VIDEO GAMES AS TOOLS TO ACHIEVE INSIGHT INTO COGNITIVE PROCESSES

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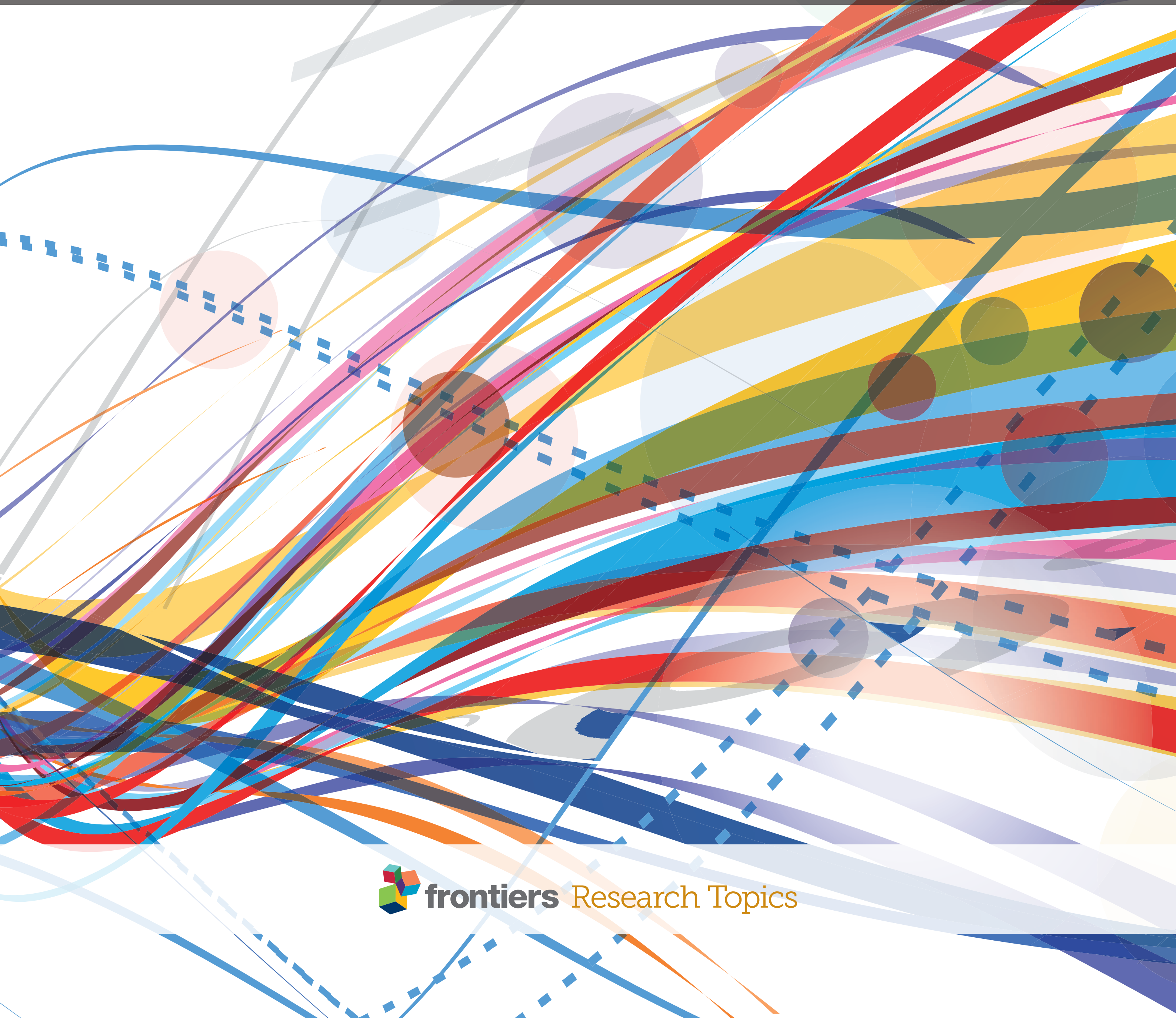

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VIDEO GAMES AS TOOLS TO ACHIEVE INSIGHT INTO COGNITIVE PROCESSES

Topic Editor:
Walter R. Boot, Florida State University, USA

Though traditionally designed for entertainment, video games are being used more and more by psychologists to understand topics such as skill acquisition, cognitive capacity and plasticity, aging, individual differences, and development. The appeal of using video games over simpler laboratory paradigms partly comes from their ability to present rich and complex cognitive challenges more representative of the demands of the complex everyday tasks we perform outside of the laboratory. However, this complexity also presents a host of methodological and analytic challenges. This Research Topic brings together research using games to explore cognitive processes, with a special focus on the challenges of this approach. Challenges are in terms of design, implementation, or data analysis.

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EDITORIAL
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Video games as tools to achieve insight into cognitive processes

Walter R. Boot*

Department of Psychology, Florida State University, Tallahassee, FL, USA
**Correspondence: boot@psy.fsu.edu*

Edited and reviewed by:
Bernhard Hommel, Leiden University, Netherlands

Keywords: video games, cognitive, entertainment, cognitive processes, human cognition

Though traditionally designed for entertainment purposes, video games are increasingly being used by psychologists to aid in our understanding of skill acquisition, cognitive capacity and plasticity, development and aging, and individual differences. Work by Green and Bavelier (2003), now published over a decade ago, generated a great deal of interest by psychologists (and the general public) and an influx of researchers into this domain. However, the tradition of using video games to understand, measure, and improve cognition goes back to at least the mid-to-late 1980s (e.g., Griffith et al., 1983; Gagnon, 1985; Metalis, 1985; Dorval and Pepin, 1986; Clark et al., 1987). The most notable, systematic attempt to use a video game to understand human cognition and performance was the Learning Strategies Program, funded by the Defense Advanced Research Projects Agency (Donchin et al., 1989). Out of this project came the Space Fortress video game, which was developed by cognitive psychologists and designed to require skills such as memory, attention, dual-tasking ability, and psychomotor control and speed. Space Fortress served as a standardized task so performance could be compared across labs (and across continents) to understand the best methods to train complex skill, the relationship between fundamental abilities (e.g., fluid intelligence) and skill development, and the degree to which training gains and task mastery transfer beyond the trained task. Space Fortress is still used across many labs today (e.g., Blumen et al., 2010; Lee et al., 2012; Scheldrup et al., 2014), and has been one of the few video games to be played while functional magnetic resonance imaging has been recorded (e.g., Voss et al., 2012).

Space Fortress has served as an invaluable research tool, and has revealed a great deal about the nature of skill acquisition and learning. However, as anyone who has played the game can attest, Space Fortress gameplay can be a frustrating and unenjoyable experience. Space Fortress was developed by psychologists, not professional game developers. Although it was similar to many arcade games at the time of its development, by today's standards Space Fortress is a relatively primitive game. It features rudimentary graphics, it lacks an engaging narrative, its level of difficulty does not adapt to the player's skill, and it is essentially the same "level" presented to the player over and over again (there are no new challenges or game elements as the player spends more time playing the game). Modern video games feature realistic graphics, compelling stories, are adaptive, have changing demands, and allow the player to approach in-game problems in many different ways. They are designed to be motivating and challenging, but not so challenging as to arouse a high level of frustration. While many of these changes make the study of modern video games more appealing and interesting, the increased complexity and diversity of these games make performance within them more difficult to understand, and this introduces challenges when using video games as tools to achieve insight into cognitive processes. This Research Topic, containing 10 articles, and featuring 45 authors, highlights the promise and challenge of using commercial and custom video games to understand cognition.

Many of the articles included in this Research Topic revolve around the theme of transfer of training from video games to other measures of perception and cognition, inspired by the now seminal work of Shawn Green, Daphne Bavelier, and others (Bavelier et al., 2012). This research suggests that action video game play is associated with superior perceptual and cognitive abilities. Cain et al. (2014) and Pohl et al. (2014) in this Research Topic present evidence in favor of cross-sectional differences between action gamers and non-gamers on measures of vision and attention. However, evidence from cross-sectional and training studies used to support action game effects has been criticized for a variety of methodological reasons (Boot et al., 2011, 2013b; Kristjánsson, 2013; Bisoglio et al., 2014; Ferguson, 2014). Importantly, Cain et al. (2014) and Pohl et al. (2014) provide a full report of their methods and the ways in which participants were recruited, following the best reporting practices outlined by critics of game effects. In their large-sampled training study, Baniqued et al. (2013) found limited transfer of training, but blunt the potential criticism of placebo effects being responsible for the transfer effects that were observed by measuring participants' expectations regarding the type of training they received (see Blacker et al., 2014; for a similar approach).

If video game interventions are determined to improve perceptual and cognitive abilities, then they must be well-designed in order to effectively and efficiently deliver training. Montani et al. (2014) present the design and validation process used to develop a game to exercise attention and executive functioning in individuals with Traumatic Brain Injury (TBI). They demonstrate that their game does tap aspects of executive control, and future intervention studies with TBI patients as participants will determine whether game improvements transfer to other measures of executive control, and more importantly, meaningful measures of everyday performance. Boot et al. (2013a) demonstrate another important issue in terms of video game intervention design. Game intervention design needs to consider the target population of the intervention and the preferences of that population, or intervention adherence will be low and the intervention will fail.

Within this Research Topic, Towne et al. (2014) and Latham et al. (2013) raise interesting and important questions regarding how to measure and classify video game expertise. Many studies use fairly simplistic, undifferentiated definitions of game experience. These definitions often don't make distinctions between very different types of game experience (lumping most fast-paced games into the category of "action game," even though perceptual and cognitive demands may differ greatly between these games). To truly understand the potential effects of game experience on the performance of other laboratory and real-world tasks, we need to better measure how often individuals are playing video games, what they are playing, and their history of gameplay across their lifetime. Towne et al. (2014) argue that methods from the study of expertise in other domains (e.g., chess) can serve as an example.

Finally, Ventura et al. (2013) present a different example of the way video games can be used to understand cognition. Custom games can be used as a way to measure cognitive abilities, much in the same way the Space Fortress game could be seen as a measure of fluid intelligence (Rabbitt et al., 1989). This "stealth assessment" has several advantages, including the reduction of test anxiety. This extremely promising approach might be ported to the laboratory to get better ability measures compared to our typically dull battery of intimidating neuropsychological tests.

This is truly an exciting and fast-moving area of research with many challenges, but also potentially many rewards. Fortunately, we are seeing more and more studies taking steps to overcome these challenges, and more discussion of best practices with respect to using games to gain insight into cognitive processes (including studies and discussion presented in this Research Topic).

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Cognitive training with casual video games: points to consider

Pauline L. Baniqued[1]*, Michael B. Kranz[1], Michelle W. Voss[2], Hyunkyu Lee[3], Joshua D. Cosman[4], Joan Severson[5] and Arthur F. Kramer[1]

[1] Department of Psychology, Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana Champaign, Urbana, IL, USA
[2] Department of Psychology, University of Iowa, Iowa City, IA, USA
[3] Brain Plasticity Institute, San Francisco, CA, USA
[4] Department of Psychology, Vanderbilt University, Nashville, TN, USA
[5] Digital Artefacts LLC, Iowa City, IA, USA

Edited by:
Bernhard Hommel, Leiden University, Netherlands

Reviewed by:
Jutta Kray, Saarland University, Germany
Lauren White, ADGi, USA

****Correspondence:***
Pauline L. Baniqued, Department of Psychology, Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana Champaign, 405 North Mathews Avenue, Urbana, IL 61801, USA
e-mail: banique1@illinois.edu

Brain training programs have proliferated in recent years, with claims that video games or computer-based tasks can broadly enhance cognitive function. However, benefits are commonly seen only in trained tasks. Assessing generalized improvement and practicality of laboratory exercises complicates interpretation and application of findings. In this study, we addressed these issues by using active control groups, training tasks that more closely resemble real-world demands and multiple tests to determine transfer of training. We examined whether casual video games can broadly improve cognition, and selected training games from a study of the relationship between game performance and cognitive abilities. A total of 209 young adults were randomized into a working memory–reasoning group, an adaptive working memory–reasoning group, an active control game group, and a no-contact control group. Before and after 15 h of training, participants completed tests of reasoning, working memory, attention, episodic memory, perceptual speed, and self-report measures of executive function, game experience, perceived improvement, knowledge of brain training research, and game play outside the laboratory. Participants improved on the training games, but transfer to untrained tasks was limited. No group showed gains in reasoning, working memory, episodic memory, or perceptual speed, but the working memory–reasoning groups improved in divided attention, with better performance in an attention-demanding game, a decreased attentional blink and smaller trail-making costs. Perceived improvements did not differ across training groups and those with low reasoning ability at baseline showed larger gains. Although there are important caveats, our study sheds light on the mixed effects in the training and transfer literature and offers a novel and potentially practical training approach. Still, more research is needed to determine the real-world benefits of computer programs such as casual games.

Keywords: attention, working memory, reasoning, fluid intelligence, video games, cognitive training, casual games, transfer of training

INTRODUCTION

What does it mean to "train your brain"? "Brain training games" have increased in popularity over the last decade, with findings and even stronger claims that computer-based tasks of working memory and attention can broadly improve cognition (Jaeggi et al., 2008; Sternberg, 2008; Karbach and Kray, 2009; Klingberg, 2010; Morrison and Chein, 2011). However, there is often insufficient data to support these claims, with many pilot experiments[1] and studies showing improved performance on trained tasks but limited transfer to unpracticed tasks (Willis and Schaie, 1986; Ball et al., 2002; Green and Bavelier, 2003; Willis et al., 2006; Ackerman et al., 2010; Boot et al., 2010; Owen et al., 2010; Mackey et al., 2011; Lee et al., 2012). Some training programs are plagued by replication failures (Boot et al., 2008; Owen et al., 2010; Chooi and Thompson, 2012; Redick et al., 2012; Shipstead et al., 2012; Kundu et al., 2013; Thompson et al., 2013), and methodological issues involving only single tests of transfer to cognitive abilities, placebo effects, and the lack of appropriate active control groups (Boot et al., 2011, 2013). Many programs are also costly and "games" based on laboratory tasks pose implementation concerns in terms of motivation, adherence, and task specialization.

In this study, we use a variety of casual video games, validated by their quantitative association with cognitive constructs, to train aspects of cognitive function such as reasoning ability, working memory, and attentional control. In the validation study (Baniqued et al., 2013), we used a combination of cognitive task analysis, correlational analyses, and structural equation modeling to identify casual games that were most highly associated with well-studied tasks of working memory and reasoning or fluid intelligence. Casual games are relatively easy to learn,

[1] For an example, see http://hcp.lumosity.com/research/bibliography

widely and freely available on the web and on handheld devices, and can be completed in short periods of time, although they still involve a wide array of cognitive skills, complex rules, and challenging objectives. Unlike laboratory-based "games" that train cognitive abilities in more sterile or controlled paradigms, video games demand execution of skills in an integrated or more externally valid environment. For example, multitasking and working memory abilities are tapped in a game (Sushi Go Round) that involves juggling between learning and preparing different recipes correctly, ordering ingredients to keep up with demand, and cleaning the tables to make way for new customers, whereas the laboratory-based dual n-back paradigm requires participants to remember pairs of auditory and visual stimuli in sequence, with predictable order (n-back), timing, and identity of stimuli.

In addition to the richness of the game environments, the novelty and challenge from playing multiple games – akin to athletic "cross-training" (Mackey et al., 2011) may better lead to maximal engagement and gains in cognitive abilities (Green and Bavelier, 2008; Holmes et al., 2009; Schmiedek et al., 2010; Bavelier et al., 2012; Brehmer et al., 2012). The overarching goal of training endeavors is to maintain or improve everyday functioning, so programs should aim to prepare an individual for a variety of challenges. Moreover, skill acquisition research has long shown that training programs that are variable, adaptive, promote cognitive flexibility, and discourage task-specific mastery lead to greater and broader learning (Schmidt and Bjork, 1992; Kramer et al., 1995, 1999). We cannot directly evaluate these concepts in the current study, though they provide a general rationale for the approach of using multiple games to improve cognition.

Training games were selected based on a quantitative analysis of the relationship between game performance and specific cognitive abilities (Baniqued et al., 2013). In the current study, a total of 209 young adults were randomized into four groups: (1) WM-REAS 1, a group that trained on four games (one adaptive across sessions) that heavily tapped working memory and reasoning ability, (2) WM-REAS 2, another working memory–reasoning group that employed four games that were all adaptive across sessions to maximally challenge performance, (3) an active control group that trained on four games (one adaptive across sessions) that did not heavily tap working memory and reasoning, as well as a (4) no-contact control group to better assess practice effects. The WM-REAS groups played a mix of working memory and reasoning games, as validation experiments (Baniqued et al., 2013) showed that these games highly correlated with tests of reasoning and working memory, with little differentiation between the degree of correlation with the two constructs – an unsurprising finding given the integrative nature of the games and the demonstrated relationship between working memory and reasoning abilities (Carpenter et al., 1990; Colom et al., 2004; Kane et al., 2004; Unsworth and Engle, 2006; Jaeggi et al., 2008; Salthouse and Pink, 2008; Conway and Getz, 2010).

In the initial validation study, principal component analysis (PCA) of the games also showed that the WM-REAS 1 games clustered together. This further confirmed that they tapped similar skills, consistent with an *a priori* cognitive task analysis on the casual games. Moreover, structural equation modeling showed that fluid intelligence best predicted performance on most of the games, but that fluid intelligence and working memory accounted for most of the variance in the WM-REAS 1 games at 27 and 14%, respectively (Baniqued et al., 2013). Not surprisingly, correlation coefficients between WM-REAS 1 games and working memory and reasoning tasks were 0.5–0.6 at a composite level, and 0.3–0.5 at an individual task level, all significant at $p < 0.001$. Meanwhile, the active control games did not cluster together and were the least correlated with working memory and reasoning measures, with individual game by task correlations ranging from non-significant to a maximum of around 0.25. Because not all of the WM-REAS 1 games could be implemented to be adaptive across sessions (limitations due to third-party sourcing of the games), we ran a similar validation study on more games that had the ability to be adaptive across sessions. We identified those that showed comparable robust relationships with the same working memory and reasoning tasks used to evaluate WM-REAS 1 games. These additional across-session adaptive games were used for the WM-REAS 2 group (for more detail, see Supplementary Methods[2]). Given the comparable results in the second validation study, the WM-REAS 1 and WM-REAS 2 games differed mainly in their adaptive component. Three out of the four WM-REAS 1 games were not across-session adaptive and may be more susceptible to automaticity or increased reliance on task-specific mastery, and thus not maximally engage working memory and reasoning skills that can better generalize to other paradigms. That is, although we hypothesize that the WM-REAS groups would show greater improvements in cognition compared to the active and no-contact control groups, the WM-REAS 2 group may show larger gains as complex skills are continually challenged for the duration of training.

To address issues in interpreting training and transfer effects, we employed comparable training groups as mentioned above, multiple tests of each cognitive ability, and a post-experiment survey that assessed perceived improvement and inquired about game play outside of the laboratory. The inclusion of a non-WM-REAS active control group was important for assessing whether differential expectations regarding the skills tapped during training may influence performance of the transfer tasks, akin to a placebo effect (Boot et al., 2011, 2013). We also aimed to shed light on the mixed results in the cognitive training literature by discussing our results in the context of previous findings, taking into account video games and laboratory-based experiments, as well as examining individual differences that may have implications for the efficacy of game training.

To summarize, our main predictions consisted of the following: (1) WM-REAS training, given its demand on complex skills, will broadly improve cognition, (2) Individuals lower in cognitive ability (as indexed by a composite measure of reasoning tasks) will show the greatest gains from WM-REAS training, and (3) Given the integrative nature of casual games, improvement expectations will not differ between the WM-REAS and active control groups, thus making a stronger case for the utility of casual game training.

[2]http://lbc.beckman.illinois.edu/pdfs/CasualGames_SuppMethods.pdf

MATERIALS AND METHODS

PARTICIPANTS

Participants were recruited from the Champaign-Urbana community through flyers, newspaper, and online postings advertising participation in a "cognitive training study." Applicants were first screened via email with a questionnaire that surveyed basic demographic information (e.g., sex, education, English language proficiency), and time spent playing video and board games. To mask the purpose of the game questions, these items were embedded with other lifestyle and activity questions that included the Godin Leisure-Time Exercise Questionnaire (Godin and Shephard, 1997). If not excluded based on the survey, a phone interview was conducted to check for medical and non-medical conditions that may affect neuropsychological testing. Although we focus only on the behavioral effects in this paper, we also collected brain scans for the study and thus screened for safety in a magnetic resonance imaging (MRI) environment. Eligible participants were (1) right-handed, (2) between the ages 18 and 30, (3) had normal or corrected-to-normal vision, (4) had no major medical conditions, (5) reported no non-removal metal on their body that might present a safety hazard in the MRI or affect image quality, and (6) reported playing video and board games for 3 h or less per week in the last 6 months. A total of 209 young adults completed the study (see **Table 1** for information on excluded participants and other basic demographic information). All participants signed an informed consent form approved by the University of Illinois Institutional Review Board. Upon study completion, participants were paid $15 an hour for laboratory visits. Participants who dropped out or were disqualified after the first testing session were paid $7.50 an hour. Due to the scale of the study and multitude of tasks administered, detailed procedures can be found in a supplementary document at http://lbc.beckman.illinois.edu/pdfs/CasualGames_SuppMethods.pdf.

STUDY DESIGN

All participants underwent three cognitive testing sessions and an MRI session in a fixed session and task order (**Table 2**). Participants were randomly assigned to one of four groups: working memory and reasoning games (WM-REAS 1), adaptive working memory and reasoning games (WM-REAS 2), active control casual games that did not correlate with working memory and reasoning, or a no-contact control group (**Table 3**). Lab personnel were not blind to group assignment. Participants assigned to the training groups completed training sessions two to three times per week, for a total of 10 sessions. During each training session, four games were played in random order, with each game played for ~20 min each. After training was completed for the training groups or, after a comparable amount of time had elapsed for the no-contact control group, participants completed the same testing sessions in reverse session order.

COGNITIVE ASSESSMENT

Assessments administered before and after training were grouped into five categories: perceptual speed, reasoning/fluid intelligence (gF), working memory, episodic memory, and attentional control (selective visual attention, divided attention). Additionally, participants played two casual video games (one reasoning, one attention) that were not used as training games in any of the groups. Participants also completed the Behavior Rating Inventory of Executive Function Adult Version (Roth et al., 2005). Below is a brief description of each task, with more details in **Table 2**. At the very last testing session, participants were asked about study expectations and gaming experience in more detail. If participants reported in this post-experiment questionnaire that they played the testing or training games outside the laboratory, or were active video game players, their data was discarded from all the analyses. If a participant had 0% accuracy (except for Attentional Blink), a negative d-prime score (where applicable), or scored more than four standard deviations below the mean in a task (mean and standard deviation taken separately for each session), their data was excluded from training-related analyses of that task only. If the outlier data identified using the aforementioned methods was from the post-testing session, that participant's pre-testing score was still used in the pre-test PCA.

Reasoning, episodic memory, and perceptual speed

With the exception of matrix reasoning, all tasks for these three constructs were taken from the Virginia Cognitive Aging Project (Salthouse and Ferrer-Caja, 2003; Salthouse, 2004, 2005, 2010). These tasks have been extensively and uniformly used so only brief descriptions are provided below.

Table 1 | Demographics.

Demographics	WM-REAS 1	WM-REAS 2	Active control	No-contact
Did not complete study due to various reasons	11	12	17	18
Dropped in analysis due to video game play	10	12	9	8
Maximum analysis *N*	43	40	44	43
Male	12	11	12	12
Age	21.16 (2.25)	21.35 (2.61)	20.80 (2.10)	20.70 (2.19)
Years of education	14.78 (1.24)	15.00 (1.83)	14.67 (1.28)	14.80 (1.64)

Shown in the first row is the number of participants excluded from analysis due to study withdrawal, non-compliance with experiment procedures, or scheduling difficulties. During the post-experiment survey, the participants reflected in the second row reported being an active game player or playing the training or testing games outside the lab. All the succeeding measures include only participants (maximum analysis N) not excluded based on the first two criteria. Standard deviations are shown in parentheses.

Table 2 | Transfer tasks.

Transfer tasks	Category	Order	Session	Reference
Shipley abstraction	Reasoning/gF	6	1	Zachary and Shipley (1986)
Paper folding	Reasoning/gF	8	1	Ekstrom et al. (1976)
Spatial relations	Reasoning/gF	10	1	Bennett et al. (1997)
Form boards	Reasoning/gF	11	1	Ekstrom et al. (1976)
Letter sets	Reasoning/gF	12	1	Ekstrom et al. (1976)
Matrix reasoning	Reasoning/gF	22	MRI	Ravens (1962), Crone et al. (2009)
Digit symbol substitution	Perceptual speed	1	1	Wechsler (1997a)
Pattern comparison	Perceptual speed	3	1	Salthouse and Babcock (1991)
Letter comparison	Perceptual speed	4	1	Salthouse and Babcock (1991)
Word recall	Episodic memory	2	1	Wechsler (1997b)
Logical memory	Episodic memory	5	1	Wechsler (1997b)
Paired associates	Episodic memory	9	1	Salthouse et al. (1996)
Visual short-term memory	Working memory	13	2	Luck and Vogel (1997)
Symmetry span	Working memory	16	2	Redick et al. (2012)
N-back	Working memory	17	3	Kirchner (1958), Kane et al. (2007)
Running span	Working memory	19	3	Broadway and Engle (2010)
Spatial working memory	Working memory	20	3	Erickson et al. (2011)
Trail making	Attention	7	1	Reitan (1958)
Attentional blink	Attention	14	2	Raymond et al. (1992)
Task switching	Attention	15	2	Kramer et al. (1999), Pashler (2000)
Color stroop	Attention	18	3	Stroop (1935), Stroop (1992)
Attention network test	Attention	21	MRI	Fan et al. (2002)
Bloxorz*	Game - reasoning/gF	23	MRI	miniclip.com
Dodge*	Game - attention	24	MRI	armorgames.com

*All tasks were administered before and after the training sessions. *For these tasks, the original game developers created local MRI-compatible versions for the study.*

***Word recall*.** Participants listen to lists of words and recall the words in any order.

Logical memory. Participants listen to stories and recall the stories in detail.

Paired associates. Participants remember word pairs and recall the second word in the pair.

Digit-symbol coding. Participants write the corresponding symbol for each digit using a coding table for reference.

Letter comparison and pattern comparison. Participants determine whether a pair of patterns or letter combinations are the same or different.

Form boards. Participants choose shapes that will exactly fill a certain space.

Spatial relations. Participants identify the three-dimensional object that would match a folded two-dimensional object.

Paper folding. Participants identify the resulting pattern of holes from a sequence of folds and a punch through the folded sheet.

Shipley abstract. Participants identify the missing stimuli in a progressive sequence of letters, words, or numbers.

***Letter sets*.** Participants see five patterns and identify the pattern that does not match the others.

Matrix reasoning. The Raven's Progressive Matrices task was modified for a functional MRI paradigm and was largely based on a relational reasoning task used in Crone et al. (2009). Participants viewed a 3×3 matrix containing patterns in all but one cell and chose the best pattern out of three options to identify the missing piece. They solved two types of problems: control trials in which no integration was required across rows and columns, and reasoning trials that required integration of information across cells.

Working memory

Visual short-term memory. An array of four shapes briefly appeared on the screen. After a delay, a shape appeared and participants had to decide whether this stimulus was in the original array. The experiment consisted of three blocks with targets varying in color, shape, and conjunctions of color and shape in each block, respectively.

Table 3 | Training games.

Training games	Group	Description	Primary measure	Source
Silversphere	WM-REAS 1, WM-REAS 2	Move a sphere to a blue vortex by creating a path with blocks of different features, while avoiding falling off the platform and other obstacles.	Maximum level	miniclip.com
Digital Switch	WM-REAS 1	In the main game, switch "digibot" positions to collect falling coins corresponding to the same "digibot" color.	Maximum level	miniclip.com
TwoThree	WM-REAS 1	Shoot down rapidly presented numbers by pointing to them and subtracting the presented numbers down to 0 using units of 2 or 3.	Maximum level	armorgames.com
Sushi Go Round	WM-REAS 1	Serve a certain number of customers in the allotted time by learning and preparing different recipes correctly, cleaning tables, and ordering ingredients.	Maximum money earned	miniclip.com
Aengie Quest	WM-REAS 2	Get character (Aengie) to move across the board and exit each level by pushing switches and boxes, finding keys, and opening doors.	Maximum level	freegamesjungle.com
Gude Balls	WM-REAS 2	Explode all plates by filling a plate with four of the same colored balls and switching balls to other plates. Obstacles are introduced and combined in each level.	Maximum level	bigfishgames.com
Block Drop	WM-REAS 2	Move around a gem on three-dimensional blocks to remove all blocks except the checkered block. Unique block arrangements are presented in each level.	Maximum level	miniclip.com
Alphattack	Active control	Prevent bombs from landing by quickly typing the characters specified on the approaching bombs. There are three main stages of difficulty with levels in each.	Estimated maximum level (level × difficulty)	miniclip.com
Crashdown	Active control	Prevent the wall from reaching the top of the screen by clicking on groups of three or more same colored blocks.	Maximum level	miniclip.com
Music Catch 2	Active control	Earn points by mousing over streams of colored shapes and avoiding contiguously appearing red shapes.	Mean points	reflexive.com
Enigmata	Active control	Navigate a ship while avoiding and destroying enemies, and collecting objects that provide armor or power.	Maximum level	maxgames.com

Games performed by each training group along with the primary measure used for analyses.

N-back. Participants viewed a sequence of centrally presented letters. For each letter, participants were instructed to determine if the letter was the same as the previous letter (first block), the same as the letter two back (second block), or the same as the letter three back (third block).

Spatial working memory. On each trial, a configuration of two, three, or four black dots was presented on the screen. After a brief delay, a red dot appeared and participants were instructed to determine if the red dot was in the same position as one of the black dots presented earlier in that trial.

Running span. Participants are presented a sequence of letters and are instructed to remember the last n items presented.

Symmetry span. Participants performed symmetry judgments while remembering a sequence of red squares within a matrix. Participants were asked to recall the order and locations of the previously presented sequence.

Attentional control

Task switching. Participants were asked to determine whether a number was odd or even, or whether it was higher or lower than five. The background color (blue or pink) determined the task to be performed. Participants completed two single task blocks and then a mixed task block where the task varied unpredictably across trials.

