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Video Games and Spatial Cognition

Ian Spence and Jing Feng
University of Toronto

Video game enthusiasts spend many hours at play, and this intense activity has the potential to alter both brain and behavior. We review studies that investigate the ability of video games to modify processes in spatial cognition. We outline the initial stages of research into the underlying mechanisms of learning, and we also consider possible applications of this new knowledge. Several experiments have shown that playing action games induces changes in a number of sensory, perceptual, and attentional abilities that are important for many tasks in spatial cognition. These basic capacities include contrast sensitivity, spatial resolution, the attentional visual field, enumeration, multiple object tracking, and visuomotor coordination and speed. In addition to altering performance on basic tasks, playing action video games has a beneficial effect on more complex spatial tasks such as mental rotation, thus demonstrating that learning generalizes far beyond the training activities in the game. Far transfer of this sort is generally elusive in learning, and we discuss some early attempts to elucidate the brain functions that are responsible. Finally, we suggest that studying video games may contribute not only to an improved understanding of the mechanisms of learning but may also offer new approaches to teaching spatial skills.

Keywords: action video game, spatial attention, perceptual learning, gender differences, brain training

Video games now rival movies and TV as a source of entertainment. Practically all children play computer games at one time or another, and this may affect their behavior (Greenfield, 1984, 2009; Olson, 2010; Subrahmanyam & Greenfield, 2008; Williams, Yee, & Caplan, 2008). Although research into the connections between video games and cognition began almost 3 decades ago, the pace of experimentation has picked up considerably since the pioneering work of Green and Bavelier in 2003. Their demonstration that playing action video games could modify spatial attentional processing has sparked new research on how we learn to solve spatial problems. In this review, we first briefly discuss the emergence of video games as a major medium of entertainment, with particular emphasis on the genres that appear to be capable of altering processes in spatial cognition. We then examine how playing video games can modify the sensory, perceptual, attentional, and other cognitive capacities that are involved in the execution of spatial tasks. Our review does not attempt to cover all areas of spatial cognition, nor all varieties of video games. Most studies in spatial cognition have concentrated on a limited range of perceptual and cognitive capacities and have explored the effects of playing only a few kinds of game. Although spatial processing often engages senses other than vision—notably audition and touch—this review is primarily concerned with visuospatial cognition. Our focus is on spatial abilities but, because spatial skills are involved in many facets of cognition, playing video games has secondary influences on verbal and analytic processes beyond the domain of spatial cognition. These secondary influences have, as yet, received little attention.

Genres of Electronic Games

Very few game genres (Arsenault, 2009) have been the subject of psychological experimentation. We refer the reader to Kent (2001) for a comprehensive account of the evolution of the rich variety of video games available today and also to a useful complementary volume by Adams (2009), which presents an authoritative analysis of the principles of game design for almost every conceivable type of electronic game. The diversity and range of games seem almost limitless, and there are many distinct varieties. Popular genres include action, adventure, dance, driving, fighting, maze, music, puzzle, role playing, simulation, sports, and strategy games. Although most individual games fit comfortably in one category or another, some are difficult to pigeonhole and others occupy more than one category. For example, simulation games, which attempt to mimic complex real-life activities like planning a city, running a corporation, or governing a country, usually have role-playing, puzzle, and strategy elements. Although there is some variation within genres, there are unquestionably much greater differences among genres. Each type of game requires different skills if the player is to be successful in coping with the challenges and tricky situations encountered during play. Many games involve problem solving and planning, whereas others demand fast reflexes and superior visuomotor coordination to do well. Yet other games call on social and interpersonal skills. Indeed, collectively, video games exercise almost all of the cognitive and social skills that we require in real life. However, it seems that only a few genres have the potential to affect cognitive processes and, of these, an even smaller number are likely to affect spatial cognition.

Because of the kinds of perceptual and cognitive skills needed, the action, driving, maze, and puzzle genres would seem to be most likely to affect spatial cognition. In Table 1, we list some of

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Ian Spence and Jing Feng, Department of Psychology, University of Toronto.

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Correspondence concerning this article should be addressed to Ian Spence, Department of Psychology, Sydney Smith Hall, University of Toronto, 100 St. George Street, Toronto, Ontario, Canada M5S 3G3. E-mail: spence@psych.utoronto.ca

Table 1
Sensory, Perceptual, and Cognitive Functions Exercised by Different Genres of Video Games

Function	Game characteristic	Action	Driving	Maze/puzzle
Sensory				
Detection	Complex 3-D setting, targets in clutter	■■■■■	■■■■	■■
Attention				
Capture	Abrupt-onset events	■■■■■	■■■■	■■
Select	Discriminate/select significant objects	■■■■■	■■	■
Switch	Task switching, multitasking	■■■■■	■■■■	■
Divide	Multiple foci, track multiple objects	■■■■■	■■■■	■■
Distribute	Peripheral events	■■■■■	■■■	■
Visuomotor				
Coordination	Aiming, shooting, operating hardware	■■■■■	■■■	■
Speed	Rapid action/reaction	■■■■■	■■■■■	■
Memory				
Working	Allocate resources, make decisions	■■■■■	■■■■	■■
Long term	Integrate knowledge	■■	■	■■■
Cognition				
Spatial	Mental rotation, wayfinding, navigation	■■■■■	■■	■■■
Analytical	Solve puzzles, devise strategies	■■	■■	■■■■
Auditory	Speech, game sounds, music	■■■	■■	■
Emotional	Arousal (threat)	■■■■■	■■■■	■

Note. Importance: ■■■■■ = very high; ■■■■ = high; ■■■ = medium; ■■ = low; ■ = very low.

the perceptual and cognitive functions that we believe are required, in greater or lesser degree, for playing games from these genres. The maze and puzzle genres share a single column because these games usually require similar skills. Our assessment of the relative importance of the cognitive functions that are required to play typical games in each genre is intended only as a rough comparative guide. Particular games can have requirements that differ substantially from the norm for that genre. Games that involve driving or similar activities (e.g., piloting an aircraft, commanding a tank or ship) share many characteristics with action games, and thus we can expect them to require similar cognitive capacities. However, as indicated in Table 1, driving games are slightly less extreme on a number of dimensions than the typical action game. Although maze and puzzle games also often present problems that require spatial skills, they rarely require the critical element of speed that is characteristic of the other two genres. Quick reflexes and split-second decision making are required to succeed in an action or driving game. Players who notice threats too late or react too slowly do not succeed or even survive in the game. Although the cognitive demands in puzzle and maze games can be considerable, they rarely require such rapid action or reaction.

In the action genre, the first-person shooter (FPS) game is probably the most prevalent, and much of our review concerns this type of game. FPS games are extremely popular, especially among young males. At the time of writing, the most successful FPS game is probably *Call of Duty*, whose publisher, Activision, claims $3 billion in sales since the introduction of the series in 2003. However, the violent nature of FPS and other action and driving games is of concern to many people given that FPS games are thought to encourage aggressive behavior (Anderson & Dill, 2000) or risk taking (Fischer et al., 2009). Although it is hard to determine whether such concerns are justified, there is at least some evidence to suggest that the positive consequences of playing action games may outweigh the negative (Ferguson, 2007; see also Ferguson, 2010).

The first commercial shooter game was a coin-operated arcade video game. Inspired by experimental games in university labs, *Computer Space* appeared in 1971, more than a year before the much better known arcade game Atari *Pong*, which was modeled on the game of table tennis. Although a financial failure, *Computer Space* established the shooter genre; in the game, the player had to fire at two flying saucers that were threatening to destroy the player's rocket ship. The player was rewarded by continued play in the game, without having to insert extra money, if the number of hits on the saucers was high enough. Although home consoles like the Magnavox Odyssey also first appeared in the 1970s, video game playing at home did not become widespread until personal computers were introduced in the late 1970s and early 1980s. Dedicated gaming consoles continued to be produced and are popular to the present day, but specialized hardware no longer had to be designed and manufactured if a young programmer had a good idea for a game. Thus, the price of entry to the video game market was drastically reduced, and a large number of small independent companies began to produce innovative games in all genres. Understandably, given that young men were designing the games and that other young men were buying them, shooters continued to be very popular and several varieties were developed. Some shooter games viewed the player's character, or avatar, from behind and slightly above and are known as third-person shooters (TPS) but, eventually, with improvements in 3-D graphics, the more popular games adopted an FPS perspective where the viewpoint was that of the player's character. However, many games still allowed the option to switch between the first-person and the third-person perspectives. In addition, the viewpoint could usually be rotated through a full 360 degrees, and the player could choose the path that the avatar would follow. Modern shooter games are predominantly FPS, but most incorporate TPS options. Opportunities for multiplayer combat, where several players can be active in the same game, are also available. The level of realism is high, and novice players sometimes experience motion sickness as they learn to navigate the complex 3-D battlegrounds. Because of the obvious need for spatial skills and quick reflexes in the original shooter games, there was good reason to believe that the practice offered was likely to boost skills in spatial cognition, and that is why early experimenters predominantly used FPS games.

