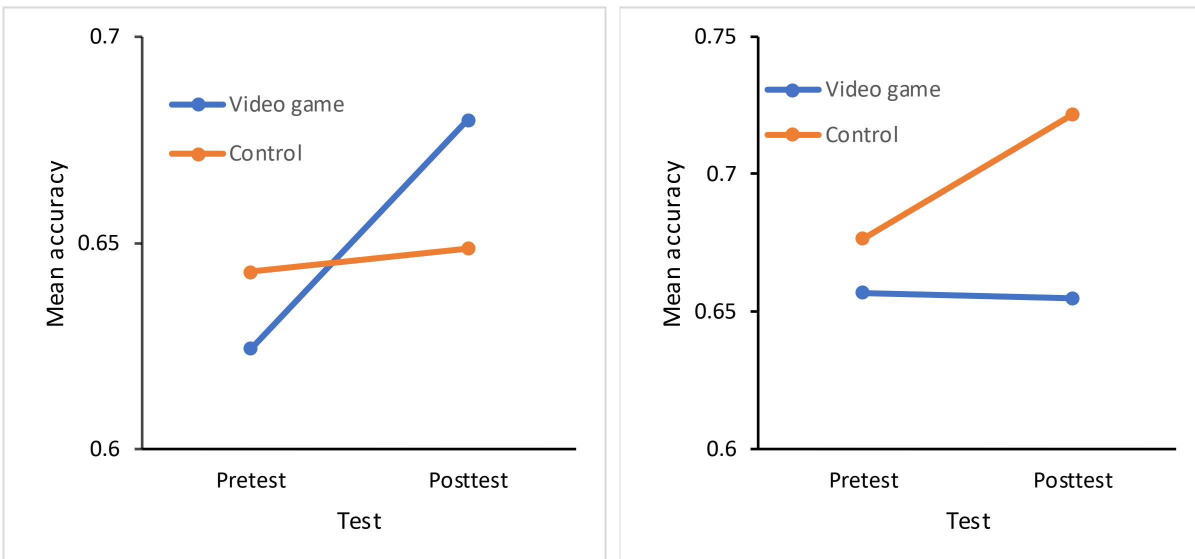
Two psychophysics tasks were used for testing participant visual skills. The first was a motion direction discrimination task, identical to the task used in Study 1. The second was a version of the orientation discrimination task used in Study 2, which was identical to Study 2's version of the task aside from 3 differences. First, unlike the Study 2 task, the stimuli were presented in the center of the screen, which was the only location where stimuli would be presented. Second, there was a guided practice phase for the orientation discrimination task identical to that used in Study 2, except that the degrees of difference in discriminated orientations were 10, 8, and 5. Third, the posttest for the orientation discrimination task did not include a calibration phase, while in the pre-test version, the contrast of the target Gabor was staircased identical to how it was calibrated in Study 2.

Participants completed the two tasks on two separate days, in order to avoid fatigue effects. Participants in the video game training group then completed 10 hours of the video game *Medal of Honor: Warfighter* (Electronic Arts Inc., 2012). Afterwards, the video game group completed the two tasks again. The no-contact control group participants completed the pre-tests and post-tests in the same week as the video game training group participants.

Initial results suggest opposite trends, where the video game training group improved on the motion discrimination task but not the orientation discrimination task (Figure 19a), whereas the control group improved on the orientation discrimination task but not the motion discrimination task (Figure 19b).

Figure 19: Initial results from control data

a) b)



Note. Data comparing participants trained on a video game and a no-contact control group. A) Video game trained participants improved on the motion discrimination task, but the control group performance remained constant. B) Video game trained participants did not improve on the orientation discrimination task, but control participants experienced improvement.

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