Attentional blink. Participants viewed sequences of rapidly presented black letters. In each sequence, a white letter appeared (location in sequence varied between trials) and on 50% of trials, a black "X" followed the white letter at varying lags. During the critical condition, participants were asked to identify the white letter and whether or not an X was presented.

Trail making. Participants first connected numbers distributed across a sheet of paper by drawing a line between numbers in ascending order. Participants then connected numbers and letters in alternating and ascending order on a second sheet.

Attention network test. Participants responded to the direction of a central arrow that pointed in the same (congruent) or opposite direction (incongruent) as four other adjacent arrows (two on each side). On some trials, warning cues appeared at the center of screen or at the location of the upcoming arrows. The task was adapted for the MRI environment, following procedures detailed in Fan et al. (2002).

Color stroop. Participants viewed a sequence of words and were asked to determine the color of the word. Three trial types were randomly presented: congruent (e.g., word "red" in red ink), neutral (e.g., word "dog" in red ink), or incongruent (e.g., word "red" in blue ink).

Casual video games used for assessment

Dodge. Participants aim to avoid enemy missiles that are actively chasing the ship under their control. Participants earn points and pass levels by guiding missiles into enemies.

Bloxorz. Participants rotate and move a rectangular block around a maze while avoiding falling off the platform. Levels are passed when the block reaches a target hole on the maze.

Self-report instruments

Behavior rating inventory of executive function by PAR™. Participants indicated the frequency that they experienced a variety of executive function problems (never, sometimes, or often). The questionnaire included several dimensions: Inhibit, Shift, Emotional Control, Self-Monitor, Initiate, Working Memory, Plan/Organize, Organization of Materials, and Task Monitor.

Post-experiment questionnaire. Participants completed a form that inquired about gameplay and lifestyle history as well as their experience in the study. In one section (hereafter referred to as perceived improvement questions), they were asked to rate whether they felt that participation in the study changed the following functions: overall intelligence, short-term or working memory, long-term memory, ability to pay attention or focus, ability to pay attention to multiple things at once (divided attention), hand-eye or visuomotor coordination, perception, vision or visual acuity, problem-solving ability, multi-tasking ability, reasoning ability, academic performance, spatial visualization ability, emotional regulation, and productivity at work or school, or tendency to procrastinate. Participants were also asked to give feedback and elaborate on strategies used in the training games, report whether they played any assessment or training games outside the lab (with no penalty to their participation in the study), and answer other questions on the nature of their knowledge and experience with video games.

CASUAL GAMES USED FOR TRAINING

The WM-REAS 1 training group was formed using games that were highly correlated with performance on working memory and reasoning tasks, and the active control training group was composed of games that were not highly correlated with working memory and reasoning tasks (Baniqued et al., 2013). After about 20 participants were run in each of these two groups, we included an adaptive reasoning training (WM-REAS 2) group and a no-contact control group. The WM-REAS 2 group played games that also showed high and comparable correlations (as the WM-REAS 1 games) with working memory and reasoning tasks[3]. Unlike the first two training groups where adaptiveness in three out of the four games was only *within session* (exceptions: Silversphere in WM-REAS 1 and Alphattack in active control), participants in the WM-REAS 2 group started on the level that they ended on in the previous session, such that the games were adaptive *across* sessions. Games were embedded and played on a research portal designed for the study by Digital Artefacts[4]. **Table 3** contains brief descriptions of each game played by the groups. After the first, fifth, and last training sessions, training participants were asked to answer the following questions for each game, rating their answers on a scale of 1–10 (1 = least, 5 = neutral, 10 = greatest): (1) How much did you enjoy/like each game, (2) How engaging was each game, (3) How demanding/effortful was each game, and (4) How motivated were you to achieve the highest possible score on each game?

RESULTS

We first analyze the training games to determine practice-related improvement across the 10 sessions of training. We also assess whether the training groups differed in their experience with their respective games. In the next section, we determine whether game training transfers to untrained tasks by comparing performance on the pre- and post-assessment tasks, first at a construct-level and then at the individual task-level to determine the consistency of the effects. Since transfer to untrained tasks may vary depending on initial cognitive ability, we also investigated the effect of baseline fluid intelligence (reasoning) ability on transfer effects. We then examined whether perceived improvement in cognitive abilities differs across the training groups, which would prompt a re-analysis of the transfer affects to take into account expectations. Finally, we analyze other variables that may affect the effectiveness of training.

PRACTICE EFFECTS

Game performance across sessions

All groups improved on their respective training games, regardless of whether the games were adaptive across sessions. If participants completed the last level of any across-session adaptive game, they started back at level one. For analysis purposes, the data for these succeeding sessions was replaced with the maximum score or level. Repeated measures ANOVA with session as a within-subjects factor (10 time points) was conducted for the primary measure of each game. The practice effects were robust, with significant main effects of session at $p < 0.001$ for all games. In games like Sushi Go Round, where participants started at level one at each session and thus highest level completed plateaued over time, participants improved in other aspects of the game such as in total number of customers served. Group averages are plotted in **Figure 1**, with scores divided by the maximum average score of each game for ease of presentation.

[3]http://lbc.beckman.illinois.edu/pdfs/CasualGames_SuppMethods.pdf
[4]http://research.cognitiveme.com

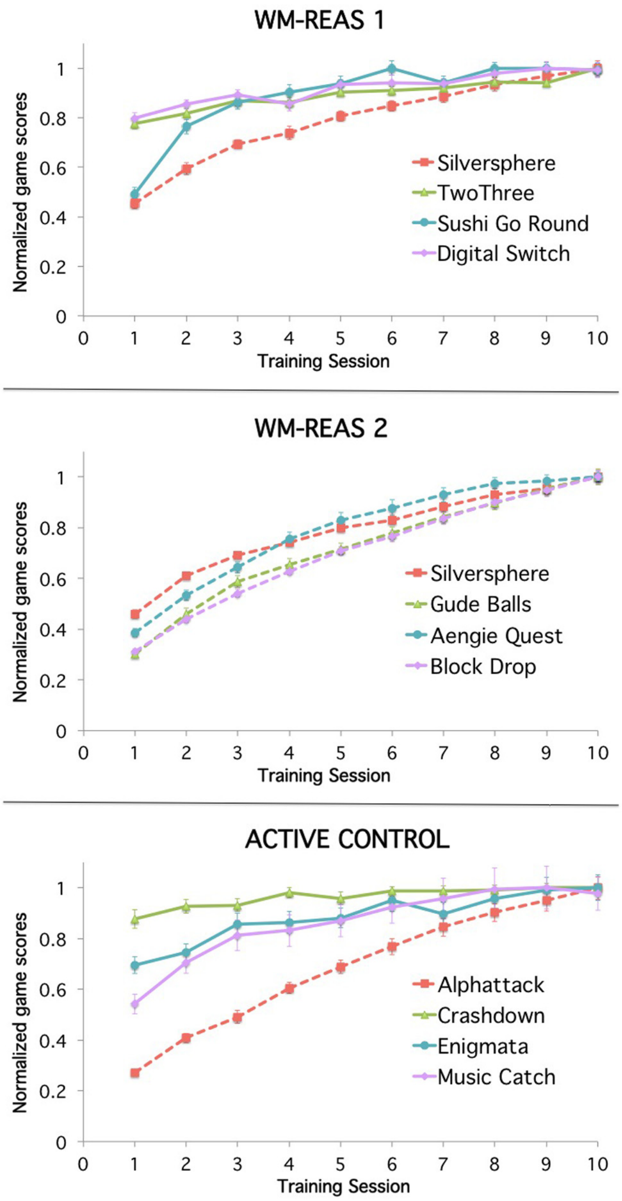

FIGURE 1 | Mean training game performance as a function of group and session. Group average scores at each session, normalized by each game's maximum average score: WM-REAS 1: Silversphere = 18.861, TwoThree = 20.265, Sushi-Go-Round = 5785.429, Digital Switch = 8.161; WM-REAS 2: Silversphere = 19.421, Gude Balls = 14.474, Aengie Quest = 20.526, Block Drop = 52.385; Active Control: Alphattack = 51.867, Music Catch = 4032358.24, Crashdown = 6.667, Enigmata = 4.069. Dashed lines indicate games that were adaptive across sessions. Error bars represent ±SEM.

Game experience across sessions

The four feedback questions of enjoyment, engagement, motivation, and effort were entered separately into repeated measures ANOVAs with group as between-subjects factor and time (training sessions 1, 5, and 10) as within-subjects factor. Ratings for each question were averaged across the four games played by each participant. Results are summarized in **Figure 2**.

For enjoyment, there was no group × time interaction, and no main effects of group and time. For engagement, there was no main effect of group, and no group × time interaction, but a main effect of time where engagement decreased across sessions [$F(2,216) = 7.389$, $p = 0.001$, $\eta_p^2 = 0.064$]. For motivation, there was no group × time interaction, but a main effect of time [$F(2,222) = 5.026$, $p = 0.007$, $\eta_p^2 = 0.043$] with decreased motivation over sessions, and a main effect of group [$F(2,111) = 6.035$, $p = 0.003$, $\eta_p^2 = 0.098$], with lower motivation for the WM-REAS 2 group compared to the WM-REAS 1 and active control groups ($ps < 0.05$). For effort, there was no main effect of time, but a main effect of group [$F(2,111) = 3.339$, $p = 0.045$, $\eta_p^2 = 0.054$], where effort ratings were higher for the WM-REAS 2 group compared to the active control group ($p = 0.017$). The WM-REAS groups were not different from each other and the WM-REAS 1 group did not differ from the active control group. The group × time interaction was significant [$F(4,222) = 2.913$, $p = 0.022$, $\eta_p^2 = 0.050$], with effort ratings for WM-REAS 2 peaking at the fifth session compared to the first session peak for WM-REAS 1. When only taking into account the first and last session, the group × time interaction was not significant [$F(2,115) = 2.364$, $p = 0.099$, $\eta_p^2 = 0.039$]. Overall, the feedback questions indicated that the three training groups were comparable in their experience of the games, although the WM-REAS 2 group reported lower motivation overall and higher effort but only at mid-training, likely due to the greater demand from the adaptive games.

Qualitative feedback regarding strategies and overall experience for each game can be found at http://lbc.beckman.illinois.edu/pdfs/CasualGames_SuppAnalyses.pdf.

TRANSFER OF TRAINING

Composite-level analyses

To ascertain whether game training had any general effect on cognitive abilities and to better address the issue of measurement error and multiple comparisons, we performed analyses at the construct level using composite scores derived by averaging standardized improvement scores (post-test – pre-test/standard deviation of pre-test, collapsed across groups) from related tasks. These task groupings were confirmed by a PCA on the pre-test data. Despite the smaller sample size ($n = 116$, using all subjects with baseline data of each task) and the addition of several measures, the PCA was comparable with the previous validation study (Baniqued et al., 2013), with seven interpretable components that in combination explained 57% of the variance (**Table 4**): reasoning or fluid intelligence (Matrix Reasoning, Paper Folding, Form Boards, Spatial Relations, Letter Sets, Shipley Abstract, Bloxorz), perceptual speed (Digit Symbol, Pattern Comparison, Letter Comparison), episodic memory (Word Recall, Logical Memory, Paired Associates), ANT-visual attention (ANT alerting, orienting effects), divided attention (Dodge, Attention Blink, Trail Making), and two working memory components [N-back, Spatial WM, Visual short-term memory (STM), Running Span, Symmetry Span], with a notable separation between more simple (Component 6: Spatial WM, N-back, Visual STM) and complex (Component 7: Symmetry Span, Running Span) working memory tasks. We also reran the PCA without the ANT measures and the

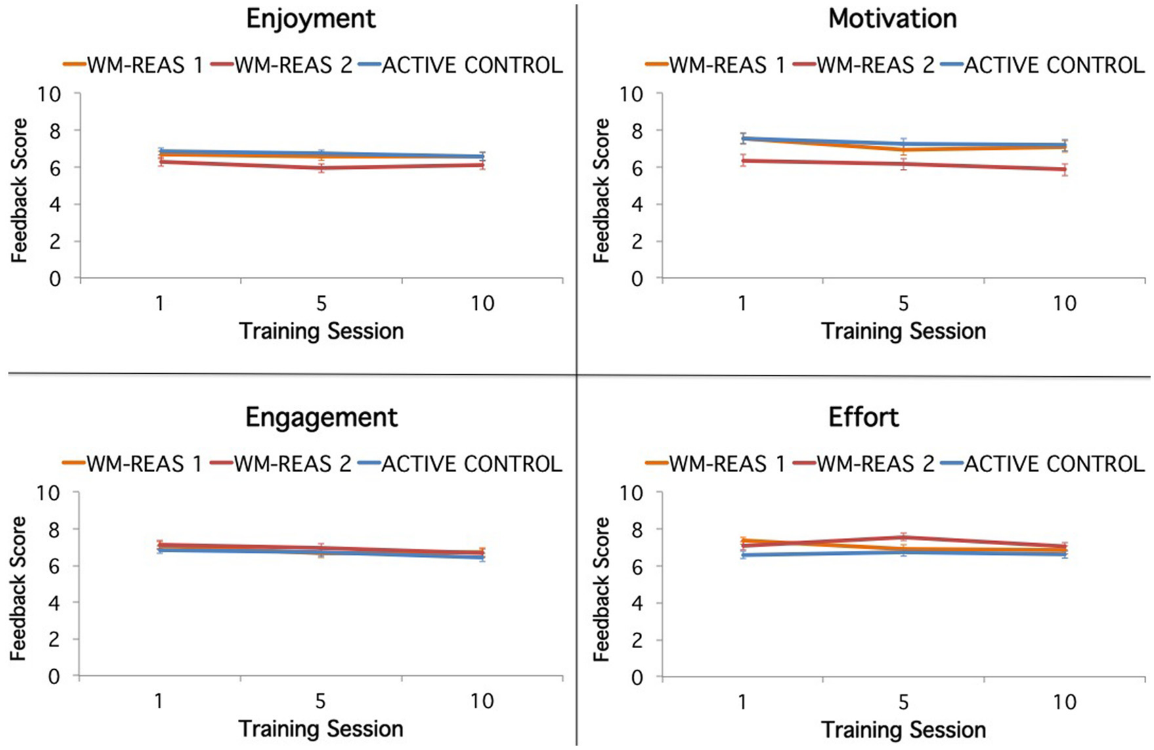

FIGURE 2 | Training game feedback as a function of group and session. Feedback regarding game enjoyment, motivation, engagement, and effort were collected during the first, fifth, and last training sessions. Feedback scale: 1 = least, 5 = neutral, 10 = greatest. Error bars represent ±SEM.

results were similar, with interpretable components of fluid intelligence, perceptual speed, episodic memory, divided attention, and working memory.

Because of the smaller PCA sample size and for ease of interpretation, only tasks that were consistent with previous literature were included in the component score calculations (e.g., WM measures that loaded highly onto the first component were excluded from the gF composite score). Given the overlap of simple and complex WM measures in Components 1, 6, and 7, we combined the simple and complex WM measures into one composite score.

We conducted ANOVAs on the composite gain scores with group as a between-subjects factor and found a significant group effect for divided attention [$F(3,166) = 5.613$, $p = 0.001$, $\eta_p^2 = 0.092$], with higher gain scores for both WM-REAS training groups (**Figure 3**). No group effects were found for fluid intelligence [$F(3,166) = 0.667$, $p = 0.573$, $\eta_p^2 = 0.012$], perceptual speed [$F(3,166) = 0.316$, $p = 0.814$, $\eta_p^2 = 0.006$], episodic memory [$F(3,166) = 0.637$, $p = 0.592$, $\eta_p^2 = 0.011$], ANT-visual attention [$F(3,154) = 0.468$, $p = 0.705$, $\eta_p^2 = 0.009$] and working memory [$F(3,166) = 1.388$, $p = 0.248$, $\eta_p^2 = 0.024$].

ANOVAs on composite scores that included all tasks with loadings of greater than 0.30 yielded similar results. The ANT composite also yielded a non-significant result when the alerting and orienting effects were summed with equal positive weight. The results were also similar for a re-analysis without the no-contact control group; training effects were only found in divided attention [$F(2,124) = 6.676$, $p = 0.002$, $\eta_p^2 = 0.097$].

Task-level analyses

To check whether the groups performed equivalently at pre-testing, one-way ANOVAs with group as between-subjects factor (all four groups) were conducted for all pre-test primary measures reported in **Table 5**. At baseline, group differences were only found in Trail Making measures ($p = 0.039$ for Trails B–A, $p = 0.063$ for Trail B). None of the other measures differed among groups at pre-testing ($ps > 0.13$).

To evaluate transfer of training, repeated measures ANOVAs were performed for each task, with time as a within-subjects factor and group as a between-subjects factor. The ANOVAs were re-run without the no-contact control group and the results were similar, although the effects described below were less robust and at times no longer significant at $p < 0.05$. For brevity, results for analyses with and without the no-contact control group are shown in **Table 5**.

Significant group × time interactions at $p < 0.05$ were found in Dodge, Attentional Blink and Trail-Making, which were also the three tasks that made up the divided attention composite. *Post hoc* tests revealed that both WM-REAS groups reached higher levels of Dodge at post-test (time effect $p < 0.001$ for both groups), while only the WM-REAS 1 group showed a reduced Trails cost at post-test ($p < 0.01$).

Table 4 | Transfer tasks: principal components analysis using baseline data.

PCA of transfer tasks (pre-test scores only)	Component									
	1	2	3	4	5	6	7	8	9	10
Spatial relations	0.828									
Form boards	0.727									
Paper folding	0.682									
Shipley abstraction	0.574		0.337							
Letter sets	0.564									−0.533
Matrix reasoning	0.563									
Spatial STM	0.506					0.418			−0.33	
Pattern comparison		0.794								
Digit symbol coding		0.764								
Letter comparison		0.735								
Symmetry span	0.402	0.515					0.399			
Word recall			0.8							
Paired associates			0.787							
Logical memory			0.633					0.351		
ANT alerting				0.803						
ANT orienting				−0.714				0.345		
Dodge					0.764					
N-back	0.464				0.529	0.428				
Attentional blink				0.385	−0.512					0.34
Trail making					−0.427		−0.427	−0.404		
Task switch local cost						−0.699				
Visual STM	0.307			−0.365		0.611				
Running span							0.81			
ANT conflict								0.75		
Stroop									0.908	
Bloxorz	0.406									0.711

Standardized component loadings from PCA solution, showing components with eigenvalues greater than 1. For clarity, only loadings above 0.30 are displayed. Rotation method: varimax with Kaiser normalization. Listwise exclusion was performed (n = 116).

Because the Trail-Making measures had significant group differences at baseline, driven by longer Trail B times for WM-REAS 1 and WM-REAS 2, we excluded the pre and post-testing data of subjects with the two longest baseline times in each WM-REAS group (which were also the four highest times overall across all groups) so that group mean values were comparable at baseline. These data points were not outliers as identified by methods described earlier. One-way ANOVAs on the subset of data confirmed that the groups were no longer significantly different at baseline. After excluding the longest times, the results were similar to the analysis with all subjects (**Table 5**), with the Trails B–A group × time interaction still significant at $[F(2,126) = 3.373, p = 0.020, \eta_p^2 = 0.061]$.

The magnitude of the attentional blink was smaller at post-test for the WM-REAS 2 ($p < 0.001$) and no-contact control ($p < 0.01$) groups. Since the pattern of results is complex[5], we also analyze lag 2 and lag 8 separately. The group by time interaction for lag 8 was driven by increased performance at post-test for the active control group ($p < 0.001$). For lag 2, the time effect was significant for the no-contact control ($p = 0.002$), WM-REAS 1 ($p = 0.026$) and WM-REAS 2 ($p < 0.001$) groups. Taken together, the results for lag 2, lag 8, and the difference effect (lag 8 – lag 2) suggest that the reduced blink effect is only reliable in the WM-REAS 2 group.

[5]http://lbc.beckman.illinois.edu/pdfs/CasualGames_SuppAnalyses.pdf

Baseline reasoning ability and transfer: composite-level analysis

To determine whether training may be more or selectively effective for those with lower abilities at initial testing, we correlated transfer gains with baseline reasoning or gF ability (pre-training composite of Matrix Reasoning, Paper Folding, Form Boards, Spatial Relations, Letter Sets, Shipley Abstract), which provides an estimate of general mental ability (Gray and Thompson, 2004).

Pre-training gF correlated with gains in divided attention, such that participants with lower baseline gF had larger gains from training. This was significant only for the WM-REAS 1 group

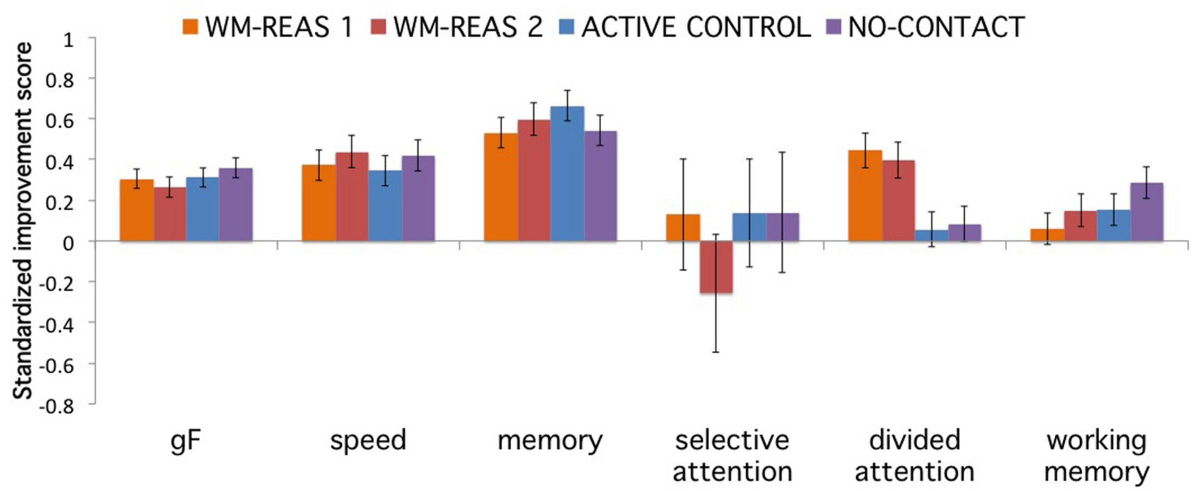

FIGURE 3 | Transfer gain as a function of composite and group. Error bars represent ±SEM.

($r = -0.327$, $p = 0.032$) and the WM-REAS 2 group ($r = -0.333$, $p = 0.036$).

An ANCOVA on the divided attention gain composite with the three training groups as between-subjects factor and with baseline gF as a covariate revealed a significant effect of training after controlling for baseline gF [$F(2,123) = 5.509$, $p = 0.005$, $\eta_p^2 = 0.082$], with larger gains from the WM-REAS groups. Baseline gF was confirmed to have an effect on divided attention gain [$F(1,123) = 6.113$, $p = 0.015$, $\eta_p^2 = 0.047$]. To confirm lack of transfer in other abilities, ANCOVAs with baseline gF as a covariate were also conducted on the other composites. The findings were consistent with previous analyses as no group effects were found.

To test the robustness of the divided attention gains in the WM-REAS groups, we reran the composite-level ANCOVAs after excluding the highest performers (upper quartile) in each group and still found a significant group effect in divided attention (and not in other cognitive abilities), with higher gains in the WM-REAS groups. This was true in analyses with [$F(3,124) = 5.554$, $p = 0.001$, $\eta_p^2 = 0.118$) and without the no-contact control group [$F(2,92) = 6.199$, $p = 0.003$, $\eta_p^2 = 0.119$].

Pre-training gF also correlated with gains in reasoning for the WM-REAS 1 ($r = -0.320$, $p = 0.036$), active control ($r = -0.299$, $p = 049$), and no-contact control ($r = -0.440$, $p = 0.003$) groups. Pre-training gF also correlated with perceptual speed ($r = 0.360$, $p = 0.018$), but this was only true for the WM-REAS 1 group.

PERCEIVED IMPROVEMENT

Post-experiment survey

Compared to the no-contact control group (12.5%), a greater percentage of participants in the three training groups reported that the study changed the way they performed their daily activities, "in a good way" [$\chi^2(3) = 10.010$, $p = 0.018$, WM-REAS 1 = 33.3%, WM-REAS 2 = 43.6%, active control = 37.2%)]. There was no difference between training groups when the no-contact control group was excluded from the chi-square analysis [$\chi^2(2) = 0.917$, $p = 0.639$]. Due to the low frequency of responses in the "Yes, but not in a good way" category (WM-REAS 1 = 2, WM-REAS 2 = 1, active control = 1, no-contact = 0), we excluded this option in the chi-square tests.

All groups reported that their overall skill at videogames was higher at post-test [$F(1,164) = 217.620$, $p < 0.001$, $\eta_p^2 = 0.570$], but a group × session interaction [$F(3,164) = 4.802$, $p = 0.003$, $\eta_p^2 = 0.081$] revealed that the training groups rated themselves significantly higher than the no-contact control group. There was, however, no difference between the three training groups in perceived video game skill after training [$F(2,125) = 0.070$, $p = 0.933$, $\eta_p^2 = 0.001$].

Due to experimenter error that resulted in a change in instructions when a web-based form of the survey was administered, for the perceived improvement questions, we only present statistics for subjects who received the same electronic version of the post-experiment survey (although all subjects are included in **Figure 4** to provide the general pattern of results). In the initial written survey completed by 22 out of 44 subjects in WM-REAS 1, and 16 out of 44 subjects in the active control group, participants checked a box to indicate whether the study changed that particular ability, and then rated the extent of the change (1 = very poorly, 10 = very desirably). In the web-based survey, each item required an answer. That is, participants had to rate change on the ability on a scale of 1–10, which lent more ambiguity as an answer of 1 could now be interpreted as no change or negative change.

Separate question ANOVAs revealed a significant group effect at $p < 0.05$ for working memory [$F(3,126) = 2.765$, $p = 0.045$], hand-eye or visuomotor coordination [$F(3,126) = 5.332$, $p = 0.002$], multitasking [$F(3,126) = 6.714$, $p < 0.001$], problem-solving [$F(3,126) = 2.944$, $p = 0.036$], reasoning [$F(3,126) = 3.730$, $p = 0.013$], and academic performance [$F(3,126) = 4.530$, $p = 0.005$], with higher ratings in general for the training groups compared to the no-contact control group. When the perceived improvement questions were analyzed without the no-contact

Table 5 | Mean task performance as a function of training group and session.