Spatial Cognition

Human cognition depends on a number of distinct mental components, with spatial, verbal, and analytic capacities being the most important. Of these three, spatial cognition is certainly the oldest—language and analytic behaviors, such as counting, evolved much later. Although we share many spatial skills and abilities with nonhuman animals, only humans have developed verbal and analytic skills to a high level. However, there is much reason to believe that spatial cognition was an essential foundation for the development of these more recent cognitive capacities (e.g., de Hevia, Vallar, & Girelli, 2008; Haun, Call, Janzen, & Levinson, 2006; Landau & Lakusta, 2009; Nieder, Diester, & Tudusciuc, 2006). Spatial cognition is an invariable precursor to action as it enables the necessary mental representations that code the positions and relationships among objects. Motor behavior would be impossible without the acquisition, storage, and manipulation of spatial information. Continuously updated knowledge of position is required to track and manipulate objects, including the parts of the body of the individual contemplating action. Spatial abilities are essential to represent, organize, understand, and navigate the environment, to attend to specific objects, to manipulate objects, and to communicate information about objects and the environment to others, among many other functions and tasks.

Although we all think that we know what spatial cognition is—in an informal way—formulating a satisfactory definition that faithfully captures all of its aspects is not at all straightforward. Thurstone (1938) was one of the first to suggest that spatial cognition is an independent component of cognition, distinct from verbal and analytic abilities, and he proposed that spatial cognition be thought of as the ability to hold the image of an object in mind and to twist, turn, or rotate it to match another object. Thurstone's characterization has held up remarkably well, but the scope of his definition is limited to the visualization and manipulation of objects and largely ignores larger scale spatial behaviors like navigation and wayfinding. In this review, we also concentrate mostly on cognitive skills that require the mental visualization and manipulation of objects in space, and we devote less attention to "large-scale" spatial tasks (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006) such as wayfinding. We have chosen to do so because most studies of the relationship between spatial skills and video games have focused on "small-scale" spatial abilities. The criteria used by several experimenters to assess these abilities have included mental rotation, embedded figures, perspective taking, paper folding, form boards, and block design. We describe some of these experiments below.

Spatial Skills and Early Video Games

Studies on the effects of playing video games on spatial processes began almost 3 decades ago when personal computers and game consoles became popular and video games were no longer restricted to the arcade (Kent, 2001). In the late 1970s and early 1980s, games like *Pong*, *Pac-Man*, *Donkey Kong*, *Battlezone*, *Space Invaders*, and, perhaps most notably, *Tetris* became very popular. Given that some of these games appeared to require superior spatial skills, it was natural to ask whether spatial skills—generally measured by paper-and-pencil tests—would show improvement after repeated play (Lowery & Knirk, 1982). There were also attempts to devise strategies for improved play on the basis of an analysis of the assumed cognitive demands of video games. For example, after concluding that *Battlezone* required elaborate spatial skills such as the ability to visualize rotation in three-dimensional space, Small and Small (1982) offered strategies for improved play in terms of what psychologists knew about mental rotation and spatial visualization.

Whether video games could provide effective training of spatial abilities was of keen interest to many psychologists following the publication of Maccoby and Jacklin (1974), the first wide-ranging examination and assessment of sex differences in development. Their comprehensive review of sex differences in spatial cognition confirmed that women did not perform as well as men on some spatial tasks, and the question of whether the disparity could be eliminated by training was soon raised. Several researchers took up the challenge (e.g., Dorval & Pepin, 1986; Gagnon, 1985; Greenfield, 1984; McClurg & Chaillé, 1987; Okagaki & Frensch, 1994; Subrahmanyam & Greenfield, 1994), using games that they thought could boost spatial skills. For example, participants in Gagnon (1985) played *Targ* and *Battlezone*, two early shooter games, with women improving their skills on tests of visual pursuit and mental rotation more than men. Subrahmanyam and Greenfield (1994) used *Marble Madness*, where the player guides a marble through 3-D courses containing objects and enemies that obstruct the player; the authors observed positive changes on spatial tasks in both men and women. Dorval and Pepin (1986) found that nonplayers of both sexes improved equally on an embedded figures task after training with *Zaxxon*, an early shooter game. Other early studies are reviewed in Achtman, Green, and Bavelier (2006a, 2008), Green, Li, and Bavelier (in press), Greenfield (1984), and Terlecki, Newcombe, and Little (2008). Unfortunately, as Achtman et al. pointed out, only a few of the early studies were able to establish a causal relationship between playing video games and improved performance on spatial tasks. Methodological and statistical problems were common, and some of the claimed improvements were quite small. Thus, the question of whether the gender gap in spatial cognition could be reduced by training with video games remained unresolved.

Methodological and Statistical Issues

A frequent approach used by many researchers was to compare video game players with nonplayers on tests of spatial ability. If there was a difference in favor of the players, it was often attributed to the experience gained while playing video games. Some interesting recent examples of this quasi-experimental approach may be found in Rosser et al. (2007), a widely cited study that found an association between laparoscopic surgical skills and video game experience, and Barlett, Vowels, Shanteau, Crow, and Miller (2009), who examined associations between game playing and a number of psychological variables, including spatial abilities. Of course, as Green and Bavelier (2003) have noted, a difference in favor of players is just as likely to have been an artifact of selection as to have been produced by playing video games. Those individuals who chose to play video games may have done so because they possessed superior spatial (or other) skills that made playing the games relatively easy and appealing. In contrast, those individuals who chose not to play may have done so because their spatial skills were not sufficiently strong to make playing the game enjoyable. Clearly, an observational study cannot decide between competing explanations for an observed association between game play and performance on a spatial task. Either a self-selection bias or training, or a combination of the two, could have been responsible for the superior performance of the players. Nonetheless, well-designed observational studies (e.g., Castel, Pratt, & Drummond, 2005; West, Stevens, Pun, & Pratt, 2009) are not without value as they may suggest fruitful lines of further experimentation, including video game training studies.

Establishing causation is better addressed by randomized, controlled experimentation with participants who have not previously played the game that will be used for training. Performance on the criterion spatial task should be evaluated both before and after training with the game. A comparison or control group is also generally necessary (see examples in Green & Bavelier, 2003, 2006b, 2007; Feng, Spence, & Pratt, 2007) to eliminate the possibility that simple repetition of the criterion spatial task may have been responsible for any improvement, or that the enhancement of performance is due to regression to the mean (Barnett, van der Pols, & Dobson, 2005). Participants should be randomly assigned to the control and training groups, and the control group should play a game that is similar to the training game but is not expected to produce training effects. Ideally, the control game should be matched in as many respects as possible (control inputs, range of difficulty, sophistication, production values, popularity, year of release, and so on), except for those aspects that are considered to be instrumental in training the targeted cognitive ability. Such a completely randomized repeated measures design may be further refined by matching participants in the training and control groups—before random assignment—so that each matched pair starts from approximately the same level of performance on the criterion task (see Spence, Yu, Feng, & Marshman, 2009, for an example.) Matching will usually result in improved precision and will also reduce the likelihood of dissimilar and possibly noncomparable learning experiences as a consequence of the groups starting from different positions.

Fundamental Processes That Support Spatial Cognition

For the most part, early efforts to investigate the effects of video games on cognition concentrated on the relationship between game playing and performance on paper-and-pencil tests of spatial abilities. In short, researchers approached the question of learning from a psychometric perspective. For example, in one of the early studies that examined how video game training affects spatial cognition, Dorval and Pepin (1986) used the spatial relations test from the Canadian version (Bennett, Seashore, Wesman, & Chevrier, 1960) of the Differential Aptitudes Test (Bennett, Seashore, & Wesman, 1947) as their measure of spatial skill. This test relies on the ability to identify objects hidden in a distracting background. Hence, the test items used by Dorval and Pepin are likely to have placed substantial demands on spatial selective attention and spatial working memory. But the authors did not discuss their measure of spatial ability in terms of the underlying sensory and perceptual processes. There was no attempt to investigate or characterize the mechanisms of spatial learning. Their approach was essentially psychometric—the authors were simply interested in whether playing a video game would improve spatial ability as measured by a standardized paper-and-pencil test. Although experiments of this sort are still relevant and often useful, the focus has shifted since the pioneering experiments of Green and Bavelier (2003), whose research was the first to investigate how playing an action video game could alter fundamental attentional processes. Since that groundbreaking paper, experimental studies have concentrated on how video games modify the fundamental sensory and perceptual processes that support spatial cognition (e.g., Feng et al., 2007; Green & Bavelier, 2003, 2006b, 2006c, 2007; Li, Polat, Makous, & Bavelier, 2009; Spence et al., 2009).