Transfer results				WM-REAS 1		WM = REAS 2		Active control		No-contact	
Task	**Measure**	**Group (4) × session**	**Group (3) × session**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Digit Symbol	Total correct	$F(3,163) = 0.739$,	$F(2,122) = 1.072$,	93.881	99.69	91.525	99.775	96.093	103.093	94.786	101.762
		$p = 0.530$, $\eta_p^2 = 0.013$	$p = 0.346$, $\eta_p^2 = 0.017$	(2.123)	(1.979)	(2.175)	(2.028)	(2.098)	(1.956)	(2.123)	(1.979)
Pattern Comparison	Mean correct	$F(3,166) = 1.065$,	$F(2,124) = 1.629$,	21.465	23.442	20.575	22.225	21.682	22.716	21.651	23.291
		$p = 0.366$, $\eta_p^2 = 0.019$	$p = 0.200$, $\eta_p^2 = 0.026$	(0.529)	(0.5)	(0.549)	(0.518)	(0.523)	(0.494)	(0.529)	(0.5)
Letter Comparison	Mean correct	$F(3,166) = 0.370$,	$F(2,124) = 0.304$,	13.302	13.57	12.50	13.062	12.977	13.523	13.058	13.779
		$p = 0.775$, $\eta_p^2 = 0.007$	$p = 0.739$, $\eta_p^2 = 0.005$	(0.359)	(0.397)	(0.373)	(0.412)	(0.355)	(0.392)	(0.359)	(0.397)
Logical Memory	Total correct	$F(3,166) = 0.252$,	$F(2,124) = 0.090$,	48.535	52.721	48.325	52.575	48.227	52.977	49.14	52.581
		$p = 0.860$, $\eta_p^2 = 0.005$	$p = 0.914$, $\eta_p^2 = 0.001$	(1.373)	(1.353)	(1.423)	(1.403)	(1.357)	(1.338)	(1.373)	(1.353)
Word Recall	Total correct	$F(3,166) = 1.275$,	$F(2,123) = 0.862$,	53.651	58.512	52.692	58.974	53.341	58.636	54.302	58.884
		$p = 0.285$, $\eta_p^2 = 0.023$	$p = 0.425$, $\eta_p^2 = 0.014$	(0.939)	(0.86)	(0.986)	(0.903)	(0.928)	(0.85)	(0.939)	(0.86)
Paired Associates	Accuracy	$F(3,160) = 1.105$,	$F(2,118) = 1.360$,	0.618	0.701	0.716	0.791	0.661	0.807	0.678	0.8
		$p = 0.349$, $\eta_p^2 = 0.020$	$p = 0.261$, $\eta_p^2 = 0.023$	(0.039)	(0.035)	(0.04)	(0.035)	(0.039)	(0.035)	(0.038)	(0.034)
Form Boards	Total correct	$F(3,165) = 0.462$,	$F(2,123) = 0.249$,	9.628	12.326	9.897	12.872	10.909	13.364	10.14	12.302
		$p = 0.709$, $\eta_p^2 = 0.008$	$p = 0.780$, $\eta_p^2 = 0.004$	(0.624)	(0.642)	(0.656)	(0.674)	(0.617)	(0.634)	(0.624)	(0.642)
Paper Folding	Total correct	$F(3,166) = 0.775$,	$F(2,124) = 0.587$,	7.953	8.698	8.8	9.3	8.932	9.773	8.279	9.256
		$p = 0.509$, $\eta_p^2 = 0.014$	$p = 0.557$, $\eta_p^2 = 0.009$	(0.343)	(0.301)	(0.355)	(0.312)	(0.339)	(0.297)	(0.343)	(0.301)
Spatial Relations	Total correct	$F(3,164) = 0.232$,	$F(2,123) = 0.191$,	11.535	13.023	12.1	13.25	13.395	14.674	12.452	14
		$p = 0.874$, $\eta_p^2 = 0.004$	$p = 0.827$, $\eta_p^2 = 0.003$	(0.675)	(0.623)	(0.7)	(0.646)	(0.675)	(0.623)	(0.683)	(0.63)
Letter Sets	Total correct	$F(3,162) = 0.271$,	$F(2,121) = 0.333$,	12.095	12.571	12.564	12.744	12.884	13.14	12.381	12.786
		$p = 0.846$, $\eta_p^2 = 0.005$	$p = 0.718$, $\eta_p^2 = 0.005$	(0.252)	(0.249)	(0.261)	(0.258)	(0.249)	(0.246)	(0.252)	(0.249)
Shipley Abstract	Total correct	$F(3,166) = 0.163$,	$F(2,124) = 0.197$,	15.814	16.86	15.325	16.575	15.909	17.114	15.419	16.674
		$p = 0.921$, $\eta_p^2 = 0.003$	$p = 0.821$, $\eta_p^2 = 0.003$	(0.326)	(0.294)	(0.338)	(0.305)	(0.322)	(0.291)	(0.326)	(0.294)
Matrix Reasoning	Reasoning	$F(3,164) = 0.559$,	$F(2,124) = 0.629$,	79.302	73.411	78.667	71.25	77.689	72.955	78.211	73.415
	accuracy	$p = 0.643$, $\eta_p^2 = 0.010$	$p = 0.535$, $\eta_p^2 = 0.010$	(1.456)	(1.513)	(1.509)	(1.569)	(1.439)	(1.496)	(1.491)	(1.55)
	Control accuracy	$F(3,164) = 0.080$,	$F(2,124) = 0.106$,	97.519	97.597	97.083	96.667	97.803	97.727	97.48	97.48
		$p = 0.971$, $\eta_p^2 = 0.001$	$p = 0.900$, $\eta_p^2 = 0.002$	(0.55)	(0.652)	(0.57)	(0.676)	(0.544)	(0.644)	(0.563)	(0.668)
Bloxorz	Last level	$F(3,158) = 0.422$,	$F(2,119) = 0.094$,	4.317	4.976	4.41	5.154	4.405	5.119	4.35	5.225
	completed	$p = 0.738$, $\eta_p^2 = 0.008$	$p = 0.910$, $\eta_p^2 = 0.002$	(0.153)	(0.153)	(0.157)	(0.157)	(0.151)	(0.151)	(0.155)	(0.155)

(Continued)

Table 5 | Continued

Transfer results				WM-REAS 1		WM = REAS 2		Active control		No-contact	
Task	**Measure**	**Group (4) × session**	**Group (3) × session**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Dodge	Last level	$F(3,159) = 3.199$,	$F(2,118) = 2.192$,	8.897	9.538	8.925	9.45	8.929	9.167	9.095	9.167
	completed	$p = 0.025$, $\eta_p^2 = 0.057$	$p = 0.116$, $\eta_p^2 = 0.036$	(0.144)	(0.109)	(0.142)	(0.107)	(0.139)	(0.105)	(0.139)	(0.105)
Attentional Blink	Lag 8 – lag 2	$F(3,164) = 4.327$,	$F(2,124) = 5.085$,	0.345	0.298	0.39	0.269	0.347	0.402	0.469	0.358
	accuracy	$p = 0.006$, $\eta_p^2 = 0.073$	$p = 0.008$, $\eta_p^2 = 0.076$	(0.045)	(0.045)	(0.046)	(0.047)	(0.044)	(0.044)	(0.046)	(0.046)
	Lag 2 accuracy	$F(3,164) = 1.616$,	$F(2,124) = 1.749$,	0.424	0.504	0.367	0.482	0.444	0.475	0.359	0.482
		$p = 0.118$, $\eta_p^2 = 0.029$	$p = 0.178$, $\eta_p^2 = 0.027$	(0.039)	(0.044)	(0.04)	(0.045)	(0.038)	(0.043)	(0.04)	(0.045)
	Lag 8 accuracy	$F(3,164) = 2.656$,	$F(2,124) = 3.407$,	0.769	0.802	0.757	0.751	0.792	0.876	0.828	0.84
		$p = 0.050$, $\eta_p^2 = 0.046$	$p = 0.036$, $\eta_p^2 = 0.052$	(0.026)	(0.024)	(0.027)	(0.025)	(0.026)	(0.024)	(0.027)	(0.025)
Trail Making	Trails B–A RT (s)	$F(3,161) = 4.271$,	$F(2,119) = 2.090$,	26.958	20.863	25.746	23.232	21.241	20.146	21.657	24.489
		$p = 0.006$, $\eta_p^2 = 0.074$	$p = 0.128$, $\eta_p^2 = 0.0341$	(1.699)	(1.593)	(1.81)	(1.697)	(1.679)	(1.574)	(1.679)	(1.574)
	Trails A (s)	$F(3,161) = 0.258$,	$F(2,119) = 0.007$,	27.592	23.434	25.608	21.527	26.497	22.222	26.306	20.962
		$p = 0.856$, $\eta_p^2 = 0.005$	$p = 0.993$, $\eta_p^2 < 0.001$	(1.423)	(0.995)	(1.516)	(1.061)	(1.406)	(0.984)	(1.406)	(0.984)
	Trails B (s)	$F(3,161) = 3.596$,	$F(2,119) = 2.255$,	54.549	44.297	51.354	44.759	47.737	42.368	47.963	45.451
		$p = 0.015$, $\eta_p^2 = 0.063$	$p = 0.109$, $\eta_p^2 = 0.037$	(2.053)	(1.864)	(2.187)	(1.986)	(2.029)	(1.842)	(2.029)	(1.842)
Task Switching	Switch-repeat RT	$F(3,159) = 0.539$,	$F(2,118) = 0.722$,	267.731	259.396	290.985	272.458	246.059	258.306	274.598	276.566
	(ms)	$p = 0.656$, $\eta_p^2 = 0.010$	$p = 0.488$, $\eta_p^2 = 0.012$	(16.745)	(18.525)	(17.393)	(19.242)	(16.544)	(18.303)	(16.544)	(18.303)
	Switch-repeat	$F(3,159) = 0.729$,	$F(2,118) = 0.177$,	−0.021	−0.016	−0.019	−0.019	−0.015	−0.015	−0.016	−0.029
	accuracy	$p = 0.536$, $\eta_p^2 = 0.014$	$p = 0.889$, $\eta_p^2 = 0.002$	(0.007)	(0.008)	(0.007)	(0.009)	(0.007)	(0.008)	(0.007)	(0.008)
	Single-repeat RT	$F(3,159) = 0.689$,	$F(2,118) = 0.714$,	192.3	172.87	202.926	168.306	180.445	180.937	206.949	173.492
	(ms)	$p = 0.560$, $\eta_p^2 = 0.013$	$p = 0.492$, $\eta_p^2 = 0.012$	(15.638)	(14.56)	(16.243)	(15.123)	(15.45)	(14.385)	(15.45)	(14.385)
	Single-repeat	$F(3,159) = 0.661$,	$F(2,118) = 0.956$,	0.023	0.032	0.031	0.019	0.014	0.029	0.023	0.021
	accuracy	$p = 0.577$, $\eta_p^2 = 0.012$	$p = 0.387$, $\eta_p^2 = 0.016$	(0.012)	(0.011)	(0.012)	(0.012)	(0.012)	(0.011)	(0.012)	(0.011)
Attention Network	No cue – center,	$F(3,152) = 0.063$,	$F(2,116) = 0.079$,	21.315	23.341	18.001	24.66	14.248	20.26	18.173	24.184
Test	RT (ms)	$p = 0.979$, $\eta_p^2 = 0.001$	$p = 0.924$, $\eta_p^2 = 0.001$	(5.42)	(6.287)	(5.866)	(6.805)	(5.292)	(6.139)	(5.705)	(6.618)
	Location – center,	$F(3,152) = 0.192$,	$F(2,116) = 0.057$,	63.479	54.724	50.722	45.086	58.953	54.6	54.19	55.472
	RT (ms)	$p = 0.902$, $\eta_p^2 = 0.004$	$p = 0.945$, $\eta_p^2 = 0.001$	(6.695)	(7.472)	(7.246)	(8.087)	(6.537)	(7.296)	(7.047)	(7.865)
	Inc-con, RT (ms)	$F(3,152) = 0.672$,	$F(2,116) = 0.759$,	132.402	117.847	134.627	112.92	125.825	120.688	122.882	103.643
		$p = 0.571$, $\eta_p^2 = 0.013$	$p = 0.471$, $\eta_p^2 = 0.013$	(9.33)	(8.849)	(10.099)	(9.578)	(9.111)	(8.641)	(9.822)	(9.315)

(Continued)

Table 5 | Continued

Transfer results				WM-REAS 1		WM = REAS 2		Active control		No-contact	
Task	**Measure**	**Group (4) × session**	**Group (3) × session**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Stroop	Inc-neu, RT (ms)	$F(3,162) = 1.019$,	$F(2,122) = 1.395$,	51.439	45.966	47.529	53.566	62.07	47.242	59.814	59.616
		$p = 0.386$, $\eta_p^2 = 0.019$	$p = 0.252$, $\eta_p^2 = 0.022$	(8.095)	(7.404)	(8.196)	(7.496)	(7.814)	(7.147)	(8.095)	(7.404)
	Inc-con, RT (ms)	$F(3,162) = 0.100$,	$F(2,122) = 0.115$,	82.642	78.122	87.682	82.264	80.306	80.088	85.58	85.25
		$p = 0.960$, $\eta_p^2 = 0.002$	$p = 0.891$, $\eta_p^2 = 0.002$	(8.795)	(8.166)	(8.904)	(8.268)	(8.49)	(7.883)	(8.795)	(8.166)
Running Span	Total correct	$F(3,163) = 1.847$,	$F(2,122) = 2.414$,	21.833	21.952	22.2	21.525	20.721	22.814	21.19	22.738
		$p = 0.141$, $\eta_p^2 = 0.033$	$p = 0.094$, $\eta_p^2 = 0.038$	(0.885)	(0.959)	(0.906)	(0.983)	(0.874)	(0.948)	(0.885)	(0.959)
Symmetry Span	Total correct	$F(3,123) = 0.797$,	$F(2,83) = 1.129$,	18.19	20.476	19.55	24.65	21.08	25.56	18.22	22.756
		$p = 0.498$, $\eta_p^2 = 0.019$	$p = 0.328$, $\eta_p^2 = 0.026$	(1.811)	(1.972)	(1.312)	(1.429)	(1.659)	(1.807)	(1.296)	(1.411)
Spatial STM	Accuracy	$F(3,164) = 2.436$,	$F(2,122) = 1.103$,	0.882	0.852	0.862	0.853	0.883	0.892	0.856	0.878
		$p = 0.067$, $\eta_p^2 = 0.043$	$p = 0.149$, $\eta_p^2 = 0.031$	(0.013)	(0.015)	(0.013)	(0.015)	(0.012)	(0.014)	(0.012)	(0.014)
	d′	$F(3,164) = 0.822$,	$F(2,122) = 1.178$,	2.941	2.807	2.641	2.634	2.846	3.065	2.789	2.95
		$p = 0.484$, $\eta_p^2 = 0.015$	$p = 0.311$, $\eta_p^2 = 0.019$	(0.157)	(0.199)	(0.159)	(0.202)	(0.152)	(0.192)	(0.153)	(0.195)
Visual STM	Overall accuracy	$F(3,165) = 0.443$,	$F(2,123) = 0.443$,	0.795	0.795	0.804	0.795	0.812	0.806	0.795	0.795
		$p = 0.722$, $\eta_p^2 = 0.008$	$p = 0.643$, $\eta_p^2 = 0.007$	(0.009)	(0.009)	(0.009)	(0.01)	(0.009)	(0.009)	(0.009)	(0.009)
	Overall d′	$F(3,165) = 0.455$,	$F(2,123) = 0.502$,	1.741	1.761	1.784	1.721	1.84	1.813	1.737	1.748
		$p = 0.714$, $\eta_p^2 = 0.008$	$p = 0.606$, $\eta_p^2 = 0.008$	(0.065)	(0.07)	(0.068)	(0.072)	(0.065)	(0.07)	(0.065)	(0.07)
	Both d′	$F(3,165) = 0.388$,	$F(2,123) = 0.324$,	1.308	1.411	1.327	1.315	1.281	1.384	1.287	1.254
		$p = 0.761$, $\eta_p^2 = 0.007$	$p = 0.724$, $\eta_p^2 = 0.006$	(0.11)	(0.105)	(0.114)	(0.109)	(0.11)	(0.105)	(0.11)	(0.105)
	Color d′	$F(3,165) = 1.316$,	$F(2,123) = 1.249$,	3.029	2.757	2.815	3.019	2.943	3.008	2.9	2.638
		$p = 0.271$, $\eta_p^2 = 0.023$	$p = 0.290$, $\eta_p^2 = 0.020$	(0.182)	(0.192)	(0.188)	(0.199)	(0.182)	(0.192)	(0.182)	(0.192)
	Shape d′	$F(3,165) = 0.357$,	$F(2,123) = 0.423$,	1.857	1.887	1.842	1.674	1.979	1.884	1.999	1.803
		$p = 0.784$, $\eta_p^2 = 0.006$	$p = 0.656$, $\eta_p^2 = 0.007$	(0.159)	(0.129)	(0.165)	(0.134)	(0.159)	(0.129)	(0.159)	(0.129)
N-back	2-Back d′	$F(3,161) = 0.287$,	$F(2,120) = 0.432$,	4.551	4.59	4.07	4.153	4.723	5.261	4.338	4.535
		$p = 0.835$, $\eta_p^2 = 0.005$	$p = 0.650$, $\eta_p^2 = 0.007$	(0.361)	(0.355)	(0.38)	(0.373)	(0.357)	(0.351)	(0.361)	(0.355)
	3-Back d′	$F(3,161) = 2.072$,	$F(2,120) = 2.049$,	2.354	2.672	2.228	2.869	2.589	2.454	2.002	2.597
		$p = 0.106$, $\eta_p^2 = 0.037$	$p = 0.133$, $\eta_p^2 = 0.033$	(0.219)	(0.26)	(0.23)	(0.273)	(0.216)	(0.257)	(0.219)	(0.26)
	2-Back accuracy	$F(3,161) = 0.753$,	$F(2,120) = 0.923$,	0.947	0.951	0.938	0.931	0.955	0.964	0.947	0.955
		$p = 0.522$, $\eta_p^2 = 0.014$	$p = 0.400$, $\eta_p^2 = 0.015$	(0.007)	(0.009)	(0.008)	(0.009)	(0.007)	(0.009)	(0.007)	(0.009)
	3-Back accuracy	$F(3,161) = 2.008$,	$F(2,120) = 1.271$,	0.882	0.88	0.85	0.878	0.861	0.878	0.845	0.885
		$p = 0.115$, $\eta_p^2 = 0.036$	$p = 0.284$, $\eta_p^2 = 0.021$	(0.012)	(0.012)	(0.013)	(0.013)	(0.012)	(0.012)	(0.012)	(0.012)

ANOVA results are shown for analyses with and without the no-contact control group. Pre-subtraction data are only displayed for tasks where the difference or effect score was significant. Parentheses indicate ±SEM.

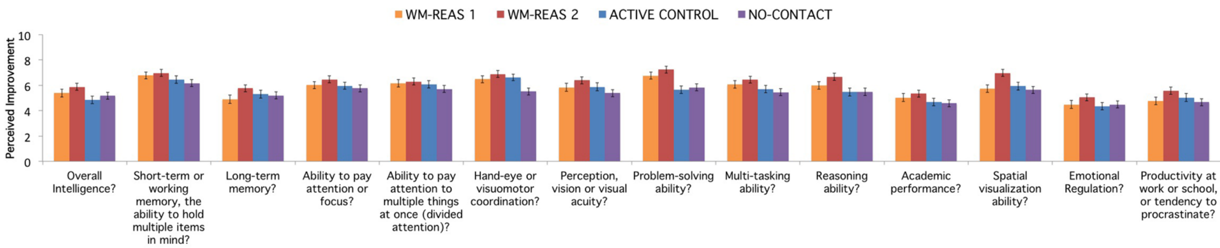

FIGURE 4 | Perceived improvement as a function of group. Average responses for each group, including data from WM-REAS 1 and active control participants who did not receive a web-based version of the post-experiment survey. Error bars represent ±SEM.

control group, however, only the group effects for multitasking [$F(2,88) = 6.300$, $p = 0.003$] and academic performance [$F(2,87) = 3.305$, $p = 0.041$] remained significant, although none of the *post hoc* comparisons between groups were significant at $p < 0.05$.

Behavioral rating inventory of executive function

Repeated measures ANOVA revealed a significant group × time interaction only for the Shift index (problems transitioning between activity, strategy or situation), both when the no-contact control group was included in the analyses [$F(3,141) = 3.995$, $p = 0.009$, $\eta_p^2 = 0.078$], and when it was not [$F(2,94) = 5.129$, $p = 0.008$, $\eta_p^2 = 0.098$]. Paired t-tests revealed that this was due to an increase in Shift problems for the WM-REAS 1 group, although this effect must be taken lightly as the WM-REAS 1 group also had a lower mean Shift score at pre-test compared to the other groups, and only 21 subjects in this group completed the questionnaire at both time-points. Given the limited range of answers (never, sometimes, often) and the relatively weak task effects, it is possible that the BRIEF questionnaire could not adequately measure any subtle changes or differences between groups. Overall, the BRIEF results are consistent with the perceived improvement findings where majority of participants reported little to no improvement in cognitive functions or daily activities.

EXPLORATORY ANALYSIS: OTHER INDIVIDUAL DIFFERENCES AND TRANSFER GAIN

We found that initial reasoning/gF ability predicted gains in divided attention, so we went a step further and conducted an exploratory analysis of other individual differences that may influence the effectiveness of WM-REAS casual game training. A few studies have found that training-related transfer is predicted by the amount of improvement in the trained tasks, such that greater "responders" show greater transfer (Jaeggi et al., 2011, 2013). We examined this in the current study by correlating transfer gain composite scores with training gain composite score. For each individual in each training group, we calculated the difference between performance in the later sessions (9, 10) and performance in the early sessions (1, 2). This difference score was then divided by the standard deviation in the early sessions (within each group). Standardized scores for the four games were then averaged to form a training gain composite score. Correlations conducted separately for each training group did not reveal any significant relationship between training gain and transfer gains, even after controlling for baseline game performance.

Mixed results from previous studies, coupled with small sample sizes and population demographic differences suggest the contribution of other factors such as gender, motivation, and other pre-existing abilities to training effectiveness (Jaeggi et al., 2013). Thus, for the WM-REAS groups, correlations were conducted between each transfer gain composite score and the following factors: gender, game play habits (only <3 h/week; combined modalities), training game experience (enjoyment, engagement, motivation, and effort after fifth and last training sessions), bilingualism, exercise (Godin Leisure-Time questionnaire), time spent watching television/movies, sleeping, reading books/magazines/newspapers, surfing the web, on social network sites, meditating, in nature, learning a new language, and learning a new instrument. Given the within-group and exploratory nature of this analysis, we only state correlations that were significant at $p < 0.01$.

For the WM-REAS 1 group, more time on social network sites ($r = 0.458$, $p = 0.002$) correlated with higher divided attention gains, and more time spent reading correlated with gains in fluid intelligence ($r = 0.461$, $p = 0.002$).

For the WM-REAS 2 group, game effort at mid-training correlated with gains in divided attention ($r = 0.443$, $p = 0.008$) such that greater effort was associated with larger gains. There was also correlation between sleep and gains in ANT-visual attention gain ($r = 0.470$, $p = 0.004$).

We did not find significant correlations with the other factors, which may be due to the lack of variability or lack of representation in certain conditions (e.g., maximum of less than 3 h weekly video game play), especially given the predominantly collegiate make-up of the sample.

DISCUSSION

We examined whether widely available casual video games can broadly improve cognition by demonstrating transfer to untrained tasks. In our relatively sizeable sample (approximately 40 participants in each group), we found that while participants improved on trained games, transfer to untrained tasks was limited. Playing casual video games for 15 h did not improve most aspects of cognition, but playing working memory and reasoning casual games improved divided attention, with some caveats to be noted. As several of the training tasks involve working memory and reasoning demands in several fast-paced situations, and given our findings of higher divided attention gains for those with lower initial reasoning ability, we also provide a link between the working memory and action video game training literature.

EFFECTS OF WM-REAS TRAINING ON COGNITIVE FUNCTION

Groups trained on working memory and reasoning games improved in a composite measure of divided attention. All three tasks used for the divided attention score (Dodge, Attentional Blink, Trail Making) involve paying attention to multiple targets, with little demand on maintaining internal representations of stimuli. Multi-object tracking demands were also part of the active control games (Enigmata, Alphattack, Crashdown, MusicCatch), but it is likely that the lack of reasoning or planning demands in the games led to a more passive strategy as participants only reacted to objects as they appeared on the screen. Indeed, participant feedback for the active control games contained more statements about psychomotor strategies such as clicking as quickly as possible in response to stimuli. On the other hand, the WM-REAS groups practiced a mix of speeded and non-speeded tasks, with the speeded tasks (Silversphere, Sushi-Go-Round, DigiSwitch, TwoThree, Gude Balls) requiring both planning ahead and attention to multiple stimuli on the screen. The additional management demands in the WM-REAS games may have better developed divided attention skills as coordinated execution of multiple elements was critical to success in many games.

In the initial game validation study (Baniqued et al., 2013), fluid intelligence best predicted performance on multi-object tracking games such as Dodge, with Dodge performance also significantly correlating with performance on reasoning games (and not just attention or multiple-object tracking games). These findings can be taken as evidence of near transfer when taking into account the previously demonstrated relationship between Dodge and reasoning ability, and relatively far transfer given the dissimilar surface features of the trained games and transfer tasks such as Dodge. Such transfer to untrained paradigms bolsters the idea that the complex and more externally valid environment found in strategy-heavy video games may provide a more useful and practical platform for developing cognitive skills (Green et al., 2010).

These results are consistent with findings that playing strategy-demanding time-limited games can enhance attention skills (Green and Bavelier, 2003, 2006a,b, 2007; Basak et al., 2008; Hubert-Wallander et al., 2011a; Glass et al., 2013; Oei and Patterson, 2013). More strikingly, our findings parallel research (Bavelier et al., 2012) showing that active video game players perform better in a variety of attention-demanding tasks, including the attention blink and multiple-object tracking paradigms. We did not find improvements in the Attention Network Test, but this is not entirely unexpected in the context of other findings that active video game players do not show benefits for exogenous attention (Hubert-Wallander et al., 2011b). It is especially interesting that despite also playing fast-paced and attention-demanding games, the active control group did not improve to the level of the participants who practiced games with greater reasoning and working memory demands.

Working memory capacity has repeatedly been shown to correlate with attention abilities, with findings that capacity can predict the magnitude of the attentional blink (Arnell and Stubitz, 2010). We did not find increases in working memory capacity or fluid intelligence, but it is plausible that such changes in higher-level abilities evolve more slowly than changes in lower level attention abilities, following the developmental trajectory of processing speed, working memory, and fluid intelligence (Fry and Hale, 1996; Kail, 2007; Coyle et al., 2011). Alternatively, it may be that at least in young adults, training abilities such as working memory does not improve capacity *per se*, but more lower-level attention or information processing mechanisms that overlap or are common elements across reasoning, working memory, and other attentional control paradigms (Thorndike, 1913). In fact, Kundu et al. (2013) found that while dual n-back training did not improve fluid intelligence or complex working memory span, training improved "efficiency of stimulus processing", as indexed by improvements in visual search and short-term memory. More and more studies find that training on a single adaptive working memory task does not transfer to working memory capacity or fluid intelligence (Chooi and Thompson, 2012; Redick et al., 2012; Lilienthal et al., 2013; Thompson et al., 2013), and studies that do find transfer observe them in attention measures (Chein and Morrison, 2010; Kundu et al., 2013; Oelhafen et al., 2013). On the other hand, it is also worth mentioning that a greater variety of training tasks may be more effective for demonstrating transfer to higher-level abilities. A study that trained participants on multiple working memory tasks for an average of 30 h over 12 weeks resulted in gains in several measures of reasoning, although the sample size in this study was relatively small (Jaušovec and Jaušovec, 2012), and transfer to other cognitive domains such as attention was not assessed. While the pattern of transfer results depends on the nature of the training tasks, overall the evidence points to working memory training as weakly beneficial for fluid intelligence, but promising in terms of enhancing attention skills.

A common difficulty in intervention studies is employing appropriate control groups to address placebo effects. We attempted to overcome this here by using multiple training groups and measuring performance expectations after training. Despite all training groups reporting equivalent increases in perceived videogame skill, only the reasoning groups improved in Dodge performance. This is especially interesting given that the active control games emphasized processing speed and tracking multiple objects on the screen. We found a group effect in multi-tasking expectations, however, the pairwise comparisons between training groups was not significant. Moreover, training feedback showed that the groups were generally comparable in enjoyment, engagement, motivation and effort. The WM-REAS 2 group reported less motivation overall and slightly greater effort at mid-training, which is likely due to the greater demands from the across-session adaptive games. Such reported challenge or difficulty can be argued to account for the transfer results, though this does not explain why the WM-REAS 1 group also demonstrated transfer even without differences in perceived effort or motivation during training. It is likely that in the context of this experiment where individuals are paid for simply playing games, motivation does not play a significant role in determining training effectiveness.

Although we cannot determine whether only a subset of WM-REAS games led to the effects in the reasoning groups, we can infer that playing a variety of reasoning games promoted more generalizable skills as opposed to task mastery. Taatgen (2013) makes a compelling argument that tasks such as working memory and task switching promote development of "proactive" control that encourages endogenous preparation. As several of the WM-REAS games and strategy video games involve fast-paced decision making, endogenous preparation likely comes into play such that sequence of actions are planned ahead of time and deployed quickly at the right moment. Conversely, it can be argued that the active control games promoted more "reactive" control that is not measurable in the cognitive abilities we tested. Taatgen further makes the argument that executive function training improves "skill" and not "capacity," which echoes a sentiment articulated by Luck and Vogel (2013) that greater working memory capacity may not lead to better problem-solving, but that individuals who can flexibly develop strategies to enhance performance may more ably execute working memory and other related tasks (Kirby and Lawson, 1983). Participants in the WM-REAS groups completed a variety of challenges in the WM-REAS games and practiced these problem solving skills (with many self-reports of "trying out new combinations, strategies") under demanding and in some occasions, extremely time-limited conditions. This idea of enhanced decision-making under high load is also a main explanation provided for why playing fast-paced action games leads to improvement in attention-demanding tasks (Hubert-Wallander et al., 2011a; Mishra et al., 2011). In this regard, our findings are in line with previous research and extend the literature by showing that game-related improvement in attention skills may also result from non-violent gaming environments.

This study was conducted with healthy young adults, which limits the extension of these results to other populations. However, the correlation between divided attention transfer gain and baseline reasoning, selected as a proxy for general ability (Gray and Thompson, 2004), suggests that these kinds of protocols may be more useful in populations that have more to gain from training, such as children or older adults who experience age-related cognitive decline. This relationship between pre-existing differences in cognitive ability and training efficacy also offers an explanation for the mixed results in training studies. As most working memory training studies have relatively small sample sizes (for a review, see Morrison and Chein, 2011), individual differences may enhance or obscure any effects of training on a subset of participants.

LIMITATIONS AND FUTURE DIRECTIONS

We acknowledge that other factors such as improvement expectations may influence the transfer results. However, due to the ambiguity of the scale in the perceived improvement questions, we could not reliably factor in expectations in the statistical analyses. Nonetheless, it is interesting to note that the training groups did not significantly differ in perceived improvement, and that the WM-REAS groups improved in divided attention, an ability where their expectations did not differ from the active control group. Although we found a group difference in perceived multitasking improvement, which can be taken as related to divided attention, the *post hoc* comparisons were not significant. Moreover, no improvements were found in Task Switching or in Symmetry Span, both of which clearly involved managing multiple tasks.

It should also be noted that the divided attention composite includes tasks that are not as extensively evaluated as the tasks used to estimate reasoning, perceptual speed and episodic memory abilities. Nonetheless, similarities in Dodge, Attention Blink and Trail Making were confirmed by a PCA and give us more confidence in the divided attention score. We also revisited the validation study and found correlations between Dodge, Attention Blink and Trail-Making measures. The tasks may also be sensitive to practice effects, although all groups performed the same tests and no improvements were found in the control groups. Nonetheless, this training approach needs to be re-examined with a more extensive battery of attentional control tasks to shed light on why benefits were not observed in tasks like Symmetry Span which also involved divided attention, albeit in the form of shifting from one task to another. The tasks that showed transfer involved distributing attention across objects in space (Trail Making, Dodge), or across a narrow time frame, as is the case with Attentional Blink, but this needs to be further evaluated.

It can also be argued that the improvement in the WM-REAS groups was due to a change in strategy when performing the assessments. This is worthwhile to explore in future studies since working memory–reasoning tasks may not improve divided attention *per se*, but planning or reasoning abilities that may be best observed or manifested in such "divided attention" tasks. It may also be the case that despite their high correlations with working memory and reasoning, the WM-REAS games demanded other skills for successful gameplay over the course of training, with a shift of emphasis from reasoning to divided attention skills as participants gained mastery of the games. Indeed, the degree to which reasoning ability predicts performance has been shown to change, with declining influence at later points of skill acquisition (Ackerman, 1988; Quiroga et al., 2009, 2011).

Ceiling performance and practice effects due to lack of alternate versions for six out of the seven fluid intelligence tasks (including Bloxorz) may contribute to the null effect in fluid intelligence, although note that gains were also not observed in the matrix reasoning task used in the magnet, which presented unique items at pre- and post-testing, with lower post-testing performance overall due to task design (**Table 5**). This null finding is consistent with decades-old literature showing that fluid intelligence is relatively stable in adulthood (Jensen, 1969; though with age-related decreases) and further challenges the claim that cognitive training can lead to improvement in this ability (Jaeggi et al., 2008; Sternberg, 2008). However, it is conceivable that the game training period in the current study was too short to train such an ability, and that more hours of practice may result in stronger and broader effects on cognition. Some participants also reached ceiling performance in the training games, so it would be useful to test whether playing more demanding games can lead to transfer to higher-level abilities of working memory and reasoning. In a recent experiment, Glass et al. (2013) found increases in cognitive flexibility following 40 h of real-time strategy game play (StarCraft) that emphasized a variety of skills including reasoning, working memory, and rapid switching in an adaptive and integrated setting.

Real-world measures of divided attention are needed to verify whether playing working memory and reasoning casual games can transfer to useful skills in daily life. Moreover, we did not conduct follow-up retention tests, so it is not known whether benefits persist beyond the training period. It is to be expected, however, in the same way as physical exercise, that continued practice is essential to maintaining or reaping intervention-related benefits.