Video games exercise a wide range of sensory, perceptual, and cognitive functions. Some games require a high degree of skill in performing relatively basic perceptual and cognitive tasks whereas others demand higher level cognitive skills, such as the ability to solve difficult logical problems. Certain genres yield greater training benefits than others (Achtman et al., 2008). For example, Feng et al. (2007) demonstrated that participants who played an action video game for 10 hr obtained significant performance improvements on both attentional and spatial tasks, whereas participants who played a maze game for the same length of time showed no gains. Compared with other genres where positive game training effects on spatial skills have also been observed (e.g., using dynamic puzzle games like *Tetris*), action video games seem to have a unique advantage in improving low-level functions such as spatial selective attention (Feng et al., 2007; Green & Bavelier, 2003), spatial perceptual resolution (Green & Bavelier, 2007), and contrast sensitivity (Li et al., 2009), in addition to more complex spatial skills such as mental rotation (Feng et al., 2007). Because fundamental sensory, perceptual, and cognitive skills serve as the building blocks for higher level cognition, the ability of action games to improve basic processes has made them attractive candidates for further experimentation.

Sensory Processes

When light falls on the retina, it interacts with approximately 100 million specialized neurons (rods, cones, and other cells), causing some of them to fire. Much computation is done at this low level of the visual processing hierarchy, and the results are transmitted to other areas in the brain via approximately 1 million fibers in the optic nerve. Further processing takes place en route to the visual cortex and along the subsequent pathways among the various areas of cortex. These pathways are not passive one-way streets; lower level computations are often modified in response to inputs from higher centers in the brain (Kellman & Garrigan, 2009; Rolls, 2008; Scolari & Serences, 2009). The early visual system computes elementary functions such as brightness detection, edge detection, orientation detection, segmentation, shape perception, 3-D perception, movement detection, and color processing (Palmer, 1999). These basic operations usually occur without conscious awareness; attention is not necessarily required to ensure their completion. However, recent research has shown that at least some of these elementary functions are modified by top-down attentional processes (e.g., Gutnisky, Hansen, Iliescu, & Dragoi, 2009; Kastner & Ungerleider, 2000; Polat, 2009).

Thanks to advances in computer graphics, many games now boast photo-realistic 3-D visual environments that are much more lifelike than the crude 2-D settings typical of early games. This makes for a better fit to our perceptual system, which evolved in a 3-D environment. As a result, initial sensory processing of the visual environment in a contemporary video game occurs with a reasonable facsimile of what we see in the real world. In an FPS game, several visual events may occur virtually simultaneously, often at widely separated locations in the visual environment. Realistic depictions of soldiers, guns, missiles, tanks, aircraft, ships, or any of the other staples of warfare may appear and disappear at any time. The player's first priority is the rapid detection of potential threats, and this requires efficient scanning of the visual scene. Because the player in an FPS game generally has unrestricted freedom of exploration (through 360 degrees), there is a very large landscape to search for threats. Thus, it is plausible that the practice afforded by extended FPS play might have some positive benefit for sensory processing. However, it was only recently that evidence to support this conjecture was obtained. Green and Bavelier (2007) demonstrated an improvement in visual spatial resolution after training with an action game, and Li et al. (2009) showed that action game training improves contrast sensitivity, a fundamental capacity that is necessary for object recognition and spatial attention. For additional commentary on this rather surprising result, see Caplovitz and Kastner (2009). Further research may uncover yet more improvements in basic sensory functions as a consequence of playing FPS games.

Attentional Processes

The visual system cannot cope with all the information in the light that reaches the retina. Detailed processing of this continuous stream of data would impose an enormous and unmanageable computational burden and, in any case, such indiscriminate processing is not needed. Most raw visual information is unimportant for survival, or for any other relevant purpose, and may be ignored. Consequently, the visual system has evolved to be sensitive primarily to changes in the position, luminance, or other elementary attributes of objects that may be significant for survival. Visual events that involve abrupt onset or change are particularly important and are said to "capture attention." Attention is diverted immediately to the location where the sudden change has occurred as, for example, when a new object has appeared (Yantis & Jonides, 1996). Abrupt-onset events are rapidly analyzed by the brain using processes that require discrimination, identification, recognition, and decision making, and are usually followed by eye movements and motor action. Although the mechanism of *attentional capture* evolved in environments and circumstances quite different from those of today, it continues to be important. For example, it helps us to be aware of objects that are likely to trip us while walking or to notice approaching vehicles that could pose a danger when crossing the road. Attentional capture is also highly relevant when playing action video games (see Table 1).

But attentional capture is only the first stage—we must discriminate and recognize the objects that have captured attention while disregarding information that is not relevant. This is *visual selective attention*. Low-level processes (bottom-up) and processes involving prior knowledge about objects and their interrelations (top-down) are involved; the influence of higher level cognitive processes is crucial. Working memory, long-term memory, and executive control functions are brought into play. More than a century of experimentation in psychology has shown that many higher level cognitive processes can be modified by training (Bourne, Dominowski, & Loftus, 1979); therefore, it is reasonable to suppose that the practice afforded by playing video games may also produce changes in basic perceptual and attentional processes because they are influenced by higher level cognitive processing. As we have previously noted, processing visual information is a two-way street. Whereas lower level perceptual processes provide the basic data for higher level cognitive processes, these higher-level processes, in turn, affect the operation of the lower level perceptual and attentional systems (Kellman & Garrigan, 2009; Rolls, 2008; Scolari & Serences, 2009).

The player of an FPS game must detect, identify, and keep track of the threats appearing in a variety of locations in a complex and often cluttered visual environment to avoid being killed in the game. Thus, practice in an FPS game may improve spatial selective attentional abilities, and this improvement in this basic skill may improve performance on other tasks by supporting functions that depend on this ability. For example, practice in discriminating small differences is likely to benefit the perceptual system as a whole. In an FPS game, the distinction between an enemy, a fellow soldier, and a static object far away can be very subtle, particularly when the player-controlled character is moving and the view is constantly changing. To avoid indiscriminately targeting both friend and foe, the player must detect and identify these slight differences quickly and accurately, under the stress of having to survive in a perilous environment. Playing games from most other genres—even dynamic maze or puzzle games that require spatial skills—is not likely to require such a high degree of skill in spatial selective attention (see Table 1).

We can divide attention among different objects, or several noncontiguous locations, or perform more than one task at the same time (Cavanagh & Alvarez, 2005; Kramer & Hahn, 1995). Simultaneous tracking of several objects, attending to multiple locations, or performing two or more tasks concurrently requires divided attention, but this division of attention comes with costs—speed and accuracy are likely to be affected. Furthermore, there is a limit on how many objects, locations, or tasks may be attended to simultaneously. This limited capacity affects many everyday tasks; for example, using a vehicle navigation system while driving will generally impair performance on both tasks (Wickens & Hollands, 2000). In addition to dividing attention, we can also shift attention from the currently deployed location, object, or task to a different one. This switch also entails costs, usually in speed of processing, as it takes time for attention to disengage and reengage. Rapid switching is normally desirable as, for example, when a driver has to switch attention to a vehicle entering an intersection to avoid a collision.

In addition to the need to divide attention, the dynamic and highly complex visual characteristics of certain genres of game require the player to switch attention quickly from one task to another (see Table 1). FPS games expect the player to deal with a variety of challenges, which can follow one another in rapid succession. Many situations require an unexpected switch of attention, such as in the case of a sudden attack where the player's attention on a navigation task has to be suspended to deal with the immediate threat. Fast disengagement of attention from the current task and rapid engagement with the new task are often difficult for novice players. After a certain amount of practice with video games requiring divided attention or task switching, the player's ability to divide and switch attention usually improves, and this improved capacity may transfer to support other nongame tasks in the real world.

Distributing attention over a wide visual field allows us to "see" the peripheral world by localizing potential targets without fixing our gaze on the many objects in the periphery. This function was vital to our ancestors because they had to be aware of peripheral events to be successful in the hunt and also to avoid being hunted. It continues to be important today. For example, because we can fixate only one small area at a time while driving a vehicle, most of our monitoring of potential hazards requires the ability to distribute attention over a wider field of view than the relatively small high-resolution area in the direction of gaze. This is the *attentional visual field*. Narrowing of the attentional field has been linked to vehicle accidents, particularly in older drivers whose attentional visual field has deteriorated with age (Ball & Owsley, 1991). The player of an action game must also be aware of events that occur in the periphery, far from the central focus. Even though the player will normally concentrate on the center while completing the mission, threats can appear in any quadrant, and if the player is not able to distribute attention over a wide field of view, an unattended threat in the periphery can prove to be disastrous. FPS games offer abundant practice in expanding the attentional visual field (Feng et al., 2007; Green & Bavelier, 2003, 2006b; Spence et al., 2009).