Other interventions have been shown to improve cognition, and we provide modest evidence that playing casual games is *one possible means* to improve attention skills. The relatively non-violent nature of casual games compared to first-person shooter games also minimizes concerns regarding the negative effects of video game play. Nevertheless, with the aggressive marketing of brain games and the liberal application of preliminary training results, we caution against using video games or other computer-based programs as a sole or primary approach to improving brain function, particularly if it leads to a more sedentary lifestyle or in the words of Weis and Cerankosky (2010) "displace(s) activities that might have greater educational value." Activities such as physical exercise have repeatedly been shown to benefit not only overall physical health, but also neurocognitive function (Hillman et al., 2008; Voss et al., 2013). Future studies should investigate the effects of combined and synergistic interventions to elucidate the ways in which activities may commonly and differentially change brain function. The goal of this line of research is not simply to evaluate the efficacy of interventions or the superiority of one over another, but to identify several avenues that promote a better quality of life, as a program that works for a certain population may not be suitable for another.

AUTHOR CONTRIBUTIONS

All the authors contributed to designing the study. Pauline L. Baniqued and Michael B. Kranz supervised data collection and analyzed the data. Pauline L. Baniqued wrote the first draft of the manuscript with help from Michael B. Kranz for the section "Materials and Methods." All the authors revised the manuscript.

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Video games as a means to reduce age-related cognitive decline: attitudes, compliance, and effectiveness

Walter R. Boot[1]*, Michael Champion[2], Daniel P. Blakely[1], Timothy Wright[1], Dustin J. Souders[1] and Neil Charness[1]

[1] Department of Psychology, Florida State University, Tallahassee, FL, USA
[2] Cognitive Science and Engineering, Technological Entrepreneurship and Innovation Management, Arizona State University, Mesa, AZ, USA

Edited by:
Shulan Hsieh, National Cheng Kung University, Taiwan

Reviewed by:
Guido P. Band, Leiden University, Netherlands
Jutta Kray, Saarland University, Germany

***Correspondence:**
Walter R. Boot, Department of Psychology, Florida State University, 1107 W. Call Street, Tallahassee, FL 32306-4301, USA.
e-mail: boot@psy.fsu.edu

Recent research has demonstrated broad benefits of video game play to perceptual and cognitive abilities. These broad improvements suggest that video game-based cognitive interventions may be ideal to combat the many perceptual and cognitive declines associated with advancing age. Furthermore, game interventions have the potential to induce higher rates of intervention compliance compared to other cognitive interventions as they are assumed to be inherently enjoyable and motivating. We explored these issues in an intervention that tested the ability of an action game and a "brain fitness" game to improve a variety of abilities. Cognitive abilities did not significantly improve, suggesting caution when recommending video game interventions as a means to reduce the effects of cognitive aging. However, the game expected to produce the largest benefit based on previous literature (an action game) induced the lowest intervention compliance. We explain this low compliance by participants' ratings of the action game as less enjoyable and by their prediction that training would have few meaningful benefits. Despite null cognitive results, data provide valuable insights into the types of video games older adults are willing to play and why.

Keywords: cognitive training, video games, transfer of training

INTRODUCTION

As we age, we can expect to experience greater difficulty with tasks involving a number of perceptual and cognitive abilities (e.g., Schaie, 1996; Salthouse, 2010). These declines are associated with decreased ability to perform the everyday tasks required for functional independence, such as the ability to drive a car, adhere to a medication schedule, and manage finances (e.g., Ball et al., 1993; Diehl et al., 1995; Royall et al., 2004). An important question is whether age-related cognitive and perceptual declines can be slowed or reversed (Hertzog et al., 2009; Lövdén et al., 2010).

Two challenges must be overcome in the development of effective cognitive aging interventions. First, over a century of research suggests that training gains are often extremely specific (Boot and Blakely, 2011). Training on one task almost invariably results in improvement, but this improvement rarely transfers to novel tasks or even tasks similar to the trained task. However, in studies involving young adults, action video game training appears to improve a broad range abilities (e.g., Green and Bavelier, 2006a,b, 2007; Li et al., 2009, 2010; Chisholm et al., 2010; Colzato et al., 2010; Granek et al., 2010; Green et al., 2010, 2012; Clark et al., 2011; but see also Boot et al., 2011). These results are remarkable because (1) transfer assessment tasks were dissimilar from the trained games, (2) improvements were observed in abilities that show large age-related decline, and (3) improvements were often engendered after a short period of training (10–50 h).

The second challenge to overcome is designing interventions that encourage intervention compliance. Interventions that include video games would seem to be ideal to encourage compliance as video games are assumed to be inherently motivating and enjoyable. However, game designers often do not consider the older adult demographic in their design and marketing of games, and the types of games that appeal to older adults may be very different from the games that appeal to younger adults. Furthermore, there may be a mismatch between the games that older adults enjoy playing and the types of games that result in the largest perceptual and cognitive gains. Older adults report a preference for games that involve intellectual challenge compared to the fast-paced action games that tend to produce the broadest transfer of training (Pearce, 2008; Nap et al., 2009; McKay and Maki, 2010). However, even games that promote intellectual challenge may not be effective in inducing compliance. Ackerman et al. (2010) asked participants who had just completed an intervention involving the brain fitness game Big Brain Academy® whether or not they planned on ever playing the game again. Sixty-three percent of participants indicated that they did not.

The current study aimed to assess the efficacy of game interventions in improving cognition. In addition, and potentially just as important, the current study investigated the factors that shape motivation and compliance with respect to game-based interventions in an older adult sample and evaluated older adults' attitudes and expectations with respect to video game interventions. One game was an action game because these types of games have been previously reported to be effective at improving a host of abilities. The other was a brain fitness game similar in style to a previous game found to be ineffective (Ackerman et al., 2010), but contained features of games that seniors typically enjoy. We were particularly interested in handheld devices as a means to deliver training since these have the advantage of being relatively cheap, easy to use, and portable compared to interventions delivered on a personal computer or gaming console. However, these advantages would need to overcome usability issues that might be associated with small screens and difficult-to-use input devices (see Boot et al., 2012 for more discussion).

MATERIALS AND METHODS

PARTICIPANTS

Sixty-two participants (Mean Age = 74 years old, SD = 6, range = 54–86) were recruited from the Tallahassee community and assigned to one of two game intervention conditions or a no-contact control group (**Table 2**). Participants lived in independent living situations, were Caucasian, received a minimum score of 25 on the MMSE (M = 29, SD = 1.04), and most (90%) were retired. Pre-screening ensured participants had an "intact" score according to the Short Portable Mental Status Questionnaire (less than or equal to two errors; Pfeiffer, 1975), and demonstrated no significant memory deficits using the Wechsler Memory Scale (Logical Memory subscale; age-adjusted criterion; Wechsler, 1997). This pre-screening helped to ensure that participants were neurologically intact; otherwise participants were not screened based on medication use or neurological function or disease. Average near visual acuity was 20/32. Participants were paid 10 dollars an hour for all laboratory visits. All procedures were approved by Florida State University's Human Subjects Committee, and written informed consent was obtained from all participants.

STUDY DESIGN

With the exception that spouses/partners were assigned to the same condition, participants were randomly assigned to one of three groups. One group received an action video game to play, another group received a "brain fitness" game to play, and the third group served as a control group for test-retest effects. A battery of ability measures was administered once before and once at the end of the study to assess any potential change as a result of gameplay over the course of three 1.5 to 2-h sessions before and after a 12-week period.

Cognitive assessment battery

Assessment measures fell into one of four broad categories: Perceptual Speed, Memory, Selective Attention/Executive Control, and Reasoning Ability (**Table 1**). Well-being was also assessed before and after training. Full details of each task can be found at: http://walterboot.net/GameStudy/DetailedMethods.pdf. Here we present a brief overview of each measure.

Processing speed. *Simple and choice reaction time* Participants saw a square appear at the center of the screen and were asked to respond quickly when they saw it (simple RT), or pushed one of two keys depending on which side of the screen the square appeared on (choice RT).

Number comparison Participants had to judge as quickly as possible whether the two strings of numbers were the same or different. The same form was used pre and post-test. Responses were indicated by writing or not writing a mark between the two number strings using a pen.

Visual search Participants viewed a briefly presented search display. Distractors were square items, and the target was a triangle within a circle. After the search display appeared it was masked, and participants were asked to indicate where the target appeared.

Memory. *Corsi block tapping* Participants viewed computer images with a number of squares that turned red, then back to gray one at a time. Participants were asked to remember the sequence of color changes, and to click using the mouse each square in the same order in which they changed. Sequences varied from four to seven color changes.

Everyday recognition Participants were given stimuli such as banking statements and prescription labels to remember. They had 1 min to memorize these materials, and 1 min to answer questions about the memorized materials. Two forms were created by dividing the Everyday Cognition Battery (ECB) Recognition Questionnaire into two. One form was administered before training and

Table 1 | List of principal cognitive outcome measures.

Task name	Construct assessed	Critical measure	Number of test trials/questions	Comments
Simple/complex RT	Processing speed	Reaction time	80	Based on Czaja et al. (2006)
Number comparison	Processing speed	Accuracy (timed)	96	Ekstrom et al. (1976)
Visual search	Processing speed	Accuracy	72	Based on Sekuler and Ball (1986)
Corsi block tapping	Spatial memory	Accuracy	24	Based on Corsi (1972)
Everyday recognition	Memory	Accuracy	15	Modification of Allaire and Marsiske (1999)
Meaningful memory	Memory	Accuracy	20	Hakstian and Cattell (1975)
MSEQ	Memory	Confidence	20	West et al. (2005)
Flanker task	Selective attention	Flanker interference	80	Based on Eriksen and Eriksen (1974)
Task switching	Executive control	Switch cost	90	Based on Basak et al. (2008)
Raven's matrices	Reasoning	Accuracy (timed)	18	Modification of Raven et al. (2003)
Everyday reasoning	Reasoning	Accuracy	21	Modification of Allaire and Marsiske (1999)
Letter sets	Reasoning	Accuracy (timed)	30	Ekstrom et al. (1976)
MIDUS	Well-being	Well-being ratings	42	Brim et al. (1996)

Table 2 | Demographics for all participants and for participants who completed the study as a function of group assignment.

	N		Mean age		Proportion male	
	All	Completed	All	Completed	All	Completed
Control	20	20	72 (1.4)	72 (1.4)	0.45	0.45
Brain fitness game	21	20	74 (1.2)	73 (1.1)	0.33	0.35
Action game	21	14	75 (1.5)	73 (1.9)	0.48	0.50

Standard errors listed within parenthesis.

For the game groups completion rates favored Brain Fitness: $X^2(1) = 5.56$, $p < 0.02$.

one after training, with the order of forms counterbalanced across participants.

Meaningful memory Participants were given a list of 20 nouns and words that described each noun and had 1 min and 15 s to memorize this information. Ten minutes later, they were given the same nouns, and a choice of four descriptors, none of which matched the original descriptor exactly. The task of the participant was to pick the word closest in meaning to the original descriptor paired with each noun. The same form was used pre and post-test.

Memory Self-Efficacy Questionnaire Participants were presented with a number of scenarios varying in difficulty and were asked to rate their confidence that they could perform the memory tasks described (from 0% confidence, to 100% confidence). Of primary interest was self-confidence of memory ability. The same form was used pre and post-test.

Selective attention/executive control. *Flanker task* Participants saw an arrow at the center of the screen and had to respond to whether the arrow pointed to the left or right. Two arrows appeared to either side of the target arrow and could be either congruent or incongruent with the target arrow (pointing in the same or different direction). Of primary interest was flanker interference, or the cost associated with the flanking arrows providing incongruous information. This is thought to reflect a failure of selective attention, or inability to restrict processing to relevant information while excluding the processing of irrelevant information.

Task switching Participants viewed sequences of numbers and judged whether numbers were high or low, or odd or even by pushing one of two keys as quickly as possible. The color of the screen informed participants which task to perform. The task to be performed was unpredictable. Switch costs were calculated to reflect the cost in terms of speed and accuracy of having to switch from one task to the other[1].

Reasoning ability. *Raven's matrices* The Raven's Advanced Matrices test was divided into two forms of approximately equal difficulty (18 questions each). Order of administration was counterbalanced across participants. Each trial presented participants a visual pattern with a piece cut out of it, and eight options to fill in the missing piece (one being correct).

Everyday reasoning Participants were given stimuli such as different nutrition labels or bank statements and were asked to answer questions about them. Two forms were created by dividing the ECB Reasoning Questionnaire into two. One form was administered before training, and one after training, with the order of forms counterbalanced across participants.

Letter sets Participants viewed sets of letters with all but one letter set being governed by a common rule. The task of the participant was to discover the rule and mark the letter set that did not follow the rule. The same form was used pre and post-test.

Well-being. *Midlife in the United States Scale* This survey asked participants to rate their well-being. The Midlife in the United States Scale (MIDUS) has subscales of well-being focusing on autonomy, environmental mastery, positive relationships with others, personal growth, life purpose, and self-acceptance.

Game perception and attitude surveys In addition to the cognitive assessment battery, participants who received a game to play were also asked to complete two surveys, one which assessed their attitudes toward the game they were given to play and one which assessed their belief that the game they were given to play was capable of improving perceptual and cognitive abilities[2].

Survey and phone data Participants who received a game to play were given a diary in which they were asked to keep a record of their game play (date and amount of time played). They were also encouraged to make notes about their game experience. Phone calls were placed every 1–2 weeks to each participant in the game groups. These calls asked participants about their gameplay frequency. These data served as measures of intervention compliance.

Game training The *Nintendo DS™ Lite* gaming system was used to deliver the video game intervention. Participants who were assigned to one of the game groups were given a brief tutorial and demonstration of their training game before they left the laboratory on the last day of the pre-training cognitive assessment battery. Participants were requested to play their assigned game five times a week, for 1 h each gaming session. In total, participants should have obtained 60 h of game experience over the course of the study.

The Action Game group received the racing game *Mario Kart DS®*. In this game, the player races against other computer-controlled characters while avoiding dangers on the race track and using items and weapons against opponents. *Mario Kart DS®* was chosen based on past research demonstrating that action game training can produce a variety of benefits. Although these previous studies have mostly used violent first-person shooters, older adults tend to dislike this type of game experience (Nap et al., 2009). Non-violent games with less realistic cartoon depictions, like *Mario Kart DS®*, have been found to be more acceptable to

[1]Note that this particular measure of task-switch cost may have put us at a disadvantage to detect an effect, the largest age-related switch costs are observed in the difference between single-task blocks and dual-task blocks of trials (i.e., general rather than specific switch costs; Kray and Lindenberger, 2000; Reimers and Maylor, 2005).

[2]http://walterboot.net/GameStudy/GameTrainingQuest.pdf

older adults (McKay and Maki, 2010). Despite differing significantly from first-person shooters, *Mario Kart DS*® shares many characteristics of an action game, with action games being defined as games "that have fast motion, require vigilant monitoring of the visual periphery, and often require the simultaneous tracking of multiple targets" (e.g., Green and Bavelier, 2006a, p. 1466). Racing success requires players to monitor multiple fast-moving racers that can attack the player with various traps and weapons, and who the player can attack to take the lead. Attention must also be divided between two different screens, one depicting an egocentric perspective and one showing a birds-eye view of the race. Monitoring of multiple locations and multiple enemies is consistent with first-person shooters. However, "monitoring of the visual periphery" may be somewhat minimized given the size of the game screens.

The Brain Fitness group received *Brain Age 2*™, a brain-training game largely targeted to older adults as a means to improve cognitive performance. Players engage in a multitude of activities emphasizing memory, reaction time, language, and mathematical ability. For most activities, the *Nintendo DS*™ is held like a book and the stylus is used to input letters, numbers, or mathematical operators depending on the nature of the activity. Some activities used voice recognition. *Brain Age 2*™ was chosen because of its explicit focus on cognitive training, although previous research has found similar training activities to produce no effect on cognition (Ackerman et al., 2010; Owen et al., 2010; but see more recently Nouchi et al., 2012).

Finally, one group received no training to control for test-retest effects. Perceptual and cognitive abilities of this group were tested, and were tested again after approximately 3 months.

RESULTS

First, we turn our attention to whether either video game intervention had a significant effect on cognition, then we discuss issues of compliance, and finally we consider perceptions and attitudes toward game interventions. Fifty-four of 62 participants completed the study. Of the participants who did not complete the study, one was assigned to the Brain Fitness group and seven were participants assigned to the Action Game Group. This differential attrition was the first indication that although we predicted the action game to be more effective at improving cognition, older adults would show a preference for the brain fitness game.

COGNITIVE BATTERY

Due to computer error, misadministration of an assessment task, or participants skipping answers or otherwise not providing a complete data set, some participants had to be excluded from analysis of individual tasks. Improvement scores were computed by comparing pre-training and post-training performance (such that positive scores always corresponded to greater improvement). Of primary interest was whether a significant effect of group (Control, Action Game, Brain Fitness Game) was observed. **Table 3** lists means and standard errors for each task as a function of time (pre, post-training) and group. Reaction time measures included only accurate trials. First, an ANOVA approach was taken looking for group differences in each individual task. This approach revealed no greater improvement for either game group (Action Game or Brain Fitness Game) relative to the no-game control group[3].

A number of additional analyses were conducted to search for any hint of a video game effect. For example, it could be that when all measures of performance are considered together rather than individually, a small but general effect of game training is present. To test for this possibility, improvement scores for all objective measures of performance (excluding subjective measures such as MIDUS and the Memory Self-Efficacy Questionnaire) were standardized. These were then averaged across tasks measuring similar constructs to produce composite improvement scores representing Processing Speed (combining Reaction Time, Number Comparison, Visual Search data), Memory (combining Corsi Block Tapping, Everyday Recognition, Meaningful Memory data), Attention/Executive Control (combining Flanker Task and Tasks Switching data), and Reasoning Ability (combining Raven's Matrices, Everyday Reasoning, and Letter Sets data). Composite measures were entered into an MANOVA with group as a factor and age as a covariate. This indeed revealed an effect of group [$F(8, 96) = 2.13$, $p < 0.05$, $\eta_p^2 = 0.15$]. While the effect of group was not significant for Processing Speed [$F(2, 50) = 0.24$, $p = 0.61$, $\eta_p^2 = 0.02$], Memory [$F(2, 50) = 0.02$, $p = 0.98$, $\eta_p^2 < 0.01$], or Reasoning Ability [$F(2, 50) = 2.92$, $p = 0.06$, $\eta_p^2 = 0.11$], there was a significant difference between groups on the composite measure of executive control [$F(2, 50) = 4.36$, $p = 0.02$, $\eta_p^2 = 0.15$]. However, this difference favored the control group rather than the game groups (**Figure 1**).

INTERVENTION COMPLIANCE

Next we explored whether differences in intervention compliance might be responsible for the absence of an action game effect. Recall that participants who received a game intervention were asked to play five times a week for 3 months for a total of approximately 60 h. Based on phone and diary data, we reconstructed the total number of hours played by each participant over the course of the 3-month period[4]. Participants who received the Brain Fitness Game, on average, came very close to the 60 h goal ($M = 56$ h, SD = 6). However, consistent with the hypothesis that older adults would prefer the Brain Fitness Game, participants who received the Action Video Game played for significantly fewer hours [$M = 22$ h, SD = 5, $F(1, 32) = 8.78$, $p < 0.01$, $\eta_p^2 = 0.22$]. There was no clear relationship between compliance and improvement, although results must be interpreted with caution given the small sample (**Table 4**; see text footnote 2 for individual task correlations).

ATTITUDES AND PERCEPTIONS

To better understand differences in compliance, we explored data on participants' attitudes and perceptions of game training. At

[3] http://walterboot.net/GameStudy/AnalysisSupplement.pdf

[4] Although we did not obtain objective measures of intervention compliance, it should be noted that each method of determining compliance (diary and phone) produced consistent estimates (Cronbach's $\alpha = 0.93$). This gives us confidence that compliance measures were reliable and valid. Compliance analyses used the average compliance assessed by each measure.

Table 3 | Pre and post-training scores.

		Control		Brain fitness		Action game	
		Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**
Simple/choice RT ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 14$)	Simple RT (ms)	365 (15)	351 (10)	359 (12)	357 (12)	352 (13)	342 (18)
	Complex RT (ms)	396 (14)	394 (13)	414 (10)	427 (17)	397 (14)	398 (13)
	Simple accuracy	0.96 (0.02)	0.97 (0.02)	0.98 (0.01)	0.99 (0.01)	0.97 (0.02)	0.97 (0.02)
	Complex accuracy	0.97 (0.01)	0.96 (0.01)	0.98 (0.01)	0.98 (0.01)	0.95 (0.04)	0.98 (0.01)
Number comparison ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 14$)		38.20 (2.40)	38.85 (2.43)	37.75 (2.40)	39.40 (2.43)	43.07 (2.97)	41.57 (2.90)
Visual search ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 14$)	Near	0.19 (0.02)	0.25 (0.04)	0.29 (0.06)	0.27 (0.06)	0.31 (0.07)	0.34 (0.07)
	Middle	0.19 (0.02)	0.20 (0.03)	0.24 (0.05)	0.26 (0.05)	0.23 (0.05)	0.27 (0.07)
	Far	0.15 (0.02)	0.18 (0.02)	0.21 (0.03)	0.18 (0.03)	0.18 (0.04)	0.24 (0.06)
Corsi block tapping ($n_c = 20$, $n_{BF} = 19$, $n_{AG} = 14$)	Set 4	0.78 (0.04)	0.77 (0.04)	0.78 (0.06)	0.76 (0.05)	0.79 (0.05)	0.83 (0.05)
	Set 5	0.64 (0.05)	0.63 (0.05)	0.58 (0.06)	0.54 (0.06)	0.60 (0.06)	0.61 (0.06)
	Set 6	0.18 (0.05)	0.21 (0.04)	0.19 (0.05)	0.20 (0.05)	0.08 (0.04)	0.15 (0.05)
	Set 7	0.02 (0.01)	0.03 (0.01)	0.04 (0.02)	0.02 (0.01)	0.04 (0.03)	0.02 (0.02)
ECB recognition ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 14$)		12.00 (0.46)	12.55 (0.42)	12.35 (0.46)	12.20 (0.42)	12.29 (0.55)	12.29 (0.51)
Meaningful memory ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 14$)		12.95 (0.97)	13.30 (0.86)	12.70 (0.97)	14.50 (0.86)	14.07 (1.16)	14.07 (1.02)
MSEQ ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 14$)	Average confidence	63 (2)	63 (4)	62 (4)	61 (5)	63 (6)	66 (6)
Flanker ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 13$)	Congruent RT (ms)	622 (23)	599 (20)	681 (20)	637 (24)	632 (26)	602 (31)
	Incongruent RT (ms)	750 (41)	678 (21)	797 (27)	738 (30)	736 (44)	670 (29)
	Congruent accuracy	0.98 (0.01)	0.99 (0.01)	0.94 (0.04)	0.93 (0.05)	0.95 (0.04)	0.93 (0.04)
	Incongruent accuracy	0.86 (0.06)	0.96 (0.02)	0.85 (0.06)	0.90 (0.04)	0.88 (0.06)	0.91 (0.04)
Task switching ($n_c = 19$, $n_{BF} = 20$, $n_{AG} = 13$)	Repeat RT (ms)	1175 (45)	1161 (53)	1193 (40)	1219 (47)	1145 (61)	1109 (46)
	Switch RT (ms)	1480 (55)	1453 (77)	1443 (63)	1553 (63)	1347 (75)	1447 (51)
	Repeat accuracy	0.71 (0.05)	0.75 (0.04)	0.78 (0.03)	0.76 (0.04)	0.79 (0.05)	0.79 (0.06)
	Switch accuracy	0.63 (0.05)	0.71 (0.04)	0.70 (0.03)	0.69 (0.04)	0.74 (0.04)	0.74 (0.05)
Raven's matrices ($n_c = 19$, $n_{BF} = 18$, $n_{AG} = 12$)		6.63 (0.78)	7.21 (0.69)	6.00 (0.79)	6.63 (0.78)	7.00 (0.86)	6.08 (0.97)
ECB reasoning ($n_c = 20$, $n_{BF} = 20$, $n_{AG} = 14$)		35.45 (1.21)	34.10 (1.27)	34.70 (1.21)	34.50 (1.27)	37.86 (1.45)	34.29 (1.51)
Letter sets ($n_c = 19$, $n_{BF} = 20$, $n_{AG} = 14$)		13.74 (1.33)	15.16 (1.51)	14.00 (1.30)	13.30 (1.47)	16.29 (1.55)	14.93 (1.75)
MIDUS ($n_c = 19$, $n_{BF} = 19$, $n_{AG} = 13$)	Autonomy	16.05 (1.17)	17.70 (1.23)	16.05 (1.20)	15.95 (1.27)	12.93 (1.40)	11.57 (1.48)
	Env. mastery	15.58 (1.29)	16.47 (1.39)	14.00 (1.26)	14.40 (1.35)	14.71 (1.51)	13.21 (1.62)
	Positive rel.	12.45 (1.16)	12.60 (1.15)	14.65 (1.16)	14.45 (1.15)	12.85 (1.44)	11.85 (1.43)
	Personal growth	15.25 (1.16)	14.75 (1.05)	11.21 (1.19)	11.68 (1.08)	12.93 (1.39)	10.21 (1.26)
	Life purpose	15.32 (1.27)	15.53 (1.32)	14.50 (1.24)	14.85 (1.29)	13.79 (1.48)	12.93 (1.54)
	Self-acceptance	15.70 (1.31)	15.30 (1.22)	13.00 (1.34)	13.32 (1.25)	12.39 (1.62)	10.31 (1.52)

Standard errors listed within parenthesis.

For the analysis of each measure, n_c = Number of participants included in Control condition, n_{BF} = Number of participants included in Brain Fitness condition, n_{AG} = Number of participants included in Action Game condition. For MIDUS, participant count reflects minimum number of participants included in the analysis of each subscale analysis.

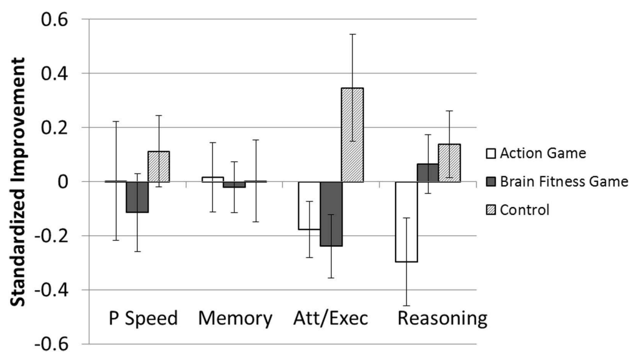

FIGURE 1 | Standardized (*Z*-score) composite improvement scores as a function or task type and group. Error bars represent ± SEM.

Table 4 | Correlation coefficients between reported hours of game play and improvement.

	Brain fitness			Action game		
	N	***r***	***p***	***N***	***r***	***p***
Perceptual speed	20	0.28	0.24	14	0.11	0.70
Memory	20	−0.05	0.84	14	0.11	0.70
Attention/executive control	20	0.16	0.49	14	−0.23	0.43
Reasoning	20	−0.33	0.16	14	0.30	0.29

post-training, participants were given two surveys, one of which focused on their experiences with the game they were given to play, and one which asked them about perceived benefits of game training. Item responses were on a Likert scale, with 1 representing strong disagreement and 7 representing strong agreement with given statements.

Perception of Game Training Questionnaire

Participants were asked to rate their agreement with the following statements: (1) I found the game I was given to play *enjoyable*, (2) I found the game I was given to play *challenging*, (3) I found the game I was given to play *frustrating*, and (4) I was *motivated* to perform well on the game I was given to play. The results from the Brain Fitness and Action Game groups are depicted in **Figure 2**. Scores for each question were entered into an ANOVA, with group as a between-participants factor and question as a within-participant factor[5]. This ANOVA revealed an interaction between group and question [$F(3, 93) = 2.63, p = 0.05, \eta_p^2 = 0.08$]. The only question to reveal a significant difference between groups was the question assessing enjoyment. Participants who received the Action Game rated the game as significantly less enjoyable compared to the Brain Fitness Game [$F(1, 33) = 5.32, p < 0.05, \eta_p^2 = 0.15$].

Perception of video game training effectiveness

Participants were asked to rate their agreement with statements in the form of: Video games like the one I was given to play

[5]One participant in the Brain Fitness Group failed to answer one question, thus their data was not included in the ANOVA, but was included in follow-up contrasts involving the other three questions.

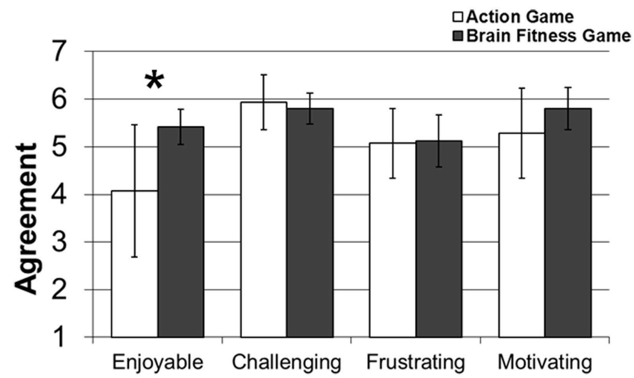

FIGURE 2 | Game perception agreement scores as a function of game type. Participants who received the Action Game rated it as significantly less enjoyable. Error bars represent 95% confidence intervals. *$p < 0.05$.

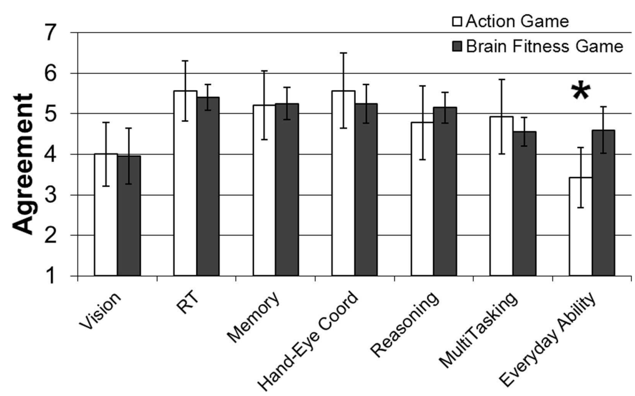

FIGURE 3 | Perceived benefit agreement scores as a function of game type. Participants who received the Action Game rated it as significantly less likely to improve everyday abilities. Error bars represent 95% confidence intervals. *$p < 0.05$.

have the potential to improve (1) vision, (2) reaction time, (3) memory, (4) hand-eye coordination, (5) reasoning ability, (6) multi-tasking ability (managing multiple tasks at the same time), (7) the performance of everyday tasks such as driving, remembering important dates, and managing finances. The results from the Brain Fitness and Action Game groups are depicted in **Figure 3**. An ANOVA revealed an interaction between group and question [$F(6, 192) = 3.08, p < 0.01, \eta_p^2 = 0.08$]. The only question to reveal a significant difference between groups was the question regarding everyday abilities. Participants who received the Action Game intervention were significantly less likely to believe the intervention would improve everyday abilities [$F(1, 32) = 7.20, p < 0.05, \eta_p^2 = 0.18$].

PREDICTORS OF COMPLIANCE

Survey data suggested two reasons for the low compliance rate of the Action Game group. First, participants found the game to be less enjoyable. Second, participants were less likely to believe that the game would improve their cognition in a meaningful way. A regression analysis, with compliance as the criterion variable, and

Table 5 | Representative positive and negative quotes regarding training.

POSITIVE BRAIN FITNESS QUOTES
"Feel good about decreasing brain age." – Participant A (Female, Age 78)
"I do all the games, I am doing them faster." – Participant B (Female, Age 70)
"Enjoying the games but not good at many of them. I like the piano, but not a 'true pianist' yet." – Participant C (Female, Age 70)
"This has been fascinating- wish I could improve, going to try in the AM." – Participant D (Female, Age 75)
"I'm addicted!! What am I going to do when this test is done? Go buy a game? Steal this one? Or tell my son I need one?" – Participant E (Female, Age 69)
NEGATIVE BRAIN FITNESS QUOTES
"The software makes more mistakes than I do." – Participant B (Female, Age 70)
"Game does not always show the numbers I want to write." – Participant A (Female, Age 78)
"Still problems with machine reading correctly – kills competitive spirit." – Participant F (Male, Age 71)
"It is frustrating to get a correct answer and have it misread!" – Participant G (Male, Age 68)
"Barking dogs can ruin rock, paper, scissors." (referring to a game involving voice recognition) – Participant H (Female, Age 79)
POSITIVE ACTION GAME QUOTES
"Did time trials, competitive nature taking over." – Participant I (Male, Age 75)
"Used booklet to note characteristics of drivers-enjoyable, more interested." – Participant J (Male, Age 80)
"Actually enjoyed it. It went very well. Many 1st places." – Participant K (Female, Age 78)
NEGATIVE ACTION GAME QUOTES
"Noticing eye strain after 30 minutes." – Participant L (Female, Age 66)
"I have arthritis in my hands. When I play more than 30 minutes it really hurts but I am trying." – Participant M (Female, Age 69)
"Awkward! Re-read manual and try[ing] to coordinate actions. Arthritis in hands makes some action uncomfortable." – Participant N (Male, Age 86)
"Mindless; challenge is dexterity rather than thinking. Utterly boring." – Participant I (Male, Age, 75)
"Running a little guy around a race track is inherently less interesting than reading, movies, or computer games like free cell, hearts, or black jack." – Participant O (Male, Age 66)

game type, enjoyment, and perceived benefit to everyday abilities as predictor variables found that game type was the only significant predictor of compliance [$b = 30.87$, $t(29) = 2.31$, $p < 0.05$]. However, exploratory analyses considering each game group separately found that for the Brain Fitness group, compliance was associated with perceived benefits to reaction time [$r(20) = 0.63$, $p < 0.01$], memory [$r(20) = 0.51$, $p < 0.05$], and hand-eye coordination [$r(20) = 0.42$, $p = 0.06$]. For the Action Game group, perceived benefits were not significantly associated with compliance; however motivation to do well in the game was significantly correlated with perceived benefits to all abilities except vision [$r(14) > 0.57$, p values < 0.05]. Game enjoyment in the Action Game group was also significantly correlated with perceived benefits to all abilities except vision [$r(14) > 0.79$, p values < 0.05], as was perceived game challenge [$r(14) > 0.63$, p values < 0.05]. This pattern of association between perceived benefits and game enjoyment, motivation, and challenge was not observed in the Brain Fitness group. Although exploratory, these results suggest that perceived benefits may play multiple roles in shaping older adults' attitudes and perceptions of game training.

QUALITATIVE DATA

Participants were given the opportunity to make comments about their game experience in the diary they were asked to keep. Comments generally mirrored survey data, with more positive comments related to the Brain Fitness Game compared to the Action Game (**Table 5**). Although participants generally liked the Brain Fitness game, some problems were noted, especially with the text and speech recognition functions of the game. Participants were frustrated in instances in which they knew the correct answer, but were marked as being incorrect because the game did not recognize what they said or wrote. Compared to the Brian Fitness Game, participants in the Action Game Group reported more problems and frustration, including difficulties interacting with the game due to arthritis and eyestrain. A number of participants explicitly noted a lack of interest in content of the game.

DISCUSSION

Previous studies have found that relatively short action video game interventions can result in dramatic improvements to a number of perceptual and cognitive abilities (but see also Boot et al., 2008, 2011). Thus video game interventions are potentially an ideal solution to address the many perceptual and cognitive declines associated with aging. Basak et al. (2008) found that in an older adult sample, a video game intervention was capable of improving memory, executive functioning, and reasoning ability. The current study built upon this prior work to examine the effectiveness of an action game intervention compared to a brain fitness game intervention and found that neither resulted in greater cognitive improvement compared to a no-game control group.

While on the surface results are disappointing, the lack of action game effect must be viewed in the context of low compliance and negative attitudes toward the game predicted to induce the largest improvements. Low intervention compliance was consistent with older gamers' preference for intellectually challenging games over games that require quick reflexes and fast reaction time (Pearce, 2008). Participants rated the action game as significantly less enjoyable compared to the brain fitness game, and did not believe the action game had the potential to improve important everyday abilities such as driving.

Additional study limitations are worth discussing. Within each game, participants had many options from which to choose. In *Mario Kart*, participants could choose any level of difficulty they felt comfortable with, concentrate on a few race tracks and racers, or explore diverse race tracks and play many different characters. In *Brain Age*, participants could play Sudoku or engage in either a few or many diverse game activities with different demands. Relatively unconstrained (but externally valid) training in which participants were free to choose activities within each game, and how long to spend on each activity, may have contributed to null results. Furthermore, given this freedom, it was impossible to compute meaningful learning curves for participants' game performance. Thus, we cannot compare amount of improvement in game to the amount of transfer observed. If some participants demonstrated no-game improvement it is unlikely they would demonstrate transfer. Additionally, the largest effects in the literature have been found with action game training, mostly training on first-person shooters (e.g., Green and Bavelier, 2003, 2006a,b). There could be important differences between these games and the racing game *Mario Kart*, which might explain a lack of effect (such as the degree to which peripheral monitoring is necessary). There are likely important game elements (such as the degree to which task switching is required) that differ between *Mario Kart* and the more strategic game used by Basak et al. (2008). Finally, the seniors in our study were relatively cognitively intact (with a high average MMSE score) and well-educated. Training may be more effective for individuals who are more impaired.

It should be noted that both groups tended to agree that the game they were given to play was frustrating (**Figure 2**). For the *Brain Age 2*™ game in particular, this frustration appears to stem partly from the game's use of handwriting recognition. Participants almost universally expressed some degree of frustration with this aspect of the game. For the *Mario Kart DS*® game, arthritis-related pain and eyestrain were reported by some participants. It is not particularly surprising that the this group reported more arthritis-related problems since the game system had to be held in such a way that the system was supported with the fingers of each hand, while the *Brain Age 2*™ game allowed participants to hold the system in the palm of one hand. The *Brain Age 2*™ interface was navigated almost exclusively with a stylus and touch screen, while *Mario Kart DS*® required using a directional pad and game buttons. A focus on ergonomics and human factors, especially with respect to the needs of the older adult user, may make technology-based cognitive interventions more accessible and enjoyable for older adults (Charness and Boot, 2009; Boot et al., 2012).

Our results contrast with those of Nouchi et al. (2012), who found broad improvements as a result of *Brain Age 2*™ training after only 5 h of gameplay (15 min of gameplay 5 days a week for 4 weeks). Our intervention was rather long. On average, participants in our Brain Fitness group played the same game for more than 50 h, yet no evidence of transfer was observed. Another recent study found transfer (but not far transfer) as a result of online brain-training (van Muijden et al., 2012). At this point the reason for conflicting results remains uncertain. Different assessment tasks used to measure cognition may be one explanation. Our results were more consistent with those of Ackerman et al. (2010) and Owen et al. (2010).

In sum, video game interventions may hold promise in terms of addressing declines associated with cognitive aging, but there are still many unknowns. A greater understanding of the mechanisms underlying general transfer induced by action video game play needs to be a major goal of this line of research, but is a particularly challenging problem given the complexity of modern action video games. Once isolated, the key components of what make action games so successful in terms of improving general abilities might be embedded within games more appealing to older adults. We found that a belief that an intervention is capable of improving abilities was associated with increased compliance, and this information might be incorporated into new video game interventions. Finally, researchers must recognize individual differences in game preference. Among younger adults, not all players enjoy the same type of game experience, and the same is true of older adults. The most successful cognitive intervention in the world is essentially worthless unless individuals are willing and able to engage in it. Thus efforts need to be made not just to understand what interventions are capable of improving cognition, but how to structure and deliver these interventions to ensure that people engage in them.

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Improved control of exogenous attention in action video game players

Matthew S. Cain[1,2]*, William Prinzmetal[1], Arthur P. Shimamura[1] and Ayelet N. Landau[1,3,4]

[1] Department of Psychology, University of California, Berkeley, CA, USA
[2] Visual Attention Lab, Brigham and Women's Hospital, Harvard Medical School, Cambridge, MA, USA
[3] Ernst Strüngmann Institute for Neuroscience in Cooperation with Max Planck Society, Frankfurt am Main, Germany
[4] Department of Psychology, Hebrew University of Jerusalem, Jerusalem, Israel

Edited by:
Walter R. Boot, Florida State University, USA

Reviewed by:
Niels A. Taatgen, University of Groningen, Netherlands
Tilo Strobach, Humboldt University Berlin, Germany

****Correspondence:***
Matthew S. Cain, Visual Attention Lab, Brigham and Women's Hospital, Harvard Medical School, 64 Sidney Street, Suite 170, Cambridge, MA 02139, USA
e-mail: mcain@partners.org

Action video game players (VGPs) have demonstrated a number of attentional advantages over non-players. Here, we propose that many of those benefits might be underpinned by improved control over exogenous (i.e., stimulus-driven) attention. To test this we used an anti-cueing task, in which a sudden-onset cue indicated that the target would likely appear in a separate location on the opposite side of the fixation point. When the time between the cue onset and the target onset was short (40 ms), non-players (nVGPs) showed a typical exogenous attention effect. Their response times were faster to targets presented at the cued (but less probable) location compared with the opposite (more probable) location. VGPs, however, were less likely to have their attention drawn to the location of the cue. When the onset asynchrony was long (600 ms), VGPs and nVGPs were equally able to endogenously shift their attention to the likely (opposite) target location. In order to rule out processing-speed differences as an explanation for this result, we also tested VGPs and nVGPs on an attentional blink (AB) task. In a version of the AB task that minimized demands on task switching and iconic memory, VGPs and nVGPs did not differ in second target identification performance (i.e., VGPs had the same magnitude of AB as nVGPs), suggesting that the anti-cueing results were due to flexible control over exogenous attention rather than to more general speed-of-processing differences.

Keywords: individual differences, video game players, exogenous attention, attentional blink, cueing

INTRODUCTION

In the previous decade, action video game players (VGPs) have demonstrated a number of advantages over non-players (nVGPs) on visual and cognitive tasks. For example, VGPs have outperformed nVGPs on multiple object tracking (Green and Bavelier, 2006b), probabilistic inference (Green et al., 2010), forming detailed memory representations of objects (Sungur and Boduroglu, 2012), task switching (Cain et al., 2012), dual-task performance (Strobach et al., 2012), and multisensory integration (Donohue et al., 2010), among others (see Hubert-Wallander et al., 2011a for a review).

One aspect of video game experience that could underlie a variety of these benefits is control of attention, particularly control over exogenous attention. Action video games often have a great deal of visual distraction, so it would be plausible for VGPs to develop some level of control over the degree to which salient distractions in the visual environment capture their attention in order to promote better performance on their primary task. Consistent with this idea, VGPs have previously demonstrated reduced exogenous (i.e., stimulus-driven) attentional capture. In particular, VGPs were better able than nVGPs to avoid exogenous capture by task-irrelevant color-singletons in an additional singleton paradigm (Chisholm et al., 2010). VGPs were also better able than nVGPs to avoid exogenous capture by a suddenly appearing distractor in a color-singleton search (Chisholm and Kingstone, 2012). While this is strong evidence for improved distractor resistance in VGPs, other studies have demonstrated that VGPs use exogenous cuing to the same extent as nVGPs (Cain and Mitroff, 2011; Hubert-Wallander et al., 2011b). The key difference between these sets of studies is that in the experiments by Chisholm et al. (2010), Chisholm and Kingstone (2012) the potentially attention-capturing stimulus always indicated a to-be-ignored location (i.e., attending to it never aided task performance). Conversely, in the studies showing no differences in attentional capture between VGPs and nVGPs (Cain and Mitroff, 2011; Hubert-Wallander et al., 2011b), attending to exogenous cues would often have been beneficial to performance.

Previous work therefore suggests that a key difference between VGPs and nVGPs is the level of control over exogenous attentional capture: VGPs may exert control when exogenous attentional capture would hurt performance, but may not choose to exert control when capture would help or have no impact upon performance. Such flexibility could naturally arise from interaction with multiple action video games and multiple visual environments within such games and might affect performance in a wide variety of contexts outside of games. This notion is broadly similar to that put forward by Green et al. (2010) that VGPs are better than nVGPs at assessing and responding to the statistics of their visual environments and in line with evidence that VGPs may learn more quickly over the course of an experimental session (e.g., West et al., 2013).

How flexible is VGPs' avoidance of exogenous capture? Is it an all or nothing capacity, or can there be more graded control over exogenous attention? To address these questions we employ an *anti-cueing paradigm* (Experiment 1). In a typical spatial cuing task, there are specific locations where targets could appear and one of those locations is cued prior to target onset, generating exogenous capture. In target-cued conditions, the cue indicates the likely position of the target. In an anti-cueing paradigm, the appearance of the cue in one location actually indicates that a target will likely appear in a different location (Posner et al., 1982; Warner et al., 1990; Prinzmetal et al., 2009). For example, if the right location is cued (see **Figure 1**), there is a high probability that the target would appear on the left. Thus, the information given by the cue is task-relevant, but the spatial location of the cue is not the to-be-attended location. If VGPs can resist exogenous capture by this stimulus, but still use the information it provides in order to endogenously shift their attention, it would imply very precise control over attention.

In Experiment 2 we address the question of visual speed of processing using an attentional blink (AB) task. It has been argued that VGPs may process visual stimuli more quickly than nVGPs (e.g., Wilms et al., 2013). But is this faster apprehension related to overall processing-speed differences between VGPs and nVGPs? Might it even be associated with greater sensitivity to distractors (e.g., West et al., 2008)? If so, this could pose a problem for interpreting results showing reduced exogenous capture for VGPs, as attending to a stimulus and then very rapidly processing and disengaging from it may have the same behavioral effect as avoiding attentional capture at certain timescales.

To preview our results, we found superior control over exogenous attention in VGPs compared with nVGPs, but no differences between groups in endogenous attention or speed of processing.

EXPERIMENT 1 – ANTI-CUE

In the anti-cue task, a cue is presented at one spatial location, but indicates that the target is likely to appear in a specific other location. This allows for the separation of the effects of exogenous attention and endogenous attention, a difference that should be more apparent in response time (RT) than in accuracy (Prinzmetal et al., 2009). If the sudden-onset of the cue exogenously captures attention, then when the interval between the cue and the target is short, participants should be faster to respond to those rare targets that appear at the location of the cue than those targets that appear in the more likely, anti-cued location. Conversely, when the interval between the cue and the target onset is longer, then participants will have sufficient time to endogenously move their attention to the likely target location, providing an advantage at the anti-cued location compared to the location of the cue. This design allows for separate assessments of the relative exogenous and endogenous attentional performance of VGPs and non-players.

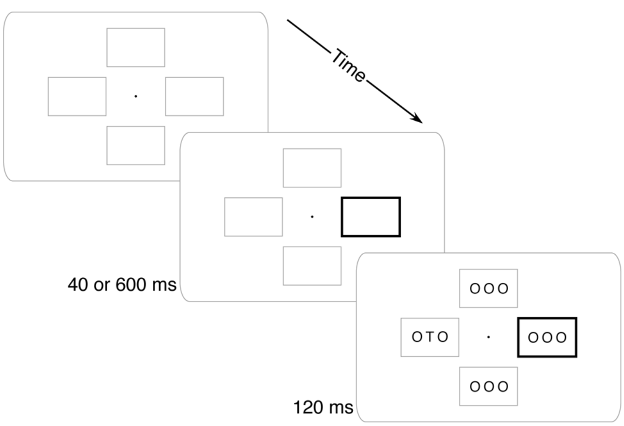

FIGURE 1 | Example trial. Four placeholder boxes and a central fixation dot were always visible. At the beginning of each trial, one box would darken. After either 40 or 600 ms, the stimulus array would appear and participants would report whether a "T" or an "F" was present.

METHODS

Participants

Forty-two members of the University of California, Berkeley community participated in exchange for a cash payment or partial fulfillment of a course requirement. Other data from a subset of these participants that were collected in the same experimental session have been reported previously (Cain et al., 2012). Participants were recruited using a variety of methods including poster advertisements specifically seeking first-person shooting (FPS) game players and non-players and e-mail advertisements selectively sent to those with high and low levels of reported FPS expertise in a prescreening survey. Participants were not informed which survey in the prescreening packet lead to their recruitment until the end of the study.

Data from two participants were excluded, one for not completing the experiment and another for performing at chance-level accuracy throughout the experiment. The remaining 40 participants were classified into two groups based on their self-reported expertise and experience with action video games. The VGP group reported expertise with FPS video games of $\geq$5 on a 1–7 scale and regular play of FPS games ($\geq$5 hr/wk) in the last 6 months. The VGP group consisted of 17 males and two females (mean age = 21.0 years). The non-player (nVGP) group reported expertise with FPS games of $\leq$2 on a 1–7 scale and recent experience with FPS games of <2 hr/wk in the last 6 months. Note that expertise or experience with other genres of video games (e.g., puzzle games) was not cause for exclusion from the nVGP group. The nVGP group consisted of eight males and 13 females (mean age = 22.5 years).

Stimuli

Four peripheral boxes and a central fixation dot were present on the screen throughout the experiment (see **Figure 1**). Each box extended approximately 2.0° × 1.25° and was 1 pixel thick. The innermost edge of each box was 1° from fixation. The fixation dot was a solid black circle 0.1° in diameter.

On each trial the cue was a thickening of the outline of one of the boxes to 0.1° wide. This thickened box remained visible until the stimulus array disappeared. The stimulus array included three characters per frame in a 36-point sans-serif font. The target letter was a "T" or an "F" and was always at the center of its array. All other placeholder letters in the display were "O".

Procedure

The procedure is identical to that in Prinzmetal et al. (2009, Experiment 3). Participants were instructed to maintain fixation at all times during each trial. Fixation was monitored online using a video camera with a researcher labeling trials in which fixation was broken as they occurred. Eye movement trials were re-run at the end of the block in which they occurred.

On each trial a cue gave participants information about the likely position of the target. On 75% of trials the target appeared in the box opposite the cue (anti-cued location). On 12.5% of trials the target appeared in the same location as the cue (cued location). On the remaining 12.5% of trials the target appeared in one of the two off-axis boxes (other location); these catch trials were not included in any of the planned comparisons. Participants were informed that the target was "most likely" to appear in the anti-cued location, but could appear in any location. Participants were not given explicit probabilities.

The stimulus array appeared after the cue at one of two randomly intermixed stimulus onset asynchronies (SOAs). The Short SOA (40 ms) was intended to generate exogenous attention capture: participants should have had their attention drawn to the sudden-onset cue, but should not have had time to endogenously move their attention to the likely target (i.e., anti-cued) location. The Long SOA (600 ms) was intended to allow time for endogenous movement of attention from the cued location to the anti-cued location. The stimulus array remained on the screen for 120 ms (to minimize the utility of eye movements) at which time both the stimuli and cue disappeared. After the stimuli disappeared, participants responded whether a "T" or an "F" was present with a speeded keypress of the "1" and "2" keys on a numeric keypad using the index and middle fingers of their right hand.

Trials were presented in seven blocks, separated with self-paced breaks. The first block was 48 trials long, considered practice, and not analyzed. The six experimental blocks were each 96 trials long. Throughout the experiment, auditory feedback was given for incorrect responses and eye movements.

RESULTS

Data from trials with RTs < 150 ms or > 1580 ms (three standard deviations above the mean RT for all correct trials) were excluded from analysis (0.9% of experimental trials). Analyses were conducted in parallel for both accuracy and RT (see **Table 1** for a full breakdown), with incorrect trials excluded from RT analysis. Data from the Other Location catch trials were not analyzed, but are reported in **Figure 2** and **Table 1** for comparison purposes.

Overall analysis

Results were primarily analyzed with linear mixed effects models (Baayen et al., 2008; Barr et al., 2013) using the lme4 package in R (Bates et al., 2013). These models are similar to repeated-measures ANOVAs, but use all experimental trials rather than averages and allow for better testing of proportional data (i.e., accuracy). For both accuracy and RT, models were constructed with Group (VGP or nVGP), Target Position (Cued or Anti-Cued), and SOA (40 or 600 ms) as fixed effects and Participant as a random effect. For accuracy, a logistic model that included a three-way Group × Target Position × SOA interaction fit the data significantly better than a model in which the Target × SOA interaction did not interact with Group [$\chi^2(3) = 9.14, p = 0.0275$]. Similarly for RT, a model that included a three-way Group × Target Position × SOA interaction fit the data significantly better than a model in which the Target × SOA interaction did not interact with Group [$\chi^2(3) = 14.41, p = 0.0024$]. To better understand how exogenous attentional capture varied between groups, we performed further analyses separately for each SOA. To preview, there was an interaction between Group and Target Position for RT, but not accuracy, in the Short SOA condition, and an interaction for accuracy, but not RT in the Long SOA condition.

Short SOA condition

Results for the Short SOA condition were analyzed using linear mixed effects models with Group and Target Position as fixed effects and Participant as a random effect. Accuracy was uniformly high and there was no difference between a logistic model that included a Group × Target Position interaction and one that did not [$\chi^2(1) = 0.25, p = 0.6170$]. RT results are summarized in **Figure 2A** and, unlike accuracy, showed evidence of a Group × Target Position interaction [$\chi^2(1) = 4.73, p = 0.0296$], implying that there are attentional cuing RT differences between groups. To understand the nature of this interaction, we performed *post hoc* paired-samples *t*-tests within each group. Consistent with previous findings, nVGPs were faster to respond when the

Table 1 | Breakdown of means and standard deviations (SDs) of accuracy and response time (RT) measures across all groups and conditions.

		Short SOA (40 ms)						Long SOA (600 ms)					
		Anti-cued		Cued		Other		Anti-cued		Cued		Other	
Measure	Group	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Accuracy (%)	nVGP	95.6	3.6	95.8	4.9	95.5	6.4	95.7	4.3	96.4	3.7	95.8	4.0
	VGP	95.5	3.3	94.7	6.0	96.5	2.8	96.0	3.3	92.7	13.4	95.3	5.6
RT (ms)	nVGP	472	98	452	89	477	105	456	103	485	126	471	116
	VGP	451	80	453	88	462	96	426	89	469	117	451	112

SOA, stimulus onset asynchrony; VGP, video game player; nVGP, non-video game player.

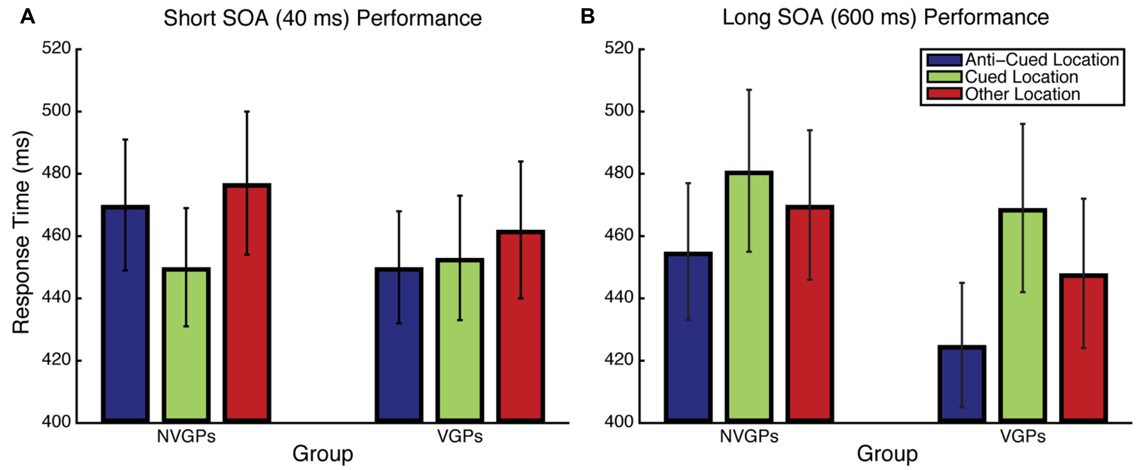

FIGURE 2 | Response time results for Experiment 1 for the Short SOA (A) and Long SOA (B) conditions. Error bars represent the standard error of the mean.

target was at the cued location than at the anti-cued location [$t(20) = 3.054$, $p = 0.006$, Cohen's $d = 0.217$]. However, VGPs were just as fast to respond to the target at the anti-cued location as at the cued location [$t(18) = 0.417$, $p = 0.681$, $d = 0.030$], suggesting reduced or eliminated exogenous attentional capture.

Long SOA condition

Results for the Long SOA condition were analyzed using the same linear mixed effects models as in the Short SOA condition. For accuracy, in contrast to the Short SOA condition, there was evidence of a Group × Target Position interaction [$\chi^2(1) = 8.69$, $p = 0.0032$]. To understand the nature of this interaction, we performed *post hoc* paired-samples *t*-tests on arcsine-square-root-transformed accuracy within each group. VGPs were more accurate when responding to targets at the anti-cued location and nVGPs were more accurate at responding to targets at the cued location, but neither of these individual comparisons was statistically significant (both $p > 0.4$). RT results are shown in **Figure 2B**. Unlike the Short SOA condition, there was no evidence of an interaction between Group and Target Position [$\chi^2(1) = 0.08$, $p = 0.7813$]. *Post hoc* paired-samples *t*-tests revealed that both groups showed significant cuing effects [VGPs: $t(18) = 2.467$, $p = 0.024$, $d = 0.415$; nVGPs: $t(20) = 3.234$, $p = 0.004$, $d = 0.259$].

DISCUSSION

VGPs were better at resisting exogenous attentional capture by a suddenly appearing cue, but were just as able to use the information from the cue to endogenously direct their attention to a likely target location. Unlike the nVGP group, which demonstrated normal levels of attentional capture in the Short SOA condition, the VGP group performed equivalently quickly at all locations in the Short SOA condition. Importantly, in the Long SOA condition, the VGP group was able to use the cue to direct their attention to the probable target location, demonstrating the expected anti-cueing effect. Thus, the VGP group was not ignoring the task-relevant cue, but was able to suppress exogenous capture from its onset. Interestingly, a similar pattern of results has previously been shown with training on the anti-cue task (Warner et al., 1990), suggesting that general action video game experience may have a similar effect on underlying attentional mechanisms as specific task training.

There is an alternative explanation for the current results that bears consideration. It has been suggested that VGPs may enjoy a speed of processing advantage over nVGPs (Dye et al., 2009; Wilms et al., 2013). Perhaps the VGPs were experiencing just as much exogenous capture as the nVGPs, but were able to very rapidly process the cue, such that they were no longer captured by it when the target array appeared, even in the Short SOA condition. We address this speed of processing question in Experiment 2.

EXPERIMENT 2 – ATTENTIONAL BLINK

Could the apparent resistance to exogenous capture seen in Experiment 1 be the result of faster processing of the cue stimulus? A few lines of evidence support this hypothesis. The most general claim is from a meta-analysis of VGP vs. nVGP studies that found that overall, VGPs perform faster than nVGPs with no loss in accuracy (Dye et al., 2009). This improvement could have come from increased speed of visual processing or from later stages such as decision processes, response execution, or some combination thereof. Other studies have demonstrated that VGPs are quicker to get information into visual working memory than nVGPs (Appelbaum et al., 2013) and are faster to accumulate visual evidence from noisy visual stimuli (Green et al., 2010). This suggests there may be a visual processing advantage for VGPs, but it's not clear if this advantage would also apply to simpler situations like sudden-onsets. Most directly, one recent study specifically found faster visual processing for VGPs in a modified whole-report task (Wilms et al., 2013).

If faster visual processing in VGPs, lead to faster processing of the cue in Experiment 1, we might also expect faster processing of stimuli presented in quick succession in a rapid serial visual presentation task. In particular, VGPs would be expected to have a reduced *AB* (Raymond et al., 1992). The AB is a phenomenon where processing of one target item impairs processing of a second item encountered 200–500 ms later. This deficit is believed to be due to a processing bottleneck in which the second target cannot be processed simultaneously with the first target (see Martens and Wyble, 2010 for a review). If VGPs are faster at processing rapidly presented items, they may be able to more completely process the first target before the second appears, reducing the impact of this bottleneck and, thus, reducing the AB. Several previous studies suggest that VGPs have a reduced AB compared to nVGPs (e.g., Green and Bavelier, 2003; Oei and Patterson, 2013), though there is not complete agreement on this point (Boot et al., 2008; Murphy and Spencer, 2009). Importantly, not all AB tasks are the same (e.g., Kelly and Dux, 2011). Previous studies have used forms of the AB paradigm that involve other factors, such as task switching and fast apprehension of stimuli – two abilities previously shown to be superior in VGPs (e.g., Cain et al., 2012; Appelbaum et al., 2013). Here, we attempt to minimize the contributions of these other factors to better examine the question of speed of processing.