Visuomotor Coordination and Speed

Much processing in spatial cognition is a prelude to action, such as pointing or grasping, and such actions require visuomotor coordination (Jeannerod, 1986). This is the ability to use visual information to control and direct the motor system to complete a task. Visuomotor coordination is a basic skill required for everyday activities involving movement, such as writing, dressing, walking, driving, or playing sports. Playing video games also requires visuomotor coordination. To perform well in action video games, the player must respond quickly (see Table 1). In FPS games, enemies appear suddenly and the player must detect the threat, determine its level of danger, and defend rapidly and appropriately. This is only possible if the necessary perceptual, cognitive, and motor actions are swiftly accomplished. Speed is important. Similarly, in driving games, quick reactions to vehicles or obstacles that appear suddenly are imperative to avoid collisions. Thus, action games offer the possibility of improving an individual's ability to react quickly. In an action game, visuomotor coordination mainly involves interactions between hand and eye. Under cortical control, the eyes control the direction of gaze and the focus of attention, and the hands accomplish the required tasks. For example, when shooting in an FPS game, the player must locate the target visually, move the aiming point to that spot, and click the mouse to fire. Even in dynamic puzzle games such as *Tetris*, the player must decide how much rotation of the moving item is required and then press a key to make the rotation; this has to be done both quickly and accurately. Almost any video game that incorporates dynamic visual presentation and a fine motor control component is likely to be effective in producing improvements in visuomotor coordination (Griffith, Voloschin, Gibb, & Bailey, 1983), although the amount of improvement may vary with the game, depending on the kinds of activities required. In an FPS game, the player not only has to shoot accurately and quickly but also must do so under conditions that are often less than ideal. The targets are sometimes distant, making detection, identification, aiming, and shooting difficult, thus demanding a high level of visuomotor coordination for success. Similarly, in a driving game, the car must be steered accurately to avoid collisions. As the player of an action game becomes more experienced, accuracy and speed tend to improve (Castel et al., 2005; Dye, Green, & Bavelier, 2009; Yuji, 1996).

Memory

Memory is the ability to store, maintain, and subsequently retrieve information. The two types of memory that are likely to be relevant to playing many video games are *working memory* and *long-term memory*. Long-term memory, as the name suggests, is the capacity to store information for a relatively long time and is probably not a crucial factor in playing most video games. Of course, players need to learn the rules of the game and also to absorb contextual information pertinent to the game, but these demands seem unlikely to provide any unique or useful opportunities for training. Working memory, in contrast, is a capacity that is essential for successful play in many games, and the opportunities for intensive training are abundant. Working memory temporarily stores information for current manipulation (Cowan, Morey, Chen, Gilchrist, & Saults, 2008) and is closely linked to the attentional system. Generally, individuals cannot simultaneously hold more than about four items in working memory, nor can they attend to more than about four objects at the same time. Failure to store and manipulate information efficiently in working memory will result in poor performance on many tasks. Working memory and long-term memory interact with and supplement each other. Information enters long-term memory via the working memory process, and working memory receives information from long-term storage according to the demands of the current task and under the control of executive processes in the brain. Thus, improvement in one type of memory might also benefit the other.

Playing some genres of video game requires an above-average ability to manipulate items in working memory (see Table 1). For example, the player in an FPS game often has to assess a number of simultaneous threats, quickly decide which enemy to engage first and which weapon to use. Making the choice rapidly and accurately is essential for survival in the game. Visual working memory and spatial attention are closely interrelated and, given that several studies have demonstrated improvements in spatial attention as a result of playing action games (e.g., Green & Bavelier, 2003; Spence et al., 2009), it seems possible that improvements in spatial working memory might also be obtained. As far as we are aware, improvements in spatial working memory have not yet been observed in a video game training study; however, experience with action video games has been associated with superior ability in visual memory recall (Ferguson, Cruz, &

Rueda, 2007). An advantage was identified not only with everyday common objects (e.g., bicycle, eyeglasses) but also with abstract items (e.g., complex geometric drawing).

Mechanisms of Learning

One of the difficulties of using commercial video games as a tool to investigate mechanisms in cognition is that gaming environments are very complicated. Players engage in multiple activities, often simultaneously, and many perceptual, cognitive, and motor skills are engaged. The demands of the game vary from moment to moment and from situation to situation, making it problematic to catalog and code behavior in the game and to make an assessment of which cognitive functions are likely to have been active and for how long. Even if this were easy to do, there would still be the problem of characterizing the interactions among the perceptual, cognitive, and motor systems that were simultaneously engaged during the execution of the wide variety of tasks and missions in the game. This complexity makes it hard to assign causality, or even to make an assessment of the associations between game activity and brain functions, and then to determine the aspects of the training that might have produced improvement. In short, the typical video game training experiment is very poorly controlled, at least if the goal is to try to identify mechanisms of learning. But video game training has one salient advantage. As Green and Bavelier (2008) have noted, although more conventional training experiments that isolate and train individual cognitive functions may lead to faster learning, they may also result in less effective retention and less effective transfer to tasks that are dissimilar to the training task. The appeal and great promise of video game training are that it seems to be capable of producing generalized training effects (e.g., Feng et al., 2007; Green & Bavelier, 2003, 2006b, 2007) and, furthermore, effects that are long lasting (Feng et al., 2007; Li et al., 2009; Spence et al., 2009).

In general, positive change (learning) can be produced by repetition on a wide variety of perceptual tasks, and the behavioral effects can be long lasting (e.g., Karni & Sagi, 1991; Stickgold, James, & Hobson, 2000). Typically, however, improvement is specific to the training task (near transfer), and generalization beyond the specific circumstances of the initial learning (far transfer) is rarely seen (Barnett & Ceci, 2002; Fahle, 2009; Polat, 2009). Whereas performance on spatial tasks that are similar to the training task is often substantially improved, many studies have found that far transfer is generally not achievable (e.g., Levene, Schulman, Brahlek, & Fleishman, 1980; Sims & Mayer, 2002). In recent years, this overly pessimistic view has been challenged, and there is mounting evidence that certain kinds of training can enhance performance on some spatial tasks in nonspecific ways (far transfer). Examples may be found in Casey, Erkut, Ceder, and Young (2008), Green and Bavelier (2007), Gutnisky et al. (2009), Polat (2009), Terlecki et al. (2008), and Wright, Thompson, Ganis, Newcombe, and Kosslyn (2008), among others. It is interesting that several studies that achieved far transfer used video games for training, and the improvements in the trained skills were frequently long lasting (e.g., Feng et al., 2007; Li et al., 2009; Spence et al., 2009).

Some tasks that require spatial abilities place heavy loads on attention and working memory, whereas others are less demanding. Some spatial tasks require complex problem-solving skills, whereas others are executed rapidly, often without conscious intervention. Task complexity varies along a continuum. A task is *basic* if it depends predominantly on fundamental capacities like spatial selective attention, spatial working memory, or other similar sensory and perceptual capacities. A task is *complex* if it requires—in addition to basic operations—additional cognitive processes such as searching, matching, and symbolic problem solving, or the use of imagery, number, language, gesture, and so on.

All tasks in spatial cognition, whether basic or complex, are supported by attention and working memory, and these essential capacities are very closely interconnected (Awh & Jonides, 2001; Olivers, 2008). Complex spatial tasks such as mental rotation require rapid allocation, disengagement, and reallocation of attention to multiple features of the stimulus (e.g., vertices, edges, faces, or cubes, in mental rotation). During the multiple stages of processing that mental rotation requires, attention must be switched selectively among the features of the stimulus in working memory to keep them active (Awh, Vogel, & Oh, 2006; Lepsien & Nobre, 2006). Spatial selective attention is the gatekeeper, selecting which features are swapped into and out of the capacity-limited workspace in visual working memory (Awh et al., 2006). In addition, executive spatial attentional processes keep track of the contents of spatial working memory and coordinate other brain systems necessary for the maintenance and selection of object representations. The efficient operation of the twin processes of spatial selective attention and spatial working memory is vital for complex spatial tasks such as mental rotation.

Playing an FPS video game boosts spatial selective attention (Feng et al., 2007; Green & Bavelier, 2003; Spence et al., 2009) and simultaneously improves performance on a mental rotation task (Feng et al., 2007), although the gains in mental rotation are not as large as in spatial selective attention. This is almost certainly because mental rotation depends on perceptual and cognitive processes above and beyond spatial selective attention. Some of these additional functions may also be improved by playing the FPS game, but others are likely to remain unaffected. For instance, in an FPS game, the player's character is free to move and—just as in real-world navigation—the player's brain will actively construct a spatial representation of the initially unfamiliar environment (Burgess, 2008). There are many opportunities to develop new spatial representations in a typical FPS game because the setting and the position of the player's character change frequently. In one scenario in *Medal of Honor: Pacific Assault* (used in Feng et al., 2007, and Spence et al., 2009), the player has to navigate inside a sinking ship to rescue wounded people and eventually find the way to the deck; in another setting, the player must navigate around an island without many clear landmarks to find specific locations required by the mission. Some of the skills acquired during the construction of these spatial representations may well transfer to tasks such as mental rotation. On the other hand, it is possible that mental rotation requires capacities that receive no benefit from playing FPS games. Consequently, there are likely limits on what may be achieved in complex spatial tasks after training with action video games.