METHODS

Participants

Fifty-two members of the University of California, Berkeley community participated in exchange for a cash payment or partial fulfillment of a course requirement, including 34 individuals who also participated in Experiment 1 as part of the same testing session. Other data from some participants have been reported previously (Cain et al., 2012). Data from three participants were excluded, one for making > 25% incorrect responses to first targets, and two for having incomplete data. Participants were divided into VGP and nVGP groups using the same criteria as for Experiment 1. The VGP group had 23 members (22 males and one female; mean age = 20.9 years) and the nVGP group had 26 members (11 males and 15 females; mean age = 22.2 years).

Stimuli and procedure

Streams of letters (distractors) and numbers (targets) were presented at the center of the screen against a gray background (see **Figure 3**). Each trial's stream contained 12 items presented for 80 ms each with a 20 ms inter-stimulus-interval (i.e., 100 ms stimulus onset asynchrony). Distractor items were black letters. Every trial contained a single white number target (T1) and 77% of trials contained an additional black number target (T2) that could only appear after T1. The remaining 23% of trials were catch trials that had no second target. Relative to T1, T2 could appear at lags of 1 (immediately after), 2, 3, 5, or 7 items.

On each of the 156 experimental trials participants observed the stream of characters and then separately reported the identity of the two target numbers using a standard computer keyboard. Participants used the space key to indicate that they did not see a particular number. Responses were unspeeded and instructions emphasized accuracy.

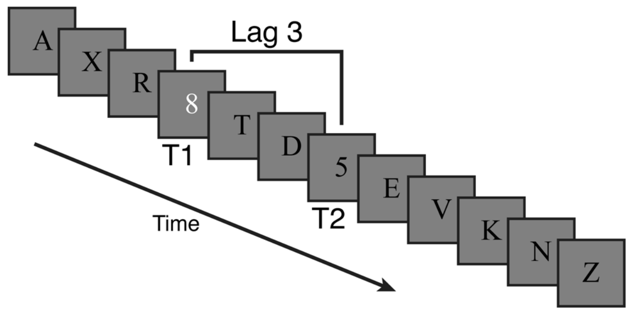

FIGURE 3 | Example trial for the attentional blink task in Experiment 2. Targets were numbers among distractor letters. The first target was white and always present. The second target was black and present on 77% of trials.

RESULTS

Accuracy data were analyzed for T2 on trials on which T1 was correct. First, T2 accuracy data were submitted to a linear mixed-model analysis with Lag (1, 2, 3, 5, or 7) and Group (VGP or nVGP) as fixed effects and Participant as a random effect. There was no evidence of an interaction between Group and Lag [$\chi^2(4) = 4.6346$, $p = 0.3269$]. Overall T2 accuracy was higher for nVGPs (92.4%) than VGPs (88.7%), but this Group difference was not statistically significant [$\chi^2(5) = 6.4782$, $p = 0.2624$]. As illustrated in **Figure 4**, this suggests that both groups experienced an AB, but that there were no differences between the groups. These models were followed up with *post hoc t*-tests comparing T2 performance between groups at each Lag and there were no significant differences at any point (all $p > 0.05$, uncorrected). There was no significant difference in T1 accuracy performance between groups [$t(47) = 0.331$, $p = 0.743$, $d = 0.087$].

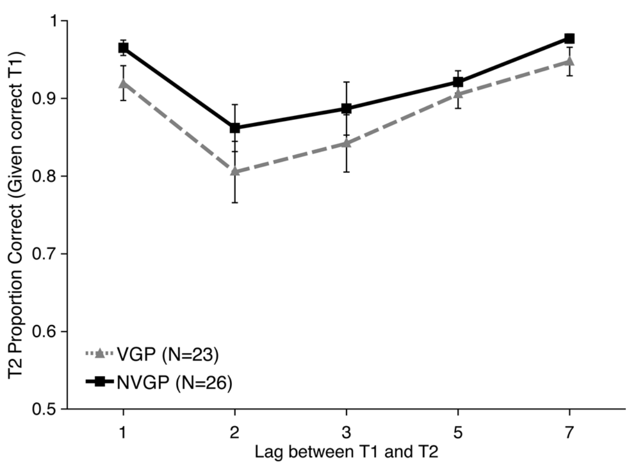

FIGURE 4 | Results from Experiment 2 showing second target accuracy for trials on which the first target was correctly identified as a function of inter-target Lag. nVGPs non-significantly outperformed VGPs at all lags. Error bars represent standard error of the mean.

Attentional blink magnitude

While there were no significant overall differences in performance between VGPs and nVGPs on this task, and nVGPs numerically outperformed VGPs, we wanted to specifically check AB performance. For each participant we calculated two AB scores: (1) Lag 7 (asymptote) performance minus Lag 2 (blink) performance and (2) the average of Lag 5 and Lag 7 minus the average of Lag 2 and Lag 3. For the Lag 7 minus Lag 2 measure, there was a significant overall AB effect of 13.39% [$t(48) = 5.702$, $p < 0.001$, $d = 0.815$], but no significant difference between groups [$t(47) = 0.629$, $p = 0.532$, $d = 0.179$]. The same pattern was seen for the average of Lags 5 and 7 minus average of Lags 2 and 3 measure: significant AB [$t(48) = 4.764$, $p < 0.001$, $d = 0.6804$], but no significant difference between groups [$t(47) = 0.416$, $p = 0.679$, $d = 0.1180$]. For both measures, VGPs had a numerically larger AB than nVGPs. While non-significant, this is noteworthy because it is opposite from the predicted direction.

DISCUSSION

The current experiment demonstrated a robust AB effect, but no differences in performance between VGPs and nVGPs. If anything, nVGPs outperformed VGPs, the opposite of what was predicted based on previous work. This suggests two key points (1) that improved anti-cue performance for VGPs in Experiment 1 was due to improved resistance to attentional capture, rather than faster processing of the cue stimulus and (2) that improved performance was not due to general effects such as motivation or knowledge that the study was about video gaming (cf. Boot et al., 2011).

The lack of a difference between VGPs and nVGPs on this task stands in contrast to several previous reports. In particular, it contrasts with the initial finding by Green and Bavelier (2003; replicated in Oei and Patterson, 2013). While both our task and that of Green and Bavelier (2003) are considered to be AB tasks, and all AB tasks have significant shared variability (Dale et al., 2013), there are important differences between AB tasks that tap into task switching abilities and those that do not (Kelly and Dux, 2011; Dale et al., 2013).

In the present experiment, participants searched for numbers among letters. This is a categorical AB task that requires no task switching, since both targets are numbers to be detected among letters (T1 white, T2 black serially following T1). However, in Green and Bavelier's (2003) experiment, participants had two different tasks to perform for the two embedded targets serially presented. First, they detected a white letter among black letters and then monitored for the presence or absence of an X. This probe-style AB task taps into task switching abilities as well as attentional selection abilities (Kelly and Dux, 2011). VGPs have been shown to switch between pairs of tasks on related stimuli more easily than nVGPs, including switching between letter and digit classification (Andrews and Murphy, 2006; Strobach et al., 2012), between global and local feature processing (Colzato et al., 2010), and between opposing stimulus-response rules (Cain et al., 2012). Thus, some of the video-game-related improvements in AB performance noted previously may have been due to superior task switching abilities in VGPs.

Additionally, in Green and Bavelier's (2003) task, stimuli were presented very briefly (15 ms) while ours were presented relatively longer (80 ms). This presentation time difference likely contributed to the higher accuracy levels in our paradigm. In the 15 ms presentation version, the need to perceive the item quickly may have given the VGPs a further advantage, as VGPs have higher visual sensitivity than nVGPs and are better able to initially encode rapidly presented information into visual sensory memory (Appelbaum et al., 2013; but see Blacker and Curby, 2013; Wilms et al., 2013).

Thus, the superior performance seen in AB tasks previously may be due, in part, to improved task switching and visual sensitivity in VGPs relative to nVGPs and not to factors more commonly associated with the AB, such as the speed of processing T1. This idea of more general performance improvement is reinforced by an examination of the results of Green and Bavelier (2003), which shows a VGP advantage across Lags 1–5, and not just at the critical AB Lags and a training benefit at only later lags. While the current null result can provide only limited evidence, in combination with prior work, it suggests that the exact parameters of the AB task may be crucial for finding differences between VGPs and nVGPs.

GENERAL DISCUSSION

Here we demonstrated that action VGPs have greater resistance to exogenous attentional capture than those who do not play action video games. In Experiment 1, when the time between the cue and the target was long, both VGPs and nVGPs showed the expected anti-cueing effect, responding faster at the anti-cued location than the cued location. Hence both groups displayed equivalent ability to utilize the information provided by the cue (i.e., predicting the anti-cue target location). However, when the SOA was short, nVGPs showed the expected exogenous cuing effect, but VGPs did not: nVGPs were faster at the location of the cue than at the most likely, anti-cued location, but VGPs were equally fast at all locations. Hence, while clearly extracting the information provided by the cue (as evident in longer SOAs) VGPs were able to avoid being captured to that same cue location. In Experiment 2, the finding that there was no difference in AB performance between VGPs and nVGPs suggests that the cuing effects were not due to speed of visual processing or motivational differences between groups.

These results are in line with recent findings that VGPs resist attentional capture by task-irrelevant distractors (Chisholm et al., 2010; Chisholm and Kingstone, 2012). However, it is seemingly at odds with a previous cuing finding: In a modified temporal-order judgment task with uninformative cues, VGPs were more likely to be captured by the cue than nVGPs (West et al., 2008; Experiment 1). The key difference between that paradigm and ours may be the informativeness of the cue. In the West et al. (2008) task, targets always appeared in both locations and the appearance of the cue carried no information about the relative target timings. Thus, from a participant's point of view, attending to the cue had no noticeable effect on performance, so there was no particular reason to attempt to resist capture. In the current paradigm, the target only appeared in the cued location on 12.5% of trials, so being captured by the cued location might have noticeably negatively impacted performance, giving participants an incentive to try and resist capture. Also, we explicitly instructed participants that the target would most likely not appear in the cued location, and it may be that the VGP group was better able to use this instructional information than the nVGP group.

Our results fill in an important gap in the existing literature on attentional capture in VGPs. Previous work has demonstrated that VGPs are captured by exogenous cues that aid in task execution (Hubert-Wallander et al., 2011b) or have a non-obvious negative impact (West et al., 2008) but are able to resist capture by exogenous distractors that obviously hindered performance (Chisholm et al., 2010; Chisholm and Kingstone, 2012). Here we presented task-relevant information at a to-be-ignored spatial location and demonstrated that VGPs were able to resist attentional capture to an irrelevant spatial location while still being able to use cue information from that location to help them on the task. Taken together these results suggest that VGPs may possess more flexible control over what does and does not capture their attention: When a stimulus facilitates performance, VGPs can get the full benefit of letting it capture their attention, but when it hinders performance VGPs can resist capture.

RELATIONSHIP WITH OTHER VISUAL ATTENTION PHENOMENA

One effect that has been much discussed in the video game literature is the flanker compatibility effect (i.e., distractor items surrounding a central target item speed responding if they are compatible with the target but slow responding if they are incompatible). If VGPs have better control over exogenous attention capture, this suggests that they might be less affected by the presence of incompatible flanking items in a display. In fact, initial reports argued that VGPs were actually more affected by incompatible flanking items than were nVGPs (Green and Bavelier, 2003, 2006a). However, subsequent reports have found equivalent levels of flanker interference in VGPs and nVGPs (Irons et al., 2011; Cain et al., 2012). While there is still some disagreement on this issue, it is clear that VGPs do not experience less flanker interference than nVGPs, which suggests some limits on their ability to control their attention. One potentially important difference between the cuing and flanker paradigms is the proportion of validly cued trials; in cases where VGPs have resisted stimulus capture, it was beneficial to do so most of the time, but in flanker experiments there is usually an even ratio of compatible trials (where capture helps) and incompatible trials (where it hinders), perhaps not providing sufficient incentive to exert control over exogenous capture. This line of argument suggests that studies manipulating cue validity may be able to more fully link these literatures.

Another attentional paradigm where VGPs have demonstrated benefits over nVGPs is multiple object tracking. In particular, VGPs are able to track more objects moving among distractors than nVGPs (Trick et al., 2005; Green and Bavelier, 2006b; Sungur and Boduroglu, 2012). This improved tracking performance is consistent with improved resistance to attentional capture: If VGPs are better able to resist capture by distracting items as those items pass near targets, this could lead to fewer instances where the target is lost. Unlike video game experience and training, specific spatial attention training does not lead to object tracking improvements (Appelbaum et al., 2011). This implicates a separate mechanism for superior performance by VGPs, such as exogenous attentional control.

PROCEDURAL ISSUES

There has been increasing dialog about the best practices for studying the cognitive effects of video game experience (e.g., Boot et al., 2011; Kristjánsson, 2013), with two central issues: training vs. expert designs and participant recruitment. In the present experiments, we compared novice VGPs with expert VGPs. This has the advantage that our expert population has a great deal of experience (our VGPs reported playing $\geq$ 130 h of FPS games in the previous 6 months, between 2 and 10 times more exposure than in a typical training study), giving us the opportunity to observe skills that may only emerge after a great deal of practice. It should be noted, however, that such a quasi-experimental design has the drawback that we cannot be sure that the effects we observe are directly due to video game experience and not some other factor such as a selection bias (e.g., individuals with better control over attentional capture may play more FPS games, if such control makes gameplay more enjoyable).

One persistent source selection bias is gender, as action video games tend to engage males more than females (e.g., Lucas and Sherry, 2004). The present groups are not balanced by gender and thus, it is possible that gender differences in attentional abilities might underlie our effects (e.g., Feng et al., 2007), or the choices of our participants to become VGPs or nVGPs. A reanalysis of the current dataset including only male participants yielded the same general pattern of results, but the reduced statistical power limits the interpretability of this reanalysis. While we consider large differences in expertise with action video games between groups to be a more parsimonious explanation of the current results than gender differences, the current results are unable to definitively resolve this question.

Participants in these experiments were recruited both from prescreening survey responses and from fliers explicitly seeking VGPs and nVGPs. The explicit recruitment of some participants opens the possibility that groups were differently motivated, for example those identifying as VGPs may have come into the experiment expecting to perform well, while nVGPs may have had lowered expectations (e.g., Boot et al., 2011). While we cannot fully rule out this possibility, the lack of group differences in the AB task in Experiment 2, performed in the same testing session as Experiment 1, suggests that the effects were not driven solely by global motivational differences (see Cain et al., 2012; Schubert and Strobach, 2012 for similar arguments).

CONCLUSION

There is no clear consensus on exactly what cognitive abilities are trained by action video game play or how such play actually leads to the generalized learning that has been observed. However, new ideas are beginning to emerge for how to characterize fundamental cognitive improvements due to video games (e.g., Baniqued et al., 2013). It seems clear that there are likely a number of factors that video games train, such as faster visual apprehension (e.g., Appelbaum et al., 2013), improved cognitive control (e.g., Cain et al., 2012; Strobach et al., 2012), and even the ability to quickly adapt within an experimental context (e.g., West et al., 2013). Here we argue that the ability to control and focus attention on task-relevant information is also a fundamental cognitive ability trained by video games. While the current study compared expert populations, and cannot speak directly about causality, one recent example more directly suggests a causal role. nVGPs were trained on custom FPS games that either required players to discriminate between hostile and friendly targets or contained exclusively hostile targets. Only those nVGPs in the target discrimination training condition showed attentional benefits from training (Brown et al., 2012).

The degree to which salient objects capture attention can vary from moment to moment (Leber, 2010). When acting in an uncertain visual environment, it would be advantageous to have flexible control over the level of exogenous attentional capture to a given location. Depending on the context, performance may be improved by allowing attention to be captured to a location by exogenous stimuli or by preventing capture. Action VGPs seem to be more adept than non-players at analyzing and adapting to the overall statistics of the visual task set at hand, likely due to extensive practice encountering, engaging with, and responding to the task demands of new environments in video games. In particular, the ability to extract information from a sudden-onset cue without allowing the cue to capture attention demonstrates a very high level of control over attention in VGPs.

AUTHOR CONTRIBUTIONS

Matthew S. Cain and Ayelet N. Landau conceived of, executed, and analyzed both experiments. Matthew S. Cain wrote the manuscript. Arthur P. Shimamura and William Prinzmetal provided guidance and support. William Prinzmetal designed and programmed the task in Experiment 1.

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Gaming to see: action video gaming is associated with enhanced processing of masked stimuli

Carsten Pohl[1,2]*, Wilfried Kunde[1], Thomas Ganz[3], Annette Conzelmann[4], Paul Pauli[4] and Andrea Kiesel[1]

[1] Department of Psychology, Cognitive Psychology, University of Würzburg, Würzburg, Germany
[2] Hospital for Psychiatry, Psychotherapy and Psychosomatic Medicine Lohr am Main, Lohr am Main, Germany
[3] University of Applied Sciences Esslingen, Esslingen, Germany
[4] Department of Psychology, Biological Psychology, Clinical Psychology and Psychotherapy, University of Würzburg, Würzburg, Germany

Edited by:
Walter R. Boot, Florida State University, USA

Reviewed by:
Walter R. Boot, Florida State University, USA
Jason S. McCarley, Flinders University, Australia

****Correspondence:***
Carsten Pohl, Department of Psychology, University of Würzburg, Röntgenring 11, 97070 Würzburg, Germany
e-mail: pohl@psychologie.uni-wuerzburg.de

Recent research revealed that action video game players outperform non-players in a wide range of attentional, perceptual and cognitive tasks. Here we tested if expertise in action video games is related to differences regarding the potential of shortly presented stimuli to bias behavior. In a response priming paradigm, participants classified four animal pictures functioning as targets as being smaller or larger than a reference frame. Before each target, one of the same four animal pictures was presented as a masked prime to influence participants' responses in a congruent or incongruent way. Masked primes induced congruence effects, that is, faster responses for congruent compared to incongruent conditions, indicating processing of hardly visible primes. Results also suggested that action video game players showed a larger congruence effect than non-players for 20 ms primes, whereas there was no group difference for 60 ms primes. In addition, there was a tendency for action video game players to detect masked primes for some prime durations better than non-players. Thus, action video game expertise may be accompanied by faster and more efficient processing of shortly presented visual stimuli.

Keywords: masked priming, action video gaming, unconscious processing, prime visibility, expertise

INTRODUCTION

Over the last three decades, public as well as scientific interest in action video gaming focused mainly on negative consequences such as video game addiction (e.g., Griffiths and Meredith, 2009) or promoting the likelihood of aggressive behavior (e.g., Anderson et al., 2003; Carnagey et al., 2007). While there is still a lively debate whether action video games do actually increase aggressive behavior or whether effects found in the laboratory can be transferred to account for aggressive behavior in real live (e.g., Anderson et al., 2010; Bushman et al., 2010; Ferguson and Kilburn, 2010; Ferguson et al., 2013), research in recent years has also revealed several positive side-effects of playing action video games on vision, perception, attention, and cognitive control.

In a series of studies, Green and Bavelier(2003; 2006a; 2006b; 2007; see Green et al., 2010a, for a review) compared action video game players and novices regarding their performance in many standard paradigms of cognitive psychology, like the flanker task, enumeration task, useful field of view task, attentional blink task, multiple object tracking task, perceptual load paradigm, and crowding paradigm. Compared to novices, action video game players performed better in peripheral and central vision tasks, better under dual task conditions, and action gamers displayed evidence of greater attentional resources, an enhanced spatial distribution of attention, and a greater temporal and spatial resolution of attention. Action video game usage also seems to promote parallel processing, as action video game players were able to enumerate and track substantially more items at once than novices (Green and Bavelier, 2006b; see also Trick et al., 2005). Further, action video game players also showed benefits for multisensory processing when visual and auditory stimuli were presented in close temporal succession (Donohue et al., 2010). Video game experience was also associated with an increased ability to switch between two tasks (Colzato et al., 2010), enhanced monitoring and updating of working memory (Colzato et al., 2013), and improved probabilistic inference (Green et al., 2010b). These tasks are considerably different from the situation of gaming itself which suggests a substantial transfer of training.

Moreover, training studies suggest that differences between gamers and non-gamers are not just correlational, but that there is a causal relationship between action video game play and improved perceptual and cognitive abilities (e.g., Green and Bavelier, 2003, 2006a,b, 2007; Li et al., 2009; Strohbach et al., 2012). Novices who were trained with an action video game (Medal of Honor, Call of Duty 2, or Unreal Tournament) performed better than novices who were trained with a non-action video game (Tetris or The Sims). Ten to 50 h of training with an action game was sufficient to induce considerable impoverishments.

Regarding more basic effects on visual processing, Li et al. (2009) reported a long-lasting enhancement of contrast sensitivity through action video game playing and intensive training. Contrast sensitivity is "the ability to detect small increments in shades of gray on a uniform background" (Li et al., 2009, p. 549). It is seen as "one of the most basic visual functions that commonly deteriorate with aging" (Caplovitz and Kastner, 2009, p. 527) and it is assumed to be important in many different visual tasks.

Contrast sensitivity was measured with a detection task for a briefly presented gabor patch. Detection performance was better in action video game players and action video game trained participants than for novices and non-action video game trained participants.

Furthermore, using a lateral masking paradigm, Li et al. (2010) found that action video game training also influences the temporal dynamics of vision. A central gabor patch was presented as target. This gabor patch was masked by two vertically flanking gabor patches. The SOA of the masks was varied in order to create forward or backward masking. Participants had to detect the central gabor patch. Action video game players showed reduced backward masking compared to non-action game players. This pattern of result was replicated in a training study, suggesting a causal relationship between action video gaming and improved cortical dynamics.

The aim of the current study is to further increase our knowledge of types of processes might be affected by video game expertise. Here, we asked whether action video game expertise enhances not just the ability to detect visible stimuli but also the ability to process stimuli that are hardly visible. To assess processing of such stimuli, we used a masked priming paradigm (e.g., Dehaene et al., 1998; Dell'Acqua and Grainger, 1999; Naccache and Dehaene, 2001; Kunde et al., 2003; Kiesel et al., 2006a) and assessed stimulus-response translation processing based on masked prime stimuli. In addition, we also assessed visibility of the masked stimuli in a visibility test.

There are two reasons for this approach. First, using masked stimuli helps to scrutinize the level of neural processing that action video gaming affects. The impact of masked stimuli is based on what Lamme calls the "forward sweep" of stimulus processing (Lamme, 2003, 2006). This relates to fast forward processing of retinal input within the first about 100 ms. Observers are not aware of stimuli at that level of processing, and normally do not become aware of them later, provided the visual representation is destroyed by masking. It is only when the visual percept is stabilized by recurrent neural processing that consciousness kicks in. Demonstrating that video gaming impacts the processing of masked stimuli would thus reveal that this impact occurs already at the first neural processing sweep, rather than at the level of later recurrent processing. A second reason relates to potential strategic influences on performance. Action video gamers might adapt performance according to demand characteristics, particularly so if they assume that game experience was a reason for choosing them as participants (cf. Boot et al., 2011; Kristjánsson, 2013). In other words gamers might make larger efforts for fast responding just because they consider themselves as a specific sample supposed to respond quickly. Whereas it is obviously possible to change responses to stimuli that are consciously discernible, it is far less obvious how to change the impact of prime stimuli that are hardly visible. In fact, with the pictorial stimulus material we used here, subliminal primes affect performance largely independent of response times to conscious targets (except perhaps for very slow responses)—a finding we will replicate here (Kiesel et al., 2009; Heinemann et al., 2010). So while gamers might try to speed up responding due to demand characteristics, this is unlikely to affect the congruency effects exerted by masked primes. Such congruency effects are thus a less demand-contaminated measure of visual processing than RTs to visible stimuli are, although demand effects that do not leave a trace in RT cannot ultimately be ruled out.

For this experiment we used a picture priming paradigm we had already established in our laboratory and that produced stable priming effects (Pohl et al., 2010). Participants saw pictures of animals that could be easily classified as being smaller or larger than a reference object. Prior to each target picture, one of the same four animal pictures is presented as prime. If this prime suggests the same response as the target (congruent), participants usually respond faster and less error-prone compared to when prime and target suggest different responses (incongruent). To reduce visibility of the prime stimuli, primes are presented very short and additionally they are masked by random dot masks (see **Figure 1**). Here in this study, we presented primes either for 20 or 60 ms to assess stimulus-response translation processes of hardly visible and more visible stimuli. If video game players (VGP) process hardly visible stimuli more efficiently than non-video game players (NVGP), we expect larger congruence effects for the players.

This design differs substantially from the lateral priming design Li et al. (2010) used. In their study, the correct temporal detection of a gabor patch was assessed. Participants had to decide in which of two intervals the gabor patch was presented. In contrast, in the present study, we were interested to find out whether action video gaming is associated with enhanced processing of masked primes in a way that affords processing of hardly visible stimuli according to their identity. In order to perform the task, participants had to identify the pictured animals and they were asked to categorize the pictured animals according their size in real life. Masked prime processing occurs when participants apply the task instructions already on the masked primes (cf. Dehaene et al., 1998). That would indicate that also masked animal pictures were processed in the same way as the clearly

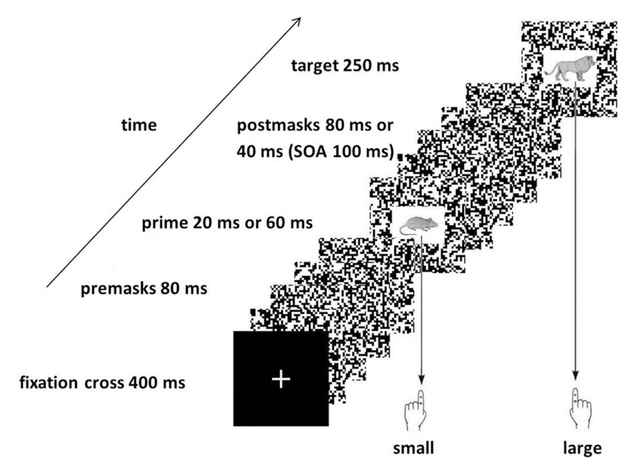

FIGURE 1 | Sequence of the events in the Experiment. The Figure shows an incongruent trial because the prime picture (the mouse) would afford the left response indicating "small" while the target picture (the lion) affords the right response indicating "large."

visible targets, i.e., they are identified and categorized according to their size in real life.

In addition, participants performed a prime visibility test after the priming study. Here, primes were presented 20, 40, 60, 80, or 100 ms. This visibility test served two purposes. First, we wanted to check to which degree participants could see the primes. Second, we aimed to replicate the findings of Li et al. (2009) as well as Li et al. (2010) and expected that VGPs can identify the primes more often correctly than NVGPs.

MATERIAL AND METHODS

PARTICIPANTS

To recruit participants we placed two advertisements on a regional online job platform, one for people who play action video games (such as Call of Duty: Modern Warfare 3, Battlefield 3, Counter Strike, Boarderlands, or Medal of Honor) and one for people who play no computer games. Then we used the platform www.SoSciSurvey.de to identify a sufficient number of VGPs and NVGPs. The criteria for VGPs were that they indicated playing at least 8 to 10 h per week during the last year. NVGPs were persons who reported that they currently played no computer games and seldom did so in the past. Consequently, we conjecture that participants were aware that they were chosen for the experiment either because of their gaming experience or because of the lack of it.

We a priori decided to match the VGP and NVPG groups for age, gender, and IQ in order to guarantee that general cognitive abilities were equally distributed in both groups and both groups were consistent in terms of demographic makeup. Accordingly, from the 360 persons who participated in the online survey, we selected a sample of sixty healthy male adults between 18 and 29 years (with an average age of 23.7 years) who met either the criteria for VGPs (30 participants) or NVGPs (30 participants). They gave informed consent to participate in a study to investigate emotional, mental and behavioral processes. Data of five participants per group were not included in the analyses because afterwards they admitted that they did not fulfill the criteria for VGP (3 participants), declared to have a mental illness (1), or reported to have not followed the instruction in the prime visibility task correctly (4). Further, data of two participants of the NVGP group[1] were discarded to ensure that the two groups did not differ with respect to intelligence. All participants reported having normal or corrected-to-normal vision, and were not familiar with the purpose of the experiment.

To check whether the VGP and the NVGP groups are similar expect for the gaming experience, we assessed fluid intelligence (via the SPM) as well as age. Intelligence was measured with a pen and pencil version of the Raven Standard Progressive Matrices Test (SPM; Heller et al., 1998) which was given without time limit. This test for fluid intelligence is widely used in research as well as in practice (Raven, 2000) for the measurement of general intelligence (reasoning ability of Spearman's g factor) and does not depend on language. For the analysis of fluid intelligence we calculated with the raw scores of the SPM because of missing current norms for the German sample (Heller et al., 1998). Independent samples *t*-tests showed no significant group differences for fluid intelligence, $t_{(48)} = 1.67$, $p > 0.10$ and age, $t_{(48)} = -1.30$, $p = 0.20$ (see **Table 1** for mean values).

APPARATUS AND STIMULI

The experiment took place in a dimly lit room. An IBM compatible computer with a 17 inch VGA-Display and the software package E-Prime™ (Schneider et al., 2002) were used for stimulus presentation and response sampling. Stimulus presentation was synchronized with the vertical retraces of a 100-Hz monitor, resulting in a refresh rate of 10 ms. Responses were executed with the index fingers of both hands and collected with an external keyboard with three response keys (1.7 cm width, distance 0.2 cm); the middle response key was not used.

The pictures used as targets and primes were derived from a set of gray scale shaded images of "Snodgrass and Vanderwart-like" objects (Rossion and Pourtois, 2004; see http://wiki.cnbc.cmu.edu/Objects)[2]. The target set consisted of four animal pictures (mouse, snail, lion and zebra,) that could be easily classified as being smaller or larger than a frame measuring 40 × 40 cm (mouse and snail—smaller; lion and zebra—larger). The same four pictures were used as primes. To vary visibility of the primes, primes were either presented for 20 ms or for 60 ms. All pictures were drawn in a white rectangle extending 2 cm high by 3 cm wide. Masks were random dot patterns extending 7.5 × 7.5 cm. They were constructed such that always 4 × 4 pixels were chosen randomly to be white or black. To increase masking, we presented always four different random dot patterns with a total duration of 80 ms as premask and four or two different random dot patterns with a total duration of 80 or 40 ms, respectively. Additionally, the prime as well as the target picture were also presented on a random dot pattern background (see **Figure 1**).

PROCEDURE AND DESIGN

The experiment was completed in a single session that lasted approximately 90 min and that was compensated with 12 Euro. The session consisted of two parts. First, participants executed a priming experiment. Second, a prime discrimination task was administered. Afterwards, individual intelligence was measured with the SPM.