Many video game training studies have examined relatively complex spatial skills, using criterion tasks such as mental rotation, embedded figures, or mental paper folding (Liu, Uttal, Marulis, & Newcombe, 2008). Although not as complex as real-world activities such as learning geometry or designing buildings, these tasks call for multiple and varied cognitive abilities. The video games in the studies reviewed by Liu et al. (2008) also differed, and not all games were equally effective in producing change. In general, the choice of game and criterion task will set boundaries on what may be achieved in a training study. If the game used for training does not improve basic spatial skills, transfer of learning will probably be limited, and any gain is likely to be the result of improvements in task-specific skills, but not all video games improve basic capacities.

Games other than FPS games have been found to improve spatial skills such as the ability to rotate objects mentally. In several studies (e.g., Cherney, 2008; De Lisi & Cammarano, 1996; De Lisi & Wolford, 2002; Okagaki & Frensch, 1994; Terlecki et al., 2008), participants who played *Tetris*, or a similar dynamic puzzle game, showed improvements on mental rotation tasks. Because the tasks in *Tetris* are similar to those in mental rotation tests, it is not surprising that gains were observed. However, in contrast to training with FPS games, no study using dynamic puzzle games has reported generalization to other dissimilar tasks. Spence et al. (2009) have suggested that because playing *Tetris* does not improve basic perceptual processes such as spatial selective attention (Green & Bavelier, 2003, 2006b) or multiple object tracking (Green & Bavelier, 2006c), its capacity for training spatial skills is limited to tasks that are similar to the game itself. Playing action games, on the other hand, does result in generalization (Feng et al., 2007; Green & Bavelier, 2003, 2006b, 2006c, 2007; Spence et al., 2009), and the learning is long lasting (Feng et al., 2007; Li et al., 2009; Spence et al., 2009). Although we are only beginning to understand which characteristics of FPS games are responsible for far transfer of learning, we consider some possibilities below.

Egocentric Versus Allocentric Perspective

The player's perspective (Klatzky, 1998) may have a significant influence on the acquisition of spatial and visuomotor skills. FPS and driving games provide a natural egocentric compatibility between the visual input and the motor output (the actions that control the player's character in the game). The control of direction of movement and the changing visual landscape are matched to the player's viewpoint. This compatibility may make tasks that require spatial orientation skills easier to learn because there is a natural match between the gaming environment and similar tasks in the real world. In some other spatial (but nonaction) games such as *Tetris*, the controls that determine movement of the objects in the game are not generally compatible with an egocentric (player-centered) viewpoint. It is well known that the time taken to recognize a set of objects from a viewpoint different from the egocentric increases linearly with the difference in angle between the two viewpoints (Diwadkar & McNamara, 1997). When participants are asked to point to an object from an imagined viewpoint, they are faster and more accurate when the imagined viewpoint is in the same direction as the egocentric viewpoint (Shelton & McNamara, 1997). Thus, the type of visuomotor coordination required in *Tetris* is less natural than in most FPS games. Because successful play requires a reconciliation of egocentric (body-centered) and allocentric (object-oriented) frames of reference (Klatzky, 1998), it is not clear whether playing *Tetris* inhibits or promotes spatial learning.

Top-Down Control of Lower Level Processing

So far, there have been few theoretical explanations of why video games—particularly action games—are so successful in producing learning that generalizes beyond the training task. Green and Bavelier (2008) have suggested that research by Ahissar, Hochstein, and colleagues (Ahissar & Hochstein, 2004; Ahissar, Nahum, Nelken, & Hochstein, 2009; Hershler & Hochstein, 2009) is relevant to understanding the mechanisms of learning while playing action video games. The reverse hierarchy theory of Ahissar, Hochstein, and colleagues purports to explain how processing of visual information proceeds and how this relates to expertise. First, a feed-forward system moves information from lower to higher levels of cortex (e.g., from primary visual cortex, to other visual areas, and to parietal and frontal cortex). Discrimination of global features begins at high cortical levels using this feed-forward information. However, it may be necessary to go back to lower levels if the discrimination cannot be completed without more detail. Thus, initial processing involves global aspects only, and improvements in sensory capacities after training are assumed to result from top-down guided processes where lower cortical levels are involved again when necessary. Trained individuals (experts) make faster judgments than those without training (novices), which suggests that high-level representations in experts are sufficient to complete the discrimination, whereas novices need further information from lower level areas before they can react. A novice becomes an expert when the processes of top-down modulation are integrated with the feed-forward processing. Thus, visual information is *actively* selected by bottom-up *and* top-down processes, with the latter being strongly influenced by the past experiences of the observer. Top-down influences confer a permanent attentional advantage. The quality of transfer of learning is predicted by this framework: Tasks that are processed mainly at the higher levels will demonstrate transfer of learning, whereas tasks that are completed at lower levels of representation will lead to specific learning only.

Suppression of Task-Irrelevant Information

Several other investigators have also emphasized the importance of top-down modulation in perceptual learning, and many have noted the importance of being able to suppress task-irrelevant information (e.g., Fahle, 2009; Rolls, 2008; Scolari & Serences, 2009; Zanto & Gazzaley, 2009). A key property of attention is the enhancement of relevant stimuli, thus providing a mechanism for separating important information in cluttered visual scenes. During learning, a visual stimulus that is important for the task at hand is often surrounded by stimuli that are irrelevant and may impede learning by capturing attention. However, the activity of neurons in early sensory cortex can be boosted substantially for a task-relevant stimulus (Kastner & Ungerleider, 2000). Selective attention selects and routes the relevant information to decision-making areas in the brain and suppresses the irrelevant clutter. This selection, initiated at higher cortical levels, is different from the solely stimulus-driven effects of attention. Kelley and Yantis (2009) recently showed that if the distracters are variable, rather than fixed in appearance, during training, this leads to an improvement in filtering information. The distracting information on the battlefields of FPS games is certainly not uniform, and the complex nature of this clutter may be an important characteristic that enhances the ability of FPS games to train the spatial selective attentional system.

Motivation and Emotion

The role of motivation, reward, and emotion has been little explored in the context of video game training. It is easy to observe that players are highly motivated to play their favorite games and that they often become highly aroused during play. This will affect the frequency and intensity of play, and this will naturally have profound effects on learning. Most video games possess a number of features that encourage players to play and also to continue to play. The availability of several levels of difficulty allows individuals with different skills to participate in the game, to move to higher levels after sufficient practice, and eventually to become experts. Providing access at different levels of difficulty recognizes that not everyone is at the same place on the learning curve. Novices who must play a game that is too difficult will quickly tire and quit. By the same token, players who find the game too easy will also quickly lose interest. Playing at an appropriate level of difficulty not only helps to keep the player interested and engaged, but as the player gains experience, he or she is being prepared for the next, more difficult level. Modern FPS games invariably feature a storyline that is intended to engage the player. For example, an FPS game that we have used in our experiments, *Medal of Honor: Pacific Assault*, follows the U.S. Marine campaign in the South Pacific during World War II. During various phases of the campaign, and even during training at boot camp, the player is rewarded for doing well by receiving positive feedback in the game (such as the number of kills, tanks or aircraft destroyed, and other objectives met in the mission). Players of FPS games also usually have the opportunity to compare scores with others, particularly in games that feature multiplayer modes, providing an additional competitive incentive. Other rewards relevant to game play are frequently available (e.g., extra ammunition or new weapons), and these, in turn, lead to more success and encourage greater participation. Sound is another motivating feature of FPS games that now routinely incorporate cinematic elements such as dramatic music, the noise of weapons and explosions that heighten tension, and the chatter and praise from teammates to reward a job well done. There has been some research on reward mechanisms and dopamine release during video game play (Koepp et al., 1998), but more work needs to be done to clarify the role of neurotransmitters during this type of learning (Egerton et al., 2009).

Ryan and collaborators (Przybylski, Rigby, & Ryan, 2010; Przybylski, Ryan, & Rigby, 2009; Ryan, Rigby, & Przybylski, 2006) have explored the relationship between the enjoyment of video games and the players' needs for autonomy, competence, and relatedness. They found that games where players experience freedom and a sense of accomplishment are likely to be attractive. Setting goals, meeting challenges, devising strategies, and importantly, being in control of one's own actions and destiny are characteristic of successful video games. Perhaps surprisingly, the researchers found that increased violence did not correlate with more enjoyment once the need for autonomy and competence was taken into account. There may be an important lesson here for game designers. Building games that have the same basic characteristics as violent FPS games, but without the killing and bloodshed, could attract new audiences that might benefit from FPS-like training. Thus, women and young girls might improve their spatial skills by playing such games. Senior citizens who are experiencing a decline in their spatial attentional capacities—and who are consequently at increased risk for vehicle accidents and falls—might also benefit by improving their attentional visual field and speed of visuomotor processing.