In the following the two parts of the computer experiment are described in more detail.

PRIMING EXPERIMENT

The sequence of the events in a trial in the priming experiment is shown in **Figure 1**. On each trial, a fixation cross was presented for 400 ms. Then the premasks were presented for 80 ms followed by the prime presented either for 20 or 60 ms. Then the postmasks were presented either for 80 or 40 ms, respectively, so that the Simulus Onset Asynchrony (SOA) between prime and target presentation was always 100 ms. Finally, the target was presented

[1]These two participants revealed 36 and 37 points in the SPM, respectively. These scores are about 5 standard deviations below the mean scores and they are clear outliers because the next lowest SPM scores were 47 points in the NVGP group and 48 points in the VGP group, respectively.

[2]We thank Bruno Rossion and Gilles Pourtois who originally commissioned the pictures and Michael J. Tarr for making the pictures available.

Table 1 | Mean values for demographic characteristics (standard deviations are given in brackets), performance for congruent and incongruent primes that were presented 20 and 60 ms, separately for VGPs and NVGPs (standard errors are given in brackets).

	VGPs		NVGPs	
SPM raw score	55.6 (3.2)		54.0 (3.5)	
Age	23.0 (3.0)		24.0 (2.8)	
Congruence	**Incongruent**	**Congruent**	**Incongruent**	**Congruent**
20 ms PRIMES				
RT (ms)	397 (7.6)	381 (9.2)	423 (7.6)	417 (9.2)
PE (%)	4.4 (0.8)	3.2 (0.7)	3.5 (0.8)	2.3 (0.7)
60 ms PRIMES				
RT (ms)	432 (8.7)	376 (8.8)	462 (8.7)	405 (8.8)
PE (%)	11.3 (1.8)	2.4 (0.5)	9.2 (1.8)	2.6 (0.5)

directly after the postmasks for 250 ms. After response execution a fixed time interval of 1000 ms elapsed before the next trial started.

Participants were instructed to categorize the depicted animals as being smaller or larger than a reference frame (40 × 40 cm) and to respond as fast as possible while they should avoid to make errors. Participants had to press a left key with the left index finger to indicate "smaller" and a right key with the right index finger to indicate "larger" as fast and as accurately as possible. Errors were indicated by the German word for wrong ("Falsch!") presented in red in the lower part of the monitor. Response times were recorded from the onset of the target until the onset of the response.

There were 32 (4 × 4× 2) different combinations of target, prime and prime duration (20 or 60 ms) that were presented 10 times each. After each block of 64 trials, participants were allowed a short, self-paced break. In addition, mean response times and percentage of errors were fed back to encourage participants to increase their performance.

ASSESSMENT OF PRIME VISIBILITY

After the priming experiment, we tested prime visibility with a separate prime discrimination task. In general, the stimuli as well as their sequence was comparable to the priming experiment. However, in this experimental part, participants were fully informed about the precise structure of a trial and the presence of the masked primes. This time, participants were asked to discriminate whether the prime picture was smaller or larger than the reference object. For the discrimination task, participants were instructed to take their time and to try to be as accurate as possible. In order to avoid that unconsciousness congruence effects influence the free response choice (see Schlaghecken and Eimer, 2004; Kiesel et al., 2006b), there was an interval of 800 ms after target offset, in which no response was possible (e.g., Vorberg et al., 2003).

In order to get a more graded assessment of prime visibility, we varied prime duration from 20 to 100 ms in steps of 20 ms. Thus, in a trial the prime picture was presented either for 20, 40, 60, 80 or 100 ms. As in the priming part of the experiment, the SOA was held constant for 100 ms. Therefore, postmasks were presented for 80, 60, 40, 20 ms, or were omitted, respectively. There were 80 (4 × 4× 5) different combinations of target, prime and prime duration (20, 40, 60, 80, and 100 ms) that were presented 5 times each leading to 400 trials altogether.

RESULTS

PRIMING EXPERIMENT

Trials with reaction times (RTs) deviating more than 2.5 standard deviations from the mean RT of each participant and each experimental condition (2.1%) were excluded.

Mean RTs for correct responses and error rates for each combination of the within-subjects factors prime duration (20 and 60 ms) and prime congruence (incongruent and congruent) for VGPs and NVGPs (between-subjects factor group) are given in **Table 1**. An analysis of variance (ANOVA) on RTs for correct responses with the between-subjects factor group and with the within subject factors prime duration and prime congruence, revealed significant main effects for all single factors: group, $F_{(1, 48)} = 6.6$, $p = 0.01$, $\eta_p^2 = 0.12$, prime duration $F_{(1, 48)} = 94.2$, $p < 0.001$, $\eta_p^2 = 0.66$, and prime congruence, $F_{(1, 48)} = 249.8$, $p < 0.001$, $\eta_p^2 = 0.84$. On average VGPs responded faster than NVGPs (397 vs. 427 ms), participants responded faster after primes that were presented for 20 ms compared to primes that were presented for 60 ms (405 vs. 419 ms), and participants responded faster with congruent primes compared with incongruent primes (395 vs. 429 ms). The interaction prime duration × prime congruence was also significant, $F_{(1, 48)} = 254.7$, $p < 0.001$, $\eta_p^2 = 0.84$. This significant interaction indicates that the congruence effect is larger for primes that were presented 60 ms than for primes that were presented 20 ms (57 vs. 11 ms). The interactions for prime duration × group and prime congruence × group were not significant, $ps = 0.31$. The three-way interaction of prime duration × prime congruence × group was marginally significant, $F_{(1, 48)} = 3.6$, $p = 0.06$, $\eta_p^2 = 0.97$. The marginal three-way interaction was further explored in order to investigate whether the RT congruence effect differed in VGPs and NVGPs for the two prime durations. We analyzed the impact of 20 ms primes and 60 ms primes separately:

An ANOVA on RTs for correct responses after primes that were presented for 20 ms, with the between-subjects factor group and the within subjects factor prime congruence, revealed significant main effects for all single factors: group, $F_{(1, 48)} = 6.8$, $p = 0.01$, $\eta_p^2 = 0.13$ and prime congruence, $F_{(1, 48)} = 27.4$, $p <$

0.001, $\eta_p^2 = 0.36$. The interaction prime congruencex group was also significant, $F_{(1, 48)} = 5.8$, $p = 0.02$, $\eta_p^2 = 0.11$, indicating that the congruence effect for VGPs was larger than for NVGPs (16 vs. 6 ms). Single comparisons show a significant congruence effect for VGPs, $t_{(24)} = 7.3$, $p < 0.001$, and a marginally significant congruence effect for NVGPs $t_{(24)} = 1.7$, $p = 0.06$.

On average VGPs responded faster than NVGPs. This was also true for primes that were only presented 20 ms (389 vs. 420 ms). To rule out that the difference in the RT levels was responsible for the difference in the congruence effects between VGPs and NVGPs, we examined RT distributions on the basis of percentile values obtained for each participant. For this we rank-ordered RTs per conditions in the 10% fastest, 10–20%,..., 80–90% RTs[3], computed the average RT per percentile and condition, and computed the congruence effect per percentile by subtracting RT incongruent—RT congruent per percentile. In **Figure 2**, the congruence effects per percentiles for NVGPs and VPGs are depicted depending on the mean RT of this percentile. The congruence effect for VGPs is rather constant over the percentiles and differences in the size of congruence effects for VGPs and NVGPs occur at similar RT levels.

An ANOVA on RTs for correct responses after primes that were presented for 60 ms, with the between-subjects factor group and the within subjects factor prime congruence, revealed significant main effects for the single factors group, $F_{(1, 48)} = 6.2$, $p = 0.02$, $\eta_p^2 = 0.12$ and prime congruence, $F_{(1, 48)} = 355.0$, $p < 0.001$, $\eta_p^2 = 0.88$. However, the interaction group × congruence was not significant, $ps > 0.84$, indicating that the congruence effect for VGPs did not differ for VGPs and for NVGPs (56 vs. 57 ms).

The overall mean error rate was 4.6%. The same ANOVA on error rates for all responses, revealed significant main effects for the within-subjects factors prime duration $F_{(1, 48)} = 54.3$, $p < 0.001$, $\eta_p^2 = 0.53$, and prime congruence, $F_{(1, 48)} = 50.1$, $p < 0.001$, $\eta_p^2 = 0.51$. Participants made more errors after primes that were presented for 60 ms compared to primes that were presented for 20 ms (6.4 vs. 3.3%) and participants made more errors after incongruent primes compared to congruent primes (7.1 vs. 2.6%). The interaction prime duration × prime congruence was also significant, $F_{(1, 48)} = 30.6$, $p < 0.001$, $\eta_p^2 = 0.39$. The congruence effect was larger for primes that were presented 60 ms than for primes that were presented 20 ms (7.7 vs. 1.3%). The between-subjects factor group was not significant, as well as the interactions for prime duration × group, prime congruence × group, and prime duration × prime congruence × group, $ps = 0.36$.

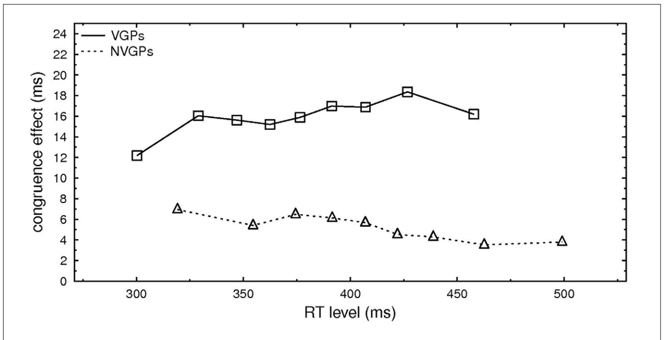

FIGURE 2 | Congruence effect (in ms) for the nine percentiles (10–90%) depending on the mean RT of each percentile separately for VGPs and NVGPs.

[3]The percentile 90–100% contains too many outliers and is thus not considered.

PRIME VISIBILITY

To assess prime visibility, we computed the signal detection measure d'. Prime pictures requiring the response "small" (animal) were treated as signal, whereas prime pictures requiring the response "large" (animal) were considered as noise. Hits and false alarms proportion of zero or one were corrected according to the log-linear rule (Goodman, 1970; cited according to Hautus, 1995) if participants had 0% hits or 100% false alarms. Prime visibility was above chance level for each group and prime duration: Separately for the different prime durations the discrimination performance for VGPs was for primes that were presented 20 ms $d' = 0.53$, $t_{(24)} = 6.80$, $p < 0.001$, for primes that were presented 40 ms $d' = 2.09$, $t_{(24)} = 14.43$, $p < 0.001$, primes that were presented 60 ms $d' = 2.55$, $t_{(24)} = 16.98$, $p < 0.001$, for primes that were presented 80 ms $d' = 2.63$, $t_{(24)} = 18.47$, $p < 0.001$, and for primes that were presented 100 ms $d' = 2.75$, $t_{(24)} = 19.07$, $p < 0.001$ (see **Figure 3**). For NVGPs the discrimination performance for the different prime durations was for primes that were presented 20 ms $d' = 0.33$, $t_{(24)} = 3.95$, $p < 0.001$, for primes that were presented 40 ms $d' = 1.74$, $t_{(24)} = 10.05$, $p < 0.001$, for primes that were presented 60 ms $d' = 2.11$, $t_{(24)} = 12.28$, $p < 0.001$, for primes that were presented 80 ms $d' = 2.44$, $t_{(24)} = 11.10$, $p < 0.001$, and for primes that were presented 100 ms $d' = 2.54$, $t_{(24)} = 13.33$, $p < 0.001$ (see **Figure 3**).

An ANOVA with the between-subjects factor group (VGPs and NVGPs) and with the within subject factor prime duration(20, 40, 60, 80, and 100 ms) showed that prime duration had a significant effect on prime visibility, $F_{(4, 192)} = 179.0$, $p < 0.001$, $\eta^2 = 0.78$, whereas the factor group and the interaction group × prime duration were not significant, $ps > 0.13$. However, when only the prime durations are analyzed that were used in the priming experiment, then an ANOVA with the between-subjects

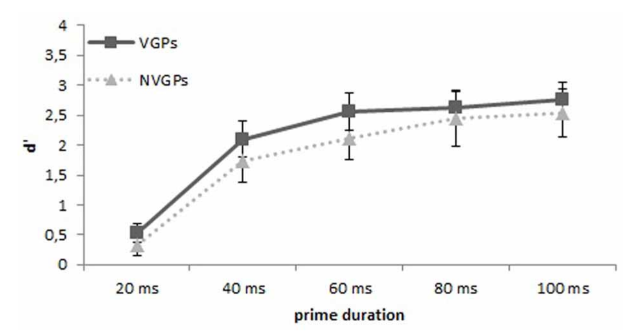

FIGURE 3 | Mean d's and 95% between-subjects confidence intervals separately for each prime duration for VGPs and NVGPs.

factor group (VGPs and NVGPs) and with the within subject factor prime duration (20 and 60 ms) revealed again that prime duration significantly effected prime visibility, $F_{(1, 48)} = 355.4$, $p < 0.001$, $\eta^2 = 0.88$, as well as a significant effect for the factor group, $F_{(1, 48)} = 4.5$, $p = 0.038$, $\eta^2 = 0.09$, providing at least some evidence that VGPs could discriminate the primes better than NVGPs at these two prime durations. The interaction group × prime duration remained insignificant, $ps = 0.22$.

CORRELATIONS OF CONGRUENCE EFFECT, PRIME VISIBILITY, AND GAME EXPERIENCE

Prime pictures that were presented for 20 ms, elicited a larger congruence effect in VGPs than in NVGPs, while prime visibility was higher in VGPs than in NVGPs when only the two prime durations of the priming experiment (20 and 60 ms) are considered. We therefore ran additional analyses in order to investigate how the two results (congruence effect and prime visibility) as well as video game experience are interrelated.

To test whether the congruence effect is related to the prime visibility, a regression analysis as proposed by Draine and Greenwald (1998, see also Greenwald et al., 1995, 1996) was computed. A priming index was calculated for each participant and each prime type, with index = 100 × (RT incongruent—RT congruent) / RT congruent. The indirect effects of individual priming indices were regressed onto the direct effects of individual d' values separately for VGPs and NVGPs. Following this methodological approach a significant slope of the regression would indicate that congruency effects rise with increasing prime visibility, whereas the "regression intercept estimates the magnitude of priming associated with zero perceptibility of the prime" (Greenwald et al., 1996, p. 1700).

The linear regression analysis revealed no significant correlation between d' and the priming index for prime pictures that were presented 20 ms, neither for VGPs with $r = 0.105$, $p = 0.62$, nor for NVGPs with $r = 0.294$, $p = 0.15$. A *post-hoc* Bayes test for correlations using the procedure of Wetzels and Wagenmakers (2012) revealed Bayes factors of 0.17 for VGPs and 0.42 for NVGPs modestly favoring the null hypothesis that the size of the congruency effects and prime visibility are not related to each other. The intercept of the regression was larger than zero for VGPs, intercept = 3.76, $t_{(24)} = 3.58$, $p < 0.01$, indicating that significant congruence effect for 20 ms in VGPS can be expected even at zero visibility in terms of d'. In contrast there was no significant intercept for NVGPs, intercept = 0.85, $p = 0.40$.

For prime pictures that were presented 60 ms, the linear regression analysis revealed again no significant correlation between d' and the priming index for prime pictures, neither for VGPs with $r = 0.100$, $p = 0.63$, nor for NVGPs with $r = 0.160$, $p = 0.45$. A *post-hoc* Bayes test for correlations using the procedure of Wetzels and Wagenmakers (2012) revealed Bayes factors of 0.17 for VGPs and 0.21 for NVGPs modestly favoring the null hypothesis for VGPs and NVGPs, indicating again that the size of the congruency effects and prime visibility are not related to each other. Here the intercept could not be interpreted because d' was > 0 for all participants. Thus, the observed congruence effect that is related to zero visibility for primes that were presented 20 ms is reliable for VGPs and independent on individual prime visibility. For primes that were presented 60 ms, the congruence effect is no longer related to null visibility, but it is still independent of individual prime visibility.

Although we found no significant correlation between individual prime visibility and the priming index in VGPs for primes that were presented for 20 ms, it is conceivable that the effect of video game experience on 20 ms prime processing was nonetheless mediated by an enhanced prime visibility. To rule out that differences in prime visibility are the driving force for increased priming effects in VGPs compared to NVPGs we conducted *post-hoc* a partial regression analysis of the variables game experience (the value was set 0 for NVGPs and 1 for VGPs) and priming index considering prime visibility (d') as confounding effect. A multiple regression with game experience and individual prime visibility as predictors and individual priming index as criterion revealed a significant correlation ($r = 0.389$, $p = 0.021$). Importantly, the correlation was also significant, when partialling the factor prime visibility ($r = 0.286$, $p = 0.046$), but not when partialling the factor game ($r = 2.15$, $p = 0.137$). These results indicate that prime visibility as possible mediator cannot completely account for priming effect differences between gamers and non-gamers with 20 ms primes. Instead, data suggest that game experience is directly related to the size of the congruency effects when prime visibility is controlled for.

DISCUSSION

We compared video game players' (VGPs) and non-video game players' (NVGPs) ability to process shortly presented near threshold-stimuli in a response priming experiment using masked pictures of drawn animals. Reaction times were faster for VGPs than NVGPs. For primes that were presented only 20 ms, VGPs showed a larger prime congruence effect than NVGPs. For primes that were presented 60 ms, both groups showed a substantial congruence effect that did not differ for VGPs and NVGPs. Additionally, an exploratory analysis gives tentative evidence that VGPs detected masked primes that were presented 20 ms as well as 60 ms better than NVGPs (please note, however, that the improved detection performance is restricted to the prime durations applied in the priming experiment and does not generally hold true). Thus, it seems that gaming expertise is accompanied by more efficient stimulus-response translation and tentatively a somewhat improved visual identification of shortly presented visual stimuli. Apparently, video gaming speeds up already the initial neural processing stream, the so called forward sweep, before recurrent neural processing comes in. Cognitive models of stimulus-response translation have assumed two stimulus-response-translation processes, one "response activation" process whereby stimuli automatically activate assigned motor responses, and another "response selection" process, that eventually determines whether activated responses are carried out (Hommel, 1998; Lien and Proctor, 2002). The masked priming effects we studied here are likely mediated by the fast response activation process (Schubert et al., 2008). Hence, gaming expertise conceivably improves the response activation process involved in the present priming task. However, because of the applied correlational design, some inconclusive findings, and due to further differential results between both groups there are a few caveats that have to be considered firstly.

First, VGPs responded on average 30 ms faster than NVGPs, reflecting a general RT advantage of video gaming experts (e.g., Green and Bavelier, 2003; Castel et al., 2005; Bialystok, 2006; Dye et al., 2009; Colzato et al., 2013). In a meta-analysis Dye et al. (2009) showed that VGPs are on average 11% faster than NVGPs whereby no speed accuracy trade-off occurred. In the present experiment VGPs were on average 8% faster than NVGs fitting well to the data of the meta-analysis (Dye et al., 2009). Similarly, overall error rates were numerically increased for VGPs compared to NVGPs and we thus cannot rule out speed accuracy trade-off. Indeed, a *post-hoc* Bayes test (http://pcl.missouri.edu/bf-two-sample) of the main difference of RTs and error rates for VGPs and NVGPs revealed Bayes factors of 0.28 for RTs and 3.56 for errors (Rouder et al., 2009).

More importantly, however, overall faster RTs for VGPs than NVGPs might be the reason for congruence effects differences because prime impact is rather short-lived. For example, Greenwald et al. (1996) showed that masked priming effects decrease rapidly when the SOA between prime and target is longer than 100 ms. A concomitant percentile analysis ruled out this suspicion. It revealed a quite constant congruence effect for VGPs for all percentiles as well as different congruence effects for VGPs and NVGPs at similar RT levels (see **Figure 2**). Thus the different congruence effects for primes that were presented for 20 ms cannot be explained by the general effect of faster responses for VGPs than for NVGPs.

Second, there is mixed evidence whether or not the larger congruency effect for VGPs compared to NVGPs for primes that were presented 20 ms is related to increased prime visibility of VGPs. In some studies, it has already been demonstrated that congruence effects increase with prime visibility (Greenwald et al., 1996; Kunde et al., 2005). The present experiment somewhat replicates this result because in both groups of participants, primes that were presented for 60 ms elicited larger congruence effects and were better discriminable than primes that were presented for 20 ms. Please note however, that here prime duration is confounded with visibility. Yet, when just considering primes that were presented for 20 and 60 ms, we found a somewhat better prime discrimination performance for VGPs than for NVGPs. To further investigate whether the size of congruence effects for primes that were presented for 20 ms and prime discrimination are related to each other we conducted two additional analyses. On the one hand, regression analyses as well as *post-hoc* Bayes tests for VGPs and NVGPs respectively, suggested that larger congruence effects were not exclusively brought by a higher individual prime visibility. Moreover, a *post-hoc* test indicated that primes that were presented for 60 ms were also better discriminated by VGPs than by NVGPs, although the amount of congruence effects was equal in both groups. On the other hand, a partial correlation analysis controlling for indirect mediation through prime visibility showed that the direct effect of video gaming expertise on the congruence effect for primes that were presented 20 ms was not driven fully by a possible indirect effect of prime visibility. Thus, in the present experiment it seems that video gaming expertise is related to more efficient stimulus-response translation.

Third, regarding prime visibility we found no statistically significant advantage for VGPs compared to NVGPs in the omnibus test of the discrimination task with prime durations ranging from 20 to 100 ms (in 20 ms steps). This is probably because for long prime durations prime detection rates were quite high and might have been insensitive for group differences. However, this explanation is post hoc and has therefore to be treated cautiously. The same holds true for restricting the analysis to the two prime durations used in the priming experiment. When only these two prime durations (20 and 60 ms) were considered in an explanatory analysis results revealed better visual discrimination performance of masked stimuli for VGPs compared to NVGPs. This result is in line with a study of Li et al. (2010) which shows that action video gaming decreases the efficiency of backwards masks. Moreover with masked letter primes it has already been shown that discrimination performance was better for typing experts than for novices (Heinemann et al., 2010). Nevertheless, additional studies may be required to provide more definitive conclusions about possible video game expertise related detection improvements of shortly presented masked primes and to tease out the underlying mechanisms.

Fourth, a problem when comparing experts and novices refers to a placebo-like effect of expectation and motivation (Boot et al., 2011). It might be that based on how participants are recruited, they already expect that their status of expertise shall be investigated and are therefore more eager to show a good performance. In the present study, we selected participants based on their self-reported gaming experience, thus it might be that VGPs were more motivated than NVPGs eventually explaining the observed RT differences and the better prime discriminability of VGPs compared to NVGPs. Yet, for the congruence effect in the masked priming paradigm such biases hardly play a role. During the priming task, participants are hardly aware of the primes that were presented for 20 ms and it is thus not possible to strategically influence the priming effects. This assumption is supported by the finding that primes affected performance largely independent of response times to conscious targets. Our participants also reported no application of reasonable strategies in the priming experiment. (Occasionally methods such as trying to avoid errors or concentrating on probabilities of targets were reported. Yet, this latter strategy is not helpful as primes and targets occurred equally frequent.) Moreover, we avoid contamination through any effects of expectations on prime processing (cf. Kunde et al., 2003) by using only primes that were also presented as clearly visible targets.

Finally, due to the correlational design of our study, the results have to be interpreted very cautiously. For example, it is conceivable that existing differences in cognitive abilities are responsible that people play action video games (cf. Boot et al., 2011; Kristjánsson, 2013). We thus take this study as a first step to demonstrate differences in stimulus-response translation processes for hardly visible stimuli. Of course, to establish unequivocal evidence for causal relation and to elucidate the exact kind of training required to faster process shortly presented stimuli, training studies are necessary.

To conclude, the results of our study are well in line with recent studies that demonstrated that action video game expertise is related to more efficient visual and cognitive processing. This expertise related processing advantage is especially interesting because the effects of expertise, i.e., improvement of executive functions as well as perceptual learning, generalize to new tasks and are not restricted the domain of the original expertise.

In addition, our results are interesting for research on masked priming because our results are well in line with other studies that observed an impact of expertise on prime processing. However, in all other studies expertise-related stimuli such as the own face (Pannese and Hirsch, 2010), the own name (Pfister et al., 2012), pictures of athletic jumps (Güldenpenning et al., 2011), chess configurations (Kiesel et al., 2009), and words in the mother tongue (Schoonbaert et al., 2009) were used to demonstrate expertise-related lager congruence effects. In the present study we used drawn pictures of animals as stimuli that can be assumed to be of equal familiarity for VGPs and NVGPs. Nonetheless VGPs produced larger congruence effects than NVGPs for primes with a very short duration (20 ms), whereas this group difference was eradicated when the prime duration was prolonged (to 60 ms). Thus, expertise related advantages seem restricted to shortly presented primes and they do not need to be restricted to expertise-related stimulus material.

To our knowledge, this is the first study to demonstrate a relation of video gaming and masked prime processing at a conceptual level based on a more efficient stimulus-response translation, extending findings that action video game training increased prime detection in a backward masking setting (Li et al., 2010). Bearing in mind all the connected caveats, it seems nevertheless appropriate to recommend that action video game experience should be considered in masked priming studies. Especially when between-group comparisons of priming effects are reported, action video game experience is an important factor to control for that might account for group differences particularly when investigating small sample sizes.

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An investigation of the validity of the virtual spatial navigation assessment

Matthew Ventura[1]*, Valerie Shute[1], Tim Wright[2] and Weinan Zhao[1]

[1] College of Education, Florida State University, Tallahassee, FL, USA
[2] Department of Psychology, Florida State University, Tallahassee, FL, USA

Edited by:
Bernhard Hommel, Leiden University, Netherlands

Reviewed by:
Mark Neider, University of Central Florida, USA
Hyunkyu Lee, Brain Plasticity Institute, USA

***Correspondence:**
Matthew Ventura, College of Education, Florida State University, 3205A Stone Building, 1114 West Call Street, Tallahassee, FL 32306-4453, USA
e-mail: mventura@fsu.edu

This correlational study investigated a new measure of environmental spatial ability (i.e., large scale spatial ability) called the virtual spatial navigation assessment (VSNA). In the VSNA, participants must find a set of gems in a virtual 3D environment using a first person avatar on a computer. The VSNA runs in a web browser and automatically collects the time taken to find each gem. The time taken to collect gems in the VSNA was significantly correlated to three other spatial ability measures, math standardized test scores, and choice to be in a STEM (science, technology, engineering, or math) career. These findings support the validity of the VSNA as a measure of environmental spatial ability. Finally, self-report video game experience was also significantly correlated to the VSNA suggesting that video game may improve environmental spatial ability. Recommendations are made for how the VSNA can be used to help guide individuals toward STEM career paths and identify weaknesses that might be addressed with large scale spatial navigation training.

Keywords: environmental spatial ability, vista spatial ability, figural spatial ability

INTRODUCTION

Spatial ability has been shown to play a significant role in achievement in science, technology, engineering, and mathematics (STEM) disciplines. For instance, Wai et al. (2009) showed that spatial ability was a significant predictor of STEM degree attainment, even after controlling for mathematical and verbal skills. Thus a thorough understanding of spatial ability and how it can be improved should be considered paramount in understanding how to engage students in STEM related fields.

One way spatial ability can be improved is through playing action video games (e.g., Dorval and Pepin, 1986; Subrahmanyam and Greenfield, 1994; De Lisi and Wolford, 2002; Green and Bavelier, 2006; Feng et al., 2007; Spence et al., 2009; Uttal et al., 2012). For example, Feng et al. (2007) found that playing an action video game improved performance on a mental rotation task. After only 10 h of training with an action video game, subjects showed gains in spatial ability via mental rotation tasks, with females performing equal to males after training. Control subjects who played a non-action game showed no improvement. Recently, Uttal et al. (2012) conducted a meta-analysis of 206 studies investigating the effect of training on spatial ability. Of these 206 studies, 24 used video games to improve spatial ability. The effect size for video game training was 54 (SE = 0.12). Findings like these have been explained due to the visual-spatial requirements of 3D action games which may enhance spatial abilities (e.g., Feng et al., 2007). However, others have found a lack of transfer effects between action video game playing and basic cognitive functions and skills (e.g., Boot et al., 2008) and have raised questions regarding the methodology of studies that observe transfer (Boot et al., 2013; Kristjánsson, 2013).

Of particular importance in understanding the malleability of spatial ability is the distinction between figural, vista, and environmental related spatial abilities (Montello, 1993; Montello and Golledge, 1999). Figural spatial ability is small in scale relative to the body and external to the individual. It can be apprehended from a single viewpoint in both flat pictorial and 3D space (e.g., small, manipulatable objects). It is most commonly associated with tests such as mental rotation and paper folding tasks. Vista spatial ability is the ability to imagine oneself in different locations within a small space without locomotion. Vista spatial ability is useful when trying to image how the arrangement of objects will look from various perspectives (Hegarty and Waller, 2004). Environmental spatial ability is large in scale relative to the body and is useful in navigating around large spaces such as buildings, neighborhoods, and cities, and typically requires locomotion (see Montello, 1993; for a discussion of other scales of space). Environmental spatial ability may require a person to mentally construct a cognitive map, or internal representation of the environment (Montello and Golledge, 1999).

Specific processes in environmental spatial ability may result from the accumulation of three main types of knowledge of the environment: landmark, route, and configurational knowledge (Tolman, 1948; Siegel and White, 1975). First, landmark knowledge is acquired of perceptual objects through visual encoding. These perceived landmarks are then assimilated and are connected sequentially along a traversed path into route knowledge. Configurational knowledge is formed through the amassing of route knowledge, as a map-like representation of the environment is formed that allows for navigational inferences (Siegel and White, 1975). For example, new routes and distance and direction judgments can be formed as a result of a navigator's configurational knowledge. The details of these environmental representations depend on a number of factors including the perception of environmental information, the speed in which the information is encoded, and how the information is maintained (Ittelson, 1973).