Implications and Applications

Gender Differences

Gender differences in spatial cognition have been well documented (Halpern, 2000; Kimura, 1999; Maccoby & Jacklin, 1974). As we have noted, starting almost 3 decades ago when video games were becoming increasingly popular, researchers have been exploring the possibility of reducing or eliminating gender differences by training with computer games (e.g., Cherney, 2008; Dorval & Pepin, 1986; Gagnon, 1985; McClurg & Chaillé, 1987; Okagaki & Frensch, 1994; Sims & Mayer, 2002; Subrahmanyam & Greenfield, 1994). The results have been mixed. Although many studies showed gains for both men and women on a variety of spatial tests, including mental rotation, no study was able to close the gender gap. In a recent large study, Terlecki et al. (2008) attempted to improve the mental rotation performance of men and women over a 12-week period using repeated testing on the mental rotation task and video game training with 2-D and 3-D *Tetris*. Both video game training and repeated testing produced significant improvements in mental rotation performance, but neither regimen reduced the preexisting gender difference. However, the shape of the learning curves suggested that it might be possible to close the gap with further training. The curves were roughly parallel, with the men starting and finishing at higher levels. Because the performance of women who received video game training came close to that of men who had received no training, Terlecki et al. speculated that, given sufficient additional training, the performance of the women might match that of the men. Although the limited training possible in laboratory experiments may not be sufficient to achieve convergence in performance on spatial tasks, there could be other reasons for the failure to close the gender gap in spatial cognition. Spence et al. (2009) suggested that preexisting differences in the basic functions that support tasks such as mental rotation may not have benefited from training with a game such as *Tetris*.

Feng et al. (2007) reported a large and previously unknown gender difference in spatial selective attention. They also showed that the deficit was virtually erased after training with an FPS game. Simultaneously, an initial difference in mental rotation scores was greatly reduced, with women realizing the greater benefit. Although mental rotation seems to have little in common with an FPS game, Spence et al. (2009) argued that because mental rotation is supported by basic capacities such as spatial selective attention, the improvement in mental rotation in Feng et al. was at least partially a consequence of improvement in the basic skill of spatial selective attention. Spence et al. hypothesized that if females are not inferior to males in the rate at which they acquire basic spatial skills, we should expect to see convergence on basic spatial tasks, given sufficient training. Women should achieve gains that match those of men after equivalent training as long as they start from equivalent levels of performance. After matching men and women on a test of spatial selective attention, Spence et al. showed that women were not inferior to men in the rate at which they acquired the basic skill of spatial selective attention after training with an FPS game. Training with dynamic puzzle games such as *Tetris* may modify task-specific skills (Green & Bavelier, 2003), but they fail to improve spatial selective attention and, as a result, may be incapable of closing the gender gap in either basic or complex spatial skills such as mental rotation. Training methods that develop an individual's ability to maintain, select, and exchange items in spatial working memory may be essential to provide a basis for gender equalization on more complex spatial tasks.

From an educational perspective, spatial cognition is essential for successful problem solving in science, technology, engineering, and mathematics (STEM) education and occupations (Terrell, 2007). Spatial abilities are necessary for a wide range of job-related skills, such as solving mathematical problems (especially those involving geometry); visualizing the consequences of actions in surgery; designing structures such as bridges, buildings, and aircraft; constructing flowcharts and other representations of computer programs; creating and interpreting charts, graphs, diagrams, maps, and engineering drawings; and so on. Excellence in STEM fields is strongly correlated with spatial ability (Wai, Lubinski, & Benbow, 2009), and spatial skills are associated with performance in mathematics and science courses (Delgado & Prieto, 2004) and standardized tests (Casey, Nuttall, Pezaris, & Benbow, 1995), as well as the choice of mathematics and science courses in college (Casey et al., 1995).

Early individual differences in cognitive abilities influence confidence, self-efficacy, and attitudes (Bandura, 1997). Thus, if an individual possesses inferior spatial skills, he or she is likely to avoid learning situations that require spatial cognition. In turn, these lost educational opportunities will have a negative effect on participation in STEM occupations. If we could improve the level of spatial functioning by training and education, this would have important intellectual and economic consequences in STEM fields. Changes in childhood play and early education, geared toward improving spatial cognition, could have a major impact on the choice of programs of study and career decisions. Training to improve spatial skills would also have a beneficial impact on gender equity. Worldwide, women are underrepresented in STEM occupations, where less than a quarter of the workforce is female (Arnold & Niederman, 2001). If the gender disparity in spatial cognition (Halpern, 2000; Kimura, 1999) could be removed by appropriate early training, the subsequent educational and career paths of girls and boys might be more closely aligned. Even if genetic differences set limits on what may be achieved by training, new methods of developing skills in spatial cognition would still be of great value in education.

Aging and Brain Training

The proportion of senior citizens in the population is increasing in almost all developed countries, and there has been a recent surge of interest in "brain training" as a possible antidote to the normal age-related decline in cognitive functioning. Inspired by the commercial success of Nintendo's *Brain Age* suite of video games, several enterprises have sprung up to capitalize on the opportunity. Various aspects of cognition, including spatial abilities, are targeted for improvement. The training procedures use simple tasks (or minigames) that are similar to items in standard psychological tests or to tasks that have been adapted from the toolbox of experimental methods in perception, learning, memory, and cognition. Alternatively, the training tasks are simple games similar to the puzzles found in the daily newspaper or tabletop games; these include crosswords, acrostics, *Scrabble*, *Boggle*, *Sudoko*, and *Where's Waldo?* The driving principle is repetition, and it is assumed that if the task is performed sufficiently often, the player will improve the skill being trained. Repetition of the task may result in change, and the behavioral effects can be long lasting (Willis et al., 2006).

However, there are two difficulties with the claims made by some brain-training enterprises. First, there are few, if any, independent studies to provide an evaluation of the claimed benefits, although this may change as use of these brain-training tools becomes more widespread. Second, if training does result in improvement, it is usually highly specific to the task used for training, and generalization is rarely observed. Moreover, the training tasks are often tedious, and the motivation of the player is likely to wane quickly, discouraging the very repetition that is responsible for improvement. A typical brain-training session is quite different from the experience of playing a commercially successful video game. Of the many thousands of electronic games that are developed each year, games that do not appeal to players quickly disappear, leaving only a few stars. The natural selection of the marketplace ensures that only the most engaging games will survive, and the surviving games are so addictive that players will spend endless hours at play. The practice afforded by this concentrated learning experience is massive and, consequently, we should not be surprised that playing video games can produce significant and long-lasting changes in cognition. But it is important to realize that games are not all equally beneficial in effecting change, and that not all sensory, perceptual, and cognitive capacities can be changed. It is far from clear that the simple brain-training games that are on offer can do anything more than increase expertise in the game itself.

We know that seniors experience particular kinds of decline in perceptual and cognitive processing as a part of normal aging. These include a narrowing of the attentional visual field (Ball & Owsley, 1991), a decreased capacity to suppress irrelevant distracting visual stimuli (Gazzaley & D'Esposito, 2007), or at least an inability to do so rapidly (Gazzaley et al., 2008). The consequences of this deterioration in cognitive processing are not merely of academic interest. A reduced attentional visual field has been associated with an increased likelihood of falls (Di Fabio et al., 2005) and vehicle crashes (Ball, Owsley, Sloane, Roenker, & Bruni, 1993). Accidents involving seniors, some of which are due to failures of spatial cognitive processing, come at a high personal and financial cost. In North America alone, the dollar expenditures run into billions. Given that playing action games has been shown to improve spatial attention, to improve the ability to suppress distracting information, and to speed processing, this could point the way to new methods of remediation in seniors. Training with action games modifies visual processing in general ways, and this learning transfers to new visual contexts. However, learning simple discriminations after repeated practice, such as when playing *Tetris*, does not transfer to new tasks (Green & Bavelier, 2003) but rather improves performance only in activities that are similar to the training task (Terlecki et al., 2008). In our opinion, games modeled on the FPS genre have much more promise for remedial training than the kinds of simple puzzle games promoted by most brain-training enterprises.

Conclusions

Playing video games can alter the brain, perhaps more frequently in beneficial than in harmful ways (Ferguson, 2007). Playing action games—particularly FPS games—produces improvements in sensory, perceptual, and spatial cognitive functions that are different from the expertise acquired in the game. The size of the attentional visual field is increased (Feng et al., 2007; Green & Bavelier, 2003, 2006c; Spence et al., 2009), and other functional improvements are observed in basic spatial tasks (Green & Bavelier, 2003, 2006c, 2007; Li et al., 2009) and complex spatial tasks (Feng et al., 2007). Furthermore, the improvements persist for a long time (Feng et al., 2007; Li et al., 2009; Spence et al., 2009). These findings have profound scientific and educational implications. Examining the effects of playing video games represents a fresh approach to studying far transfer in learning and may inspire the development of new methodologies for investigating the brain mechanisms that are responsible for these effects. Principles derived from studying the role of video games in modifying processes in spatial cognition could eventually revolutionize the teaching of spatial skills and concepts to children and even reduce or eliminate the gender differences in spatial cognition. An improvement of this kind in basic education would have social and economic consequences of great magnitude. At the other end of the educational continuum, new methods of cognitive training based on action video games could help to maintain, or even improve, spatial cognition as we age. Although much basic science remains to be done, and although the underlying brain mechanisms are still only partially understood, studying the training effects of video games represents an important and innovative way of investigating learning processes in spatial cognition. Video games are not just for kids any more.

References

Achtman, R. L., Green, C. S., & Bavelier, D. (2008). Video games as a tool to train visual skills. *Restorative Neurology and Neuroscience, 26,* 435–446.

Adams, E. (2009). *Fundamentals of game design* (2nd ed.). Indianapolis, IN: New Riders Publishing.

Ahissar, M., & Hochstein, S. (2004). The reverse hierarchy theory of visual perceptual learning. *Trends in Cognitive Sciences, 8,* 457–464.

Ahissar, M., Nahum, M., Nelken, I., & Hochstein, S. (2009). Reverse hierarchies and sensory learning. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences, 364,* 285–299.

Anderson, C. A., & Dill, K. E. (2000). Video games and aggressive thoughts, feelings, and behavior in the laboratory and in life. *Journal of Personality and Social Psychology, 78,* 772–790.

Arnold, D., & Niederman, F. (2001). The global IT workforce: introduction. *Communications of the ACM, 44,* 30–33.

Arsenault, D. (2009). Video game genre, evolution and innovation. *Eludamos. Journal for Computer Game Culture, 3,* 149–176. Retrieved from http://www.eludamos.org/index.php/eludamos/article/view/65

Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences, 5,* 119–126.

Awh, E., Vogel, E. K., & Oh, S.-H. (2006). Interactions between attention and working memory. *Neuroscience, 139,* 201–208.

Ball, K., & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors, 33,* 583–595.

Ball, K., Owsley, C., Sloane, M. E., Roenker, D. L., & Bruni, J. R. (1993). Visual attention problems as a predictor of vehicle crashes among older drivers. *Investigative Ophthalmology & Visual Science, 34,* 3110–3123.

Bandura, A. (1997). *Self-efficacy: The exercise of control*. New York: W. H. Freeman.

Barlett, C. P., Vowels, C. L., Shanteau, J., Crow, J., & Miller, T. (2009). The effect of violent and non-violent computer games on cognitive performance. *Computers in Human Behavior, 25,* 96–102.

Barnett, A. G., van der Pols, J. C., & Dobson, A. J. (2005). Regression to the mean: What it is and how to deal with it. *International Journal of Epidemiology, 34,* 215–220.

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn? A taxonomy for far transfer. *Psychological Bulletin, 128,* 612–637.

Bennett, G. K., Seashore, H. G., & Wesman, A. G. (1947). *Manual for the Differential Aptitude Tests.* New York: Psychological Corporation.

Bennett, G. K., Seashore, H. G., Wesman, A. G., & Chevrier, J. M. (1960). *Test différentials d'aptitude: Manuel et normes (Formules A et B)* [Manual and Norms (Forms A and B) for the Differential Aptitudes Tests]. Montréal, PQ: Institut de Recherches Psychologiques.

Bourne, L. E., Dominowski, R. L., & Loftus, E. L. (1979). *Cognitive processes.* Englewood Cliffs, NJ: Prentice Hall.

Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences, 1124,* 77–97.

Caplovitz, G. P., & Kastner, S. (2009). Carrot sticks or joysticks: Video games improve vision. *Nature Neuroscience, 12,* 527–528.

Casey, B., Erkut, S., Ceder, I., & Young, J. M. (2008). Use of a storytelling context to improve girls' and boys' geometry skills in kindergarten. *Journal of Applied Developmental Psychology, 29,* 29–48.

Casey, M. B., Nuttall, R., Pezaris, E., & Benbow, C. P. (1995). The influence of spatial ability on gender differences in mathematics college entrance test scores across diverse samples. *Developmental Psychology, 31,* 697–705.

Castel, A. D., Pratt, J., & Drummond, E. (2005). The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychologica, 119,* 217–230.

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences, 9,* 349–354.

Cherney, I. D. (2008). Mom, let me play more computer games: They improve my mental rotation skills. *Sex Roles, 59,* 776–786.

Cowan, N., Morey, C. C., Chen, Z., Gilchrist, A. L., & Saults, J. S. (2008). Theory and measurement of working memory capacity limits. In B. H. Ross (Ed.), *The psychology of learning and motivation* (Vol. 49, pp. 49–104). Amsterdam: Elsevier.

de Hevia, M. D., Vallar, G., & Girelli, L. (2008). Visualizing numbers in the mind's eye: The role of visuo-spatial processes in numerical abilities. *Neuroscience & Biobehavioral Reviews, 32,* 1361–1372.

Delgado, A. R., & Prieto, G. (2004). Cognitive mediators and sex-related differences in mathematics. *Intelligence, 32,* 25–32.

De Lisi, R., & Cammarano, D. M. (1996). Computer experience and gender differences in undergraduate mental rotation performance. *Computers in Human Behavior, 12,* 351–361.

De Lisi, R., & Wolford, J. (2002). Improving children's mental rotation accuracy with computer game playing. *Journal of Genetic Psychology, 163,* 272–283.

Di Fabio, R. P., Zampieri, C., Henke, J., Olson, K., Rickheim, D., & Russell, M. (2005). Influence of elderly executive cognitive function on attention in the lower visual field during step initiation. *Gerontology, 51,* 94–107.

Diwadkar, V. A., & McNamara, T. P. (1997). Viewpoint dependence in scene recognition. *Psychological Science, 8,* 302–307.

Dorval, M., & Pepin, M. (1986). Effect of playing a video game on a measure of spatial visualization. *Perceptual and Motor Skills, 62,* 159–162.

Dye, M. W. G., Green, C. S., & Bavelier, D. (2009). The development of attention skills in action video game players. *Neuropsychologia, 47,* 1780–1789.

Egerton, A., Mehta, M. A., Montgomery, A. J., Lappin, J. M., Howes, O. D., Reeves, S. J., . . . Grasby, P. M. (2009). The dopaminergic basis of human behaviors: A review of molecular imaging studies. *Neuroscience & Biobehavioral Reviews, 33,* 1109–1132.

Fahle, M. (2009). Perceptual learning and sensomotor flexibility: Cortical plasticity under attentional control? *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences, 364,* 313–319.

Feng, J., Spence, I., & Pratt, J. (2007). Playing an action video game reduces gender differences in spatial cognition. *Psychological Science, 18,* 850–855.

Ferguson, C. J. (2007). The good, the bad, and the ugly: A meta-analytic review of positive and negative effects of violent video games. *Psychiatric Quarterly, 78,* 309–316.

Ferguson, C. J. (2010). Blazing angels or resident evil? Can violent video games be a force for good? *Review of General Psychology, 14,* 68–81.

Ferguson, C. J., Cruz, A. M., & Rueda, S. M. (2007). Gender, video game playing habits and visual memory tasks. *Sex Roles, 58,* 279–286.

Fischer, P., Greitemeyer, T., Morton, T., Kastenmuller, A., Postmes, T., Frey, D., . . . Odenwälder, J. (2009). The racing-game effect: Why do video racing games increase risk-taking inclinations? *Personality and Social Psychology Bulletin, 35,* 1395–1409.

Gagnon, D. (1985). Videogames and spatial skills: An exploratory study. *Educational Communication and Technology Journal, 33,* 263–275.

Gazzaley, A., Clapp, W., Kelley, J., McEvoy, K., Knight, R. T., & D'Esposito, M. (2008). Age-related top-down suppression deficit in the early stages of cortical visual memory processing. *Proceedings of the National Academy of Sciences, USA, 105,* 13122–13126.

Gazzaley, A., & D'Esposito, M. (2007). *Top-down modulation and normal aging.* Oxford, England: Blackwell Publishing.

Green, C. S., & Bavelier, D. (2003, May 29). Action video game modifies visual selective attention. *Nature, 423,* 534–537.

Green, C. S., & Bavelier, D. (2006a). The cognitive neuroscience of video games. In L. Humphreys & P. Messaris (Eds.), *Digital media: Transformations in human communication* (pp. 211–223). New York: Peter Lang Publishing.

Green, C. S., & Bavelier, D. (2006b). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 1465–1478.

Green, C. S., & Bavelier, D. (2006c). Enumeration versus multiple object tracking: The case of action video game players. *Cognition, 101,* 217–245.

Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological Science, 18,* 88–94.

Green, C. S., & Bavelier, D. (2008). Exercising your brain: A review of human brain plasticity and training-induced learning. *Psychology and Aging, 23,* 692–701.

Green, C. S., Li, R., & Bavelier, D. (in press). Perceptual learning during action video game playing. *Topics in Cognitive Science*. Advance online publication. doi:10.1111/j.1756–8765.2009.01054.x

Greenfield, P. M. (1984). *Mind and media: The effects of television, video games, and computers.* Cambridge, MA: Harvard University Press.

Greenfield, P. M. (2009, January 2). Technology and informal education: What is taught, what is learned. *Science, 323,* 69–71.

Griffith, J. L., Voloschin, P., Gibb, G. D., & Bailey, J. R. (1983). Differences in eye–hand motor coordination of video-game users and nonusers. *Perceptual and Motor Skills, 57,* 155–158.

Gutnisky, D. A., Hansen, B. J., Iliescu, B. F., & Dragoi, V. (2009). Attention alters visual plasticity during exposure-based learning. *Current Biology, 19,* 555–560.

Halpern, D. F. (2000). *Sex differences and cognitive abilities.* Mahwah, NJ: Erlbaum.

Haun, D. B. M., Call, J., Janzen, G., & Levinson, S. C. (2006). Evolutionary psychology of spatial representations in the hominidae. *Current Biology, 16,* 1736–1740.

Hegarty, M., Montello, D. R., Richardson, A. E., Ishikawa, T., & Lovelace, K. (2006). Spatial abilities at different scales: Individual differences in aptitude-test performance and spatial-layout learning. *Intelligence, 34,* 151–176.

Hershler, O., & Hochstein, S. (2009). The importance of being expert: Top-down attentional control in visual search with photographs. *Attention, Perception, & Psychophysics, 71,* 1478–1486.

Jeannerod, M. (1986). Mechanisms of visuomotor coordination: A study in normal and brain-damaged subjects. *Neuropsychologia, 24,* 41–78.

Karni, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. *Proceedings of the National Academy of Sciences, USA, 88,* 4966–4970.

Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience, 2,* 315–341.

Kelley, T. A., & Yantis, S. (2009). Learning to attend: Effects of practice on information selection. *Journal of Vision, 9,* 1–18.

Kellman, P. J., & Garrigan, P. (2009). Perceptual learning and human expertise. *Physics of Life Reviews, 6,* 53–84.

Kent, S. L. (2001). *The ultimate history of video games: From* Pong *to* Pokemon*.* New York: Prima Publishing.

Kimura, D. (1999). *Sex and cognition.* Cambridge, MA: MIT Press.

Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Lecture Notes in Artificial Intelligence 1404: Spatial cognition—An interdisciplinary approach to representation and processing of spatial knowledge* (pp. 1–17). Berlin: Springer-Verlag.

Koepp, M. J., Gunn, R. N., Lawrence, A. D., Cunningham, V. J., Dagher, A., Jones, T., . . . Grasby, P. M. (1998, May 21). Evidence for striatal dopamine release during a video game. *Nature, 393,* 266–268.

Kramer, A. F., & Hahn, S. (1995). Splitting the beam: Distribution of attention over noncontiguous regions of the visual field. *Psychological Science, 6,* 381–386.

Landau, B., & Lakusta, L. (2009). Spatial representation across species: Geometry, language, and maps. *Current Opinion in Neurobiology, 19,* 12–19.

Lepsien, J., & Nobre, A. C. (2006). Cognitive control of attention in the human brain: Insights from orienting attention to mental representations. *Brain Research, 1105,* 20–31.

Levene, J. M., Schulman, D., Brahlek, R., & Fleishman, E. A. (1980). *Trainability of abilities: Training and transfer of spatial visualization* (Defense Technical Information Center Report No. AD-A283497). Washington, DC: Advanced Research Resources Organization.

Li, R. J., Polat, U., Makous, W., & Bavelier, D. (2009). Enhancing the contrast sensitivity function through action video game training. *Nature Neuroscience, 12,* 549–551.

Liu, L. L., Uttal, D. H., Marulis, L. M., & Newcombe, N. S. (2008, May). *Training spatial skills: What works, for whom, why and for how long?* Poster presented at the 20th annual meeting of the Association for Psychological Science, Chicago.

Lowery, B. R., & Knirk, F. G. (1982). Micro-computer video games and spatial visualization acquisition. *Journal of Educational Technology Systems, 11,* 155–166.

Maccoby, E. E., & Jacklin, C. N. (1974). *Psychology of sex differences.* Stanford, CA: Stanford University Press.

McClurg, P. A., & Chaillé, C. (1987). Computer games: Environments for developing spatial cognition. *Journal of Educational Computing Research, 3,* 95–111.

Nieder, A., Diester, I., & Tudusciuc, O. (2006, September 8). Temporal and spatial enumeration processes in the primate parietal cortex. *Science, 313,* 1431–1435.

Okagaki, L., & Frensch, P. A. (1994). Effects of video game playing on measures of spatial performance: Gender effects in late adolescence. *Journal of Applied Developmental Psychology, 15,* 33–58.

Olivers, C. N. L. (2008). Interactions between visual working memory and visual attention. *Frontiers in Bioscience, 13,* 1182–1191.

Olson, C. K. (2010). Children's motivations for video game play in the context of normal development. *Review of General Psychology, 14,* 180–187.

Palmer, S. E. (1999). *Vision science: Photons to phenomenology.* Cambridge, MA: MIT Press.

Polat, U. (2009). Making perceptual learning practical to improve visual functions. *Vision Research, 49,* 2566–2573.

Przybylski, A. K., Rigby, C. S., & Ryan, R. M. (2010). A motivational model of video game engagement. *Review of General Psychology, 14,* 154–166.

Przybylski, A. K., Ryan, R. M., & Rigby, C. S. (2009). The motivating role of violence in video games. *Personality and Social Psychology Bulletin, 35,* 243–259.

Rolls, E. T. (2008). Top-down control of visual perception: Attention in natural vision. *Perception, 37,* 333–354.

Rosser, J. C., Lynch, P. J., Cuddihy, L., Gentile, D. A., Klonsky, J., & Merrell, R. (2007). The impact of video games on training surgeons in the 21st century. *Archives of Surgery, 142,* 181–186.

Ryan, R. M., Rigby, C. S., & Przybylski, A. (2006). The motivational pull of video games: A self-determination theory approach. *Motivation and Emotion, 30,* 347–364.

Scolari, M., & Serences, J. T. (2009). Adaptive allocation of attentional gain. *Journal of Neuroscience, 29,* 11933–11942.

Shelton, A. L., & McNamara, T. P. (1997). Representing space: Reference frames and multiple views. In M. G. Shafto & P. Langley (Eds.), *Proceedings of the Nineteenth Annual Conference of the Cognitive Science Society* (p. 1048). Mahwah, NJ: Erlbaum.

Sims, V., & Mayer, E. (2002). Domain specificity of spatial expertise: The case of the video game players. *Applied Cognitive Psychology, 16,* 97–115.

Small, D., & Small, S. (1982). The experts' guide to beating *Asteroids, Battlezone, Galzian Ripoff* and *Space Invaders*. *Creative Computing, 18,* 18–33.

Spence, I., Yu, J. J. J., Feng, J., & Marshman, J. (2009). Women match men when learning a spatial skill. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 1097–1103.

Stickgold, R., James, L., & Hobson, J. A. (2000). Visual discrimination learning requires sleep after training. *Nature Neuroscience, 3,* 1237–1238.

Subrahmanyam, K., & Greenfield, P. M. (1994). Effect of video game practice on spatial skills in girls and boys. *Journal of Applied Developmental Psychology, 15,* 13–32.

Subrahmanyam, K., & Greenfield, P. (2008). Media symbol systems and cognitive processes. In S. Calvert & B. J. Wilson (Eds.), *The Blackwell handbook of children, media, and development* (pp. 166–187). London: Blackwell Publishing.

Terlecki, M. S., Newcombe, N. S., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology, 22,* 996–1013.

Terrell, N. (2007). STEM occupations: High-tech jobs for a high-tech economy. *Occupational Outlook Quarterly, 51,* 26–33.

Thurstone, L. L. (1938). *Primary mental abilities.* Chicago: University of Chicago Press.

Wai, J., Lubinski, D., & Benbow, C. P. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology, 101,* 817–835.

West, G. L., Stevens, S. A., Pun, C., & Pratt, J. (2008). Visuospatial experience modulates attentional capture: Evidence from action video game players. *Journal of Vision, 8,* 1–9.

Wickens, C. D., & Hollands, J. G. (2000). *Engineering psychology and human performance* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

Williams, D., Yee, N., & Caplan, S. E. (2008). Who plays, how much, and why? Debunking the stereotypical gamer profile. *Journal of Computer-Mediated Communication, 13,* 993–1018.

Willis, S. L., Tennstedt, S. L., Marsiske, M., Ball, K., Elias, J., Koepke, K. M., . . . Wright, E. (2006). Long-term effects of cognitive training on everyday functional outcomes in older adults. *Journal of the American Medical Association, 296,* 2805–2814.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review, 15,* 763–771.

Yantis, S., & Jonides, J. (1996). Attentional capture by abrupt onsets: New perceptual objects or visual masking? *Journal of Experimental Psychology: Human Perception and Performance, 22,* 1505–1513.

Yuji, H. (1996). Computer games and information processing skills. *Perceptual and Motor Skills, 83,* 643–647.

Zanto, T. P., & Gazzaley, A. (2009). Neural suppression of irrelevant information underlies optimal working memory performance. *Journal of Neuroscience, 29,* 3059–3066.

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