Existing measures of environmental spatial ability include map retracing, distance estimation, direction estimation (Hegarty et al., 2006), and self-report measures (Hegarty et al., 2002). Map retracing and distance and direction estimation (Hegarty et al., 2006) require a participant first to navigate through an environment (real world, 3D virtual environment, or first-person video). Afterwards, a person can be asked to (a) judge the distance among various features in the environment, (b) provide direction estimates among features in the environment, or (c) draw a 2D map of the environment. While these measures may seem distinct, factor analysis has revealed that these three measures were highly correlated and loaded on one factor, suggesting they measure a common ability (Hegarty et al., 2006). Additionally, factor analysis has shown measures based on virtual and video environments load on one factor (video factor) while measures based on real environments load on a second factor (real environment factor). The correlation between the two factors was high ($r = 0.61$) suggesting that the cognitive processes being used in virtual simulations are similar to the ones being used in real environments (Hegarty et al., 2006).

THE PRESENT STUDY

Hegarty et al. (2006) proposed three main sources of variance in environmental spatial ability: (1) ability to encode spatial information from sensory experience, (2) ability to maintain a high quality internal representation of that information in memory, and (3) ability to perform spatial transformations in order to make inferences from this spatial information. In line with this theory, we developed the Virtual Spatial Navigation Assessment (VSNA). Advances in game development software now enable researchers with little programing experience to create virtual environments. These virtual environments are increasing being used to assess large scale spatial ability. For example, Herting and Nagel (2012) created a virtual water maze task to assess visuospatial memory. The VSNA requires a participant to explore a virtual 3D environment using a first person avatar on a computer. One significant difference between the VSNA and traditional measures of environmental spatial ability (e.g., map retracing) is that the VSNA collects data while a person is *in* the environment itself as opposed to collection of data *post hoc outside* of the environment. Measures (e.g., direction and distance estimation) based on one's memory of an environment may be a source of construct irrelevant variance in the assessment of environmental spatial ability (Hegarty et al., 2006). Additionally, measurement outside of navigation in the environment requires individuals to make inferences that were not made within the environment (Montello et al., 2004). For example, the ability to point accurately to locations or estimate distances requires one to remember spatial configurations encoded in an environment. Assessing navigational performance in the task itself removes the additional burden of memory requirements that may contaminate the assessment of environmental spatial ability.

In each VSNA environment, a person must collect a set of brightly colored gems which are scattered throughout the environment. Participants need to complete the task twice for each environment. The first collection of gems is the training phase, which is intended to familiarize the person with the environment. The second collection of gems is the testing phase, which requires the person to obtain all the gems again as fast as possible. While no questions are explicitly asked about distance or direction between objects, the time to complete the VSNA require distance and direction estimation.

In this correlational study, we address two research questions centered around the validity of the VSNA as a measure of environmental spatial ability. The first question refers to how the VSNA relates to other measures of spatial ability. We compare the VSNA to a measure of figural spatial ability (mental rotation test, MRT; adapted from Vandenberg and Kuse, 1978), vista spatial ability (spatial orientation test, SOT; Hegarty and Waller, 2004) and a self-report measure of environmental spatial ability (SBSOD; Hegarty et al., 2002). In the MRT, participants view a 3D target figure and four test figures. The task is to determine which two test figures are correct rotations of the target figure as quickly and accurately as possible. The SOT requires the participant to make direction estimations from different perspectives relative to a 2D picture. For example, the person may be asked to give the direction of a car from the perspective as if the person is standing at a tree facing a traffic light. The degree to which a person can give the correct direction of objects from various perspectives is proposed to assess vista spatial ability. The SBSOD scale measures a person's self-report belief about various navigation abilities in the real world (e.g., I don't have a very good "mental map" of my environment, I enjoy reading maps). The SBSOD has been found to correlate (e.g., $r = 0.44$) with tests of spatial knowledge that involve orienting oneself within real-life environments (Hegarty et al., 2002). We also compare the VSNA to verbal and math scholastic aptitude test (SAT) scores since spatial ability has been shown to correlate to math achievement but not verbal achievement (e.g., Hegarty et al., 2006). Thus we expect to show divergent validity of the VSNA by showing it does not relate to verbal SAT scores.

Finally, regarding criterion related validity, we will investigate the relationship between the VSNA scores and choosing a STEM career path. Addressing this question expands on the work by Wai et al. (2009) showing that spatial ability predicts STEM degree attainment.

We make the following hypotheses regarding question one:

(1) *The VSNA should relate more to the SBSOD scale than the SOT and the MRT.* While the SOT and the MRT have been shown to relate to the SBSOD scale (e.g., Kozhevnikov and Hegarty, 2001), the VSNA should more accurately assess environmental spatial ability than the MRT or the SOT.

(2) *The VSNA will relate higher to math SAT scores than verbal SAT scores.* Spatial skills correlate to math achievement (e.g., Hegarty et al., 2006). Therefore the VSNA should relate more to math SAT scores than to verbal SAT scores.

(3) *The VSNA, SOT, and MRT will relate to STEM career path and achievement after controlling for gender, verbal and math ability (via SAT scores).* Spatial ability has been found to predict STEM degree attainment (Wai et al., 2009). Thus we expect to see a similar result for the VSNA as well as for the MRT and SOT.

The second question refers to the extent to which video game use influences environmental spatial ability (as measured by the VSNA). The question further addresses the malleability argument that video game use can impact spatial ability and specifically, environmental spatial ability. While this study focuses on correlational relationships, it is informative since it may show that even casual video game use can have a potential effect on environmental as well as vista and figural spatial ability.

Despite the large body of work investigating the role of video games on spatial ability, we are aware of only three studies that have specifically investigated the relationship between video game use and environmental spatial ability (Rehfeld et al., 2005; Schuster et al., 2008; Richardson et al., 2012). Schuster et al. (2008) found that video game experience correlated with college students' ability to plan routes for unmanned vehicles in a 3D virtual simulation.

We make the following hypothesis regarding question two:

(4) *Video game use will relate to performance on all measures of spatial ability (figural, vista, environmental).* Higher video game use will be associated with in better spatial abilities compared to less video game use.

MATERIALS AND METHODS

PARTICIPANTS

323 undergraduate students (129 males, 194 females) enrolled in introductory psychology and education courses at a large south-eastern state university volunteered to participate in the study for course credit.

MEASURES

Virtual spatial navigation assessment

The VSNA was created in Unity, a free video game development software tool. In the VSNA, a participant explores a virtual 3D environment using a first person avatar on a computer. The avatar is controlled by a single key on the keyboard and the mouse. Pressing the key moves the avatar forward and the mouse controls the direction of the avatar. Participants are instructed that the goal is to collect three gems in an environment and return to the starting position. Participants first complete a short familiarization task that requires them to collect three gems in a small room. The VSNA consists of: (a) a small indoor environment consisting of halls (easy indoor), (b) a larger indoor environment (hard indoor), (c) a small outdoor environment (easy outdoor), and (d) a larger outdoor environment (hard outdoor). In each environment three gems are strategically located in the four environments so that an optimal path can be used to collect all the gems. In each environment the participant must collect the gems twice. The first collection is the training phase and the second collection is the testing phase. **Figure 1** displays a screenshot of the easy indoor environments.

The VSNA records the time taken to complete the training and testing phases per environment (i.e., time taken to collect the gems). The training phase is intended to measure one's ability to *search* and *encode* information in the environment, while the testing phase is intended to measure one's ability to *retrieve* and *apply* the encoded information. There is a 5 min time limit (per phase) in the easy indoor environment. The hard indoor and both outdoor environments each have a 10 min time limit per phase. If a person times out in a training phase, the participant skips the testing phase and goes to the next environment. The automated skip was done to keep the testing phase a recall task not a searching task. Lower score indicate higher environmental spatial ability. For ease of reading we reverse coded the VSNA scores so higher scores mean better performance.

The Santa Barbara sense of direction scale (Hegarty et al., 2002)

This test consists of 15 self-report items pertaining to environmental spatial ability (e.g., I am good at reading maps) that are rated on a five point likert scale. Higher score indicate higher environmental spatial ability.

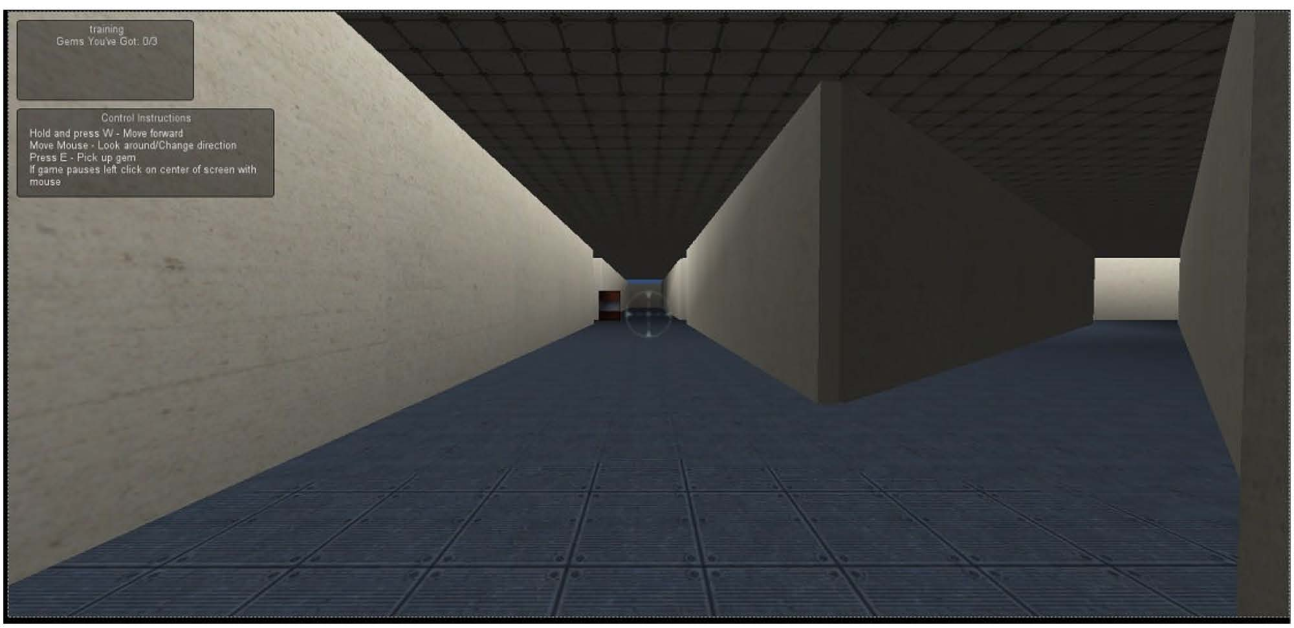

FIGURE 1 | Indoor environment in the VSNA.

Spatial orientation test (Hegarty and Waller, 2004)
This test consists of 12 questions requiring the participant to estimate locations of objects from different perspectives in one picture. In each item the participant is told to imagine looking at one object from a particular location in the picture and then point to a second location. An example item is as follows: *Imagine you are looking at the tree from the position of the cat, now point to the car.* The participant must draw the direction in a circle relative to an arrow in the circle that is always pointing to the 12 o'clock position. Each response is scored as a difference between the participant's angle and the correct angle (ranges from 0° to 180°). Larger differences between a participant's drawn angle and the correct angle indicate lower vista spatial ability. For ease of reading we reverse coded the SOT scores so higher difference scores mean greater vista spatial ability.

Mental rotation test (adapted from Vandenberg and Kuse, 1978)
In this test, participants view a three-dimensional target figure and four test figures. Their task is to determine which of the test figures are rotations of the target figure. The MRT has two correct answers for each of the 10 items. The total score is based on the total number of items where both correct objects are found. Higher score indicate higher figural spatial ability.

Video game use and VSNA-video game similarity
Participants answered one question about general video game use: How often do you play video games? 1 = not at all, 2 = about once a month, 3 = a few times a month, 4 = a few times a week, 5 = everyday, but for less than 1 h, 6 = every day for 1–3 h, 7 = every day for more than 3 h (Jackson et al., 2012). Additionally, participants were asked a question about the similarity between the VSNA and the video games they play: How similar was the navigation task to a video game you play (not at all, somewhat similar, similar, very similar, completely identical)?

PROCEDURE
The study was conducted online in a web browser without supervision. Participants first reported their GPA, SAT scores, academic major, and completed the SBSOD scale. Then they completed the VSNA, the SOT, and the MRT. Finally, they completed some questions about video game use and usability of the VSNA. No tests were counterbalanced since we wanted to see how participants performed on the VSNA without the influence of fatigue from other spatial ability tests.

RESULTS
Table 1 displays the means and standard deviations of the SBSOD, times across the eight phases of the VSNA, the SOT, and MRT (listed in the order they were presented). Due to the difficult nature of the VSNA hard environments, and the study being unproctored, not all participants completed all tests. In some cases a participant timed-out of a training environment which results in the participant skipping its corresponding testing phase (as described in the VSNA measures section). In order to maximize power we still included participants in analysis who completed the training phase for each environment.

Reliability was good for the SBSOD (α = 0.89), MRT (α = 0.76), and SOT (α = 0.87). Based on the high correlation between VSNA testing and training times ($r = 0.61$), we took the average score across training and testing. Easy and hard times were also highly related ($r = 0.56$) so we took the average score across easy and hard times to yield an indoor and outdoor VSNA score. While the correlation between indoor and outdoor environments was also high ($r = 0.53$), we report results for them separately since the sample size differs between the indoor and outdoor environments. Additionally, combining the time data across the indoor and outdoor environments could give an added advantage to participants who did not complete the outdoor task (i.e., give lower means to a person who did not complete the outdoor versus a person who did complete the outdoor).

We recoded students' self-reported major into two categories: STEM related and non-STEM related. Examples of STEM related majors include: biology, engineering, computer science, and chemistry. Examples of non-STEM related majors include: English, education, business, communication, and history. Non-majors ($n = 36$) were excluded from the STEM major variable. **Table 2** displays the correlations between STEM career path (0 = non-STEM, 1 = STEM), gender (males = 0, females = 1), SAT math scores, MRT, SOT, and the indoor and outdoor VSNA scores (time data, where less time is better). GPA was omitted from **Table 2** since it did not relate to any spatial ability measures.

Regarding hypothesis one (i.e., VSNA should relate more to the SBSOD scale than the SOT and the MRT) both the indoor and outdoor VSNA scores significantly relate to the SBSOD, MRT, and the SOT. However, only the indoor VSNA scores appear to support hypothesis one: indoor VSNA scores are more highly correlated to the SBSOD ($r = 0.37$) relative to the MRT ($r = 0.24$) and the SOT ($r = 0.18$). The Steiger test (1980) was conducted to test if the VSNA indoor scores are significantly higher to the SBSOD versus the MRT and SOT (using a one-tailed test). The difference between the SBSOD ($r = 0.37$) and SOT ($r = 0.18$) is significant ($z = 2.51$, $p < 0.05$). The difference between SBSOD ($r = 0.37$)

Table 1 | Means and SDs of the SBSOD, VSNA phases, SOT, and MRT.

	N	Mean	SD
SBSOD	323	3.16	0.79
Easy indoor train*	323	132.69	55.59
Easy indoor test*	310	102.64	41.89
Hard indoor train*	322	206.64	115.66
Hard indoor test*	308	161.36	82.87
Easy outdoor train*	300	279.49	178.35
Easy outdoor test*	252	93.70	32.47
Hard outdoor train*	282	350.94	177.97
Hard outdoor test*	212	118.51	93.54
SOT	273	38.11	27.30
MRT	271	4.77	2.73

**Measured in seconds*

Table 2 | Correlations (*r*) among gender, STEM major, SAT, spatial measures, and video game experience.

	Gender	STEM	SATm	SATv	SBSOD	MRT	SOT	Indoor	Outdoor
STEM	−0.12*								
SATm	−0.17**	0.16*							
SATv	0.05	0.10	0.62**						
SBSOD	−0.33**	0.14*	0.17**	−0.01					
MRT	−0.23**	0.10	0.24**	0.14	0.17**				
SOT	−0.24**	0.08	0.24**	0.01	0.17**	0.45**			
Indoor	−0.44**	0.22**	0.16**	0.02	0.37**	0.24**	0.18**		
Outdoor	−0.37**	0.14*	0.15*	−0.04	0.19**	0.26**	0.18**	0.53**	
VG use	−0.62**	0.03	0.19**	−0.00	0.18**	0.17**	0.29**	0.37**	0.33**

$^*p < 0.05$; $^{**}p < 0.01$; SATm, SAT math; VG use, video game experience

and MRT ($r = 0.24$) is significant ($z = 1.74$, $p < 0.05$). The VSNA indoor and outdoor times both account for unique variance in the SBSOD after controlling for MRT and SOT scores ($pr = 0.36$, $p < 0.001$; $pr = 0.18$, $p < 0.001$).

Regarding hypothesis two (i.e., VSNA will relate higher to math SAT scores than verbal SAT scores), all spatial ability measures related to SAT math scores. No spatial ability measures related to GPA or verbal SAT.

Regarding hypothesis three (i.e., VSNA, SOT, and MRT will relate to STEM major and achievement after controlling for gender, verbal and math ability), gender, SAT math scores, SBSOD, and both indoor and outdoor VSNA scores significantly relate to STEM majors. A hierarchical regression was run to predict STEM major. Predictors were entered in the following order: gender, math SAT scores, SBSOD scores, and finally VSNA indoor scores. Only VSNA indoor was a significant predictor of STEM interest after controlling for all other predictors (std $\beta = 0.24$, $p < 0.01$; R^2 change $= 0.04$, $F(1,219) = 10.13$, $p < 0.05$). The same analysis was conducted entering VSNA outdoor scores last (gender, math SAT scores, SBSOD scores, VSNA outdoor scores) but the R^2 change was not significant. GPA did not relate to any spatial ability measures for the STEM majors ($n = 119$).

Regarding hypothesis four (i.e., video game use will relate to performance on all measures of spatial ability), video game use significantly relates to the four spatial ability measures. However, after controlling for gender and video game similarity (for VSNA only), video game use only relates to SOT ($pr = 0.21$, $p < 0.01$) and VSNA indoor scores and ($pr = 0.15$, $p < 0.05$).

DISCUSSION

Hypothesis one (i.e., VSNA should relate more to the SBSOD scale than the SOT and the MRT) was partially confirmed. We found that indoor VSNA scores had moderately highly correlations to SBSOD scores than to MRT and SOT scores. Both the VSNA indoor and outdoor scores accounted for unique variance in the SBSOD after controlling for MRT and SOT scores. These findings partially supports the construct validity of the VSNA as a measure of environmental spatial ability. We did not find evidence of construct validity for the outdoor VSNA scores (i.e., outdoor scores were more highly correlated to the MRT than to SBSOD). This finding may be due to the outdoor environments always being after the indoor environments which could cause fatigue effects on the outdoor environments. Finally, method effects (i.e., different task requirements) and well known psychometric issues related to self-report measures (e.g., social desirability) could be a reason why the correlation was not higher between the SBSOD and the VSNA.

Hypothesis two (i.e., VSNA will relate higher to math SAT scores than verbal SAT scores) was confirmed. We found that the VSNA, MRT, and SOT scores were all significantly related to math SAT scores and not verbal SAT scores. This is consistent with other research (e.g., Hegarty et al., 2006) that has shown a relation between mathematical and spatial abilities. This finding further supports the construct validity of the VSNA as a measure of spatial ability.

Hypothesis three (i.e., VSNA, SOT, and MRT will relate to STEM major and achievement after controlling for verbal and math ability) was partially supported. The VSNA indoor scores significantly correlated to being a STEM career path after controlling for gender, math SAT scores, and SBSOD scores (verbal SAT scores were not related to STEM career path). Thus we established criterion related validity of the VSNA. This finding extends the work by Wai et al. (2009) who showed that spatial ability was a significant predictor of STEM career path, even after controlling for math and verbal skills. However, we did not find the VSNA outdoor scores predicted STEM career path. This may be due to the lower number of participants who completed the outdoor VSNA. We also did not find that figural or vista spatial ability related to STEM career path. Thus environmental spatial ability may be a unique spatial ability separate from figural and vista ability that affects STEM career path. Additionally, no spatial ability measures related to GPA. Spatial ability may not give students an added academic advantage in STEM courses. However, the GPA variable was based on a variety of courses outside of STEM subjects. Future work research should investigate how environmental spatial ability relates to grades and performance in specific STEM courses.

Hypothesis four (i.e., video game use will relate to performance on all measures of spatial ability) was partially supported. Video game use was significantly correlated with the SOT and the indoor

VSNA after controlling for gender. Importantly, the VSNA does not just assess one's ability to play video games–video game use significantly relates to the VSNA after controlling for VSNA-video game similarity. The relation between video game use and the VSNA might be underestimated considering we only asked a broad question about video game use. Future work should consider using more detailed questions regarding video game use to further identify if specific video game use (e.g., 3D video games) relates more strongly to the VSNA.

A case can also be made that the VSNA-video game similarity question might not be sufficient to measure how similar the VSNA is to video games. For example, a particular video game player might see lots of differences between the VSNA and video games in general (e.g., lack of controls, gameplay options), while another video game player might see lots of similarities (e.g., first-person exploration in a 3D world). Future work should consider more detailed questions regarding the similarity between the VSNA and video games. However, the VSNA requires little motor control beyond skills learned by normal computer use (single button press with one hand and mouse control with the other hand). In this regard, the VSNA can be seen as a transfer task of environmental spatial ability independent from other video game play heuristics (e.g., effective use of controllers). These results are consistent with experimental evidence that video game use can improve spatial ability (e.g., Uttal et al., 2012). Thus exposure to video games may affect one's ability to encode, store, retrieve, and apply environmental spatial information. Contrary to this theory, Richardson et al. (2012) found video game use was related to a pointing task after navigating through a virtual environment but not a pointing task after navigating through a real environment. However, Richardson et al. (2012) states the limitation of using pointing tasks to assess environmental spatial ability in that pointing tasks do not require actual navigation to targets. Thus it is possible that video game use does improve actual navigation performance *in* real environments (i.e., environmental spatial ability) but not to pointing performance *after* navigating through real environments.

Finally, the positive relation between video game use and environmental spatial ability also shows what lifestyle factors might indirectly affect interest in STEM (i.e., both the VSNA and SAT math scores relate to STEM major). While we did not find that video game use directly relates to STEM interest, video game use may indirectly affect interest in STEM by positively affecting environmental spatial ability and math ability.

Consistent with other work on spatial abilities (e.g., Spence et al., 2009), we found robust gender differences among the spatial ability measures. Females scored significantly worse on the SBSOD, SOT, MRT, and the VSNA (indoor and outdoor) compared to males. Follow up analysis revealed that after controlling for video game experience this gender effect was only eliminated for performance on the SOT. Future research should investigate how training can eliminate the gender gap in environmental spatial ability.

Looking forward, the VSNA could potentially be used for large scale assessment since it is scalable (i.e., run in a web browser) and quick to administer (as short as 10 min). This is important due to the growing number of studies suggesting the need to assess spatial ability in our education system (e.g., Wai et al., 2009; Uttal et al., 2012). There are many STEM related careers (e.g., engineering, medicine) and non-STEM careers (e.g., transportation, military, tourism) that require high levels of environmental spatial ability. These fields could benefit from having an assessment to be used for selection as well as intervention work. Additionally, the VSNA is a performance-based assessment not subject to social desirability effects. This gives it an advantage over traditional environmental spatial ability measures (e.g., SBSOD). Finally, assessment studies of environmental spatial ability using the VSNA can be covert since the gem finding activity does not explicitly cue participants about the purpose of the VSNA. This can be useful in situations where test anxiety could potentially affect the validity of the test.

This study cannot rule out the selection hypothesis that people with high environmental spatial ability may enjoy playing video games more than people with low environmental spatial ability. Future work should focus on experimental research investigating how using 3D simulations or video games can improve performance in the environmental spatial ability. Another limitation in this study was students completed all tests online without proctor supervisions. Results might have been more robust if participants were directed to stay on task throughout the session.

Another limitation of this study was we were not able to investigate the latent factorial structure of the VSNA. Given the limited time we had to run reach participant we could only investigate two levels of difficulty (easy vs. hard) in two distinct environments (indoor vs. outdoor). Future work should investigate creating "forms" of the VSNA that contain multiple isomorphic environments of similar difficulty (e.g., five outdoor nature environments). These forms can be compared to other forms that contain other features of the VSNA (e.g., five outdoor nature environments, five indoor environments, five outdoor urban environments). This design allows for confirmatory factor analysis and structural equation modeling. Additionally, counterbalancing and time spacing between forms should be implemented to control for any fatigue effects that may be occurring as a function of extended VSNA testing.

Finally, virtual environments do not provide any information to body-based senses (i.e., vestibular, proprioceptive) and thus may afford less detailed representations than real world environments (Waller et al., 2004; Richardson et al., 2012). However, Wan et al. (2009) provide evidence that participants still spatially update (e.g., remember locations of objects and landmarks) information in virtual environments much like in real environments. Future work should investigate how performance in the VSNA relates to real world navigation tasks.

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A new adaptive videogame for training attention and executive functions: design principles and initial validation

Veronica Montani[1], Michele De Filippo De Grazia[1] and Marco Zorzi[1,2,3] *

[1] Department of General Psychology, University of Padova, Padova, Italy
[2] Center for Cognitive Neuroscience, University of Padova, Padova, Italy
[3] IRCCS San Camillo Neurorehabilitation Hospital, Venice Lido, Italy

Edited by:
Walter R. Boot, Florida State University, USA

Reviewed by:
Evan Palmer, Wichita State University, USA
Joseph Chisholm, University of British Columbia, Canada

***Correspondence:**
Marco Zorzi, Department of General Psychology, University of Padova, Via Venezia 8, 35131 Padova, Italy
e-mail: marco.zorzi@unipd.it

A growing body of evidence suggests that action videogames could enhance a variety of cognitive skills and more specifically attention skills. The aim of this study was to develop a novel adaptive videogame to support the rehabilitation of the most common consequences of traumatic brain injury (TBI), that is the impairment of attention and executive functions. TBI patients can be affected by psychomotor slowness and by difficulties in dealing with distraction, maintain a cognitive set for a long time, processing different simultaneously presented stimuli, and planning purposeful behavior. Accordingly, we designed a videogame that was specifically conceived to activate those functions. Playing involves visuospatial planning and selective attention, active maintenance of the cognitive set representing the goal, and error monitoring. Moreover, different game trials require to alternate between two tasks (i.e., task switching) or to perform the two tasks simultaneously (i.e., divided attention/dual-tasking). The videogame is controlled by a multidimensional adaptive algorithm that calibrates task difficulty on-line based on a model of user performance that is updated on a trial-by-trial basis. We report simulations of user performance designed to test the adaptive game as well as a validation study with healthy participants engaged in a training protocol. The results confirmed the involvement of the cognitive abilities that the game is supposed to enhance and suggested that training improved attentional control during play.

Keywords: videogames, attention, attention deficits, executive functions, cognitive enhancement

INTRODUCTION

Cognitive enhancement through videogame playing is a hot topic in cognitive science. Most of the literature on the effect of videogame play is centred on "action" videogames, which are remarkably challenging in terms of visual and attention demands. Indeed, many investigations have focused on the modulation of visual skills and have revealed that videogame players (VGPs) outperform non-videogame players (NVGPs) on a variety of visuo-attentional tasks (Green and Bavelier, 2003, 2006a; for reviews see Spence and Feng, 2010; Boot et al., 2011; Hubert-Wallander et al., 2011a; Latham et al., 2013). For example, VGPs showed to be better in localizing the target in many different visual search tasks (e.g., Castel et al., 2005; West et al., 2008; Hubert-Wallander et al., 2011b), they were better in suppressing irrelevant information (e.g., Mishra et al., 2011; Wu et al., 2012) and in general they showed to have more available attentional resources (e.g., Green and Bavelier, 2003, 2006b; Dye et al., 2009a).

Nevertheless, there is also evidence that videogame playing enhances a variety of other cognitive skills (Green and Bavelier, 2003; Dye et al., 2009a; Anguera et al., 2013) and that cognitive processes different from visuo-spatial ability might benefit from playing more strategic games (e.g., Basak et al., 2008). For example, Colzato et al. (2010) reported that VGPs suffer smaller task switching cost than NVGPs, suggesting that they have better cognitive control (see also Cain et al., 2012; Strobach et al., 2012). Karle et al. (2010) suggested that the smaller switch cost is the consequence of more efficient task reconfiguration due to a superior ability to control attentional resources (also see Meiran et al., 2000).

Action videogame playing also seems adequate for training executive control skills that are crucial for the coordination of different tasks in complex situations. For example, Strobach et al. (2012) showed that VGPs outperformed NVGPs in a dual task condition (but see Donohue et al., 2012, for contrasting results) and, even more convincingly, that non-gamers trained with an action videogame suffered less dual-task cost after training in comparison to non-gamers trained with a puzzle game. It is worth nothing that the latter result was confirmed in the study of Chiappe et al. (2013) using a more complex task that was shown to predict performance in real-life settings.

Selective and controlled aspects of attention appear to benefit more of videogame playing relative to transient, automatic aspects (Chisholm et al., 2010). Clark et al. (2011) suggested that better performance of VGPs is explained by an improvement in higher-level abilities such as attentional control, in addition to better bottom-up visual processing. Accordingly, a neuroimaging study confirmed lesser recruitment of the network associated with the control of top-down attention in VGPs, despite their superior performance in a visual search task relative to NVGPs (Bavelier et al., 2011). This result was interpreted as evidence that VGPs are more efficient in the allocation of attention.

Studies comparing VGPs and NVGPs on many different tasks invariably show that VGPs are faster across a wide range of tasks and they do not show speed-accuracy trade-offs (Dye et al., 2009b; but see Nelson and Strachan, 2009). Moreover, videogame training was shown to be a helpful training regimen for providing a marked increase in speed of information processing in elderly (Drew and Waters, 1986; Clark et al., 1987; Anguera et al., 2013).

It is worth noting that most of these studies do not establish a causal link between videogame play and cognitive enhancement because they do not control for pre-existing differences between VGPs and NVGPs (Kristjánsson, 2013). However, some studies have compared the performance of two groups of non-players before and after a different type of training. For example, an action videogame was compared to a game that made heavy demands on visuomotor coordination but, unlike action video games, did not require the participant to process multiple objects at once at a fast pace. Action-trained participants showed greater training-induced improvements than participants trained on a control game, thereby showing that the benefits of play are trainable to a non-game player population (Green and Bavelier, 2003, 2006a,b; Feng et al., 2007; Strobach et al., 2012). There is also some evidence that learning/enhancement is not specific to the trained task but there is some degree of generalization to untrained aspects (Green and Bavelier, 2006b; Mathewson et al., 2012) and some transfer to a completely different and more "ecological" domain (Gopher et al., 1994; Rosenberg et al., 2005; see Boot et al., 2011, for a critical discussion).

The aim of the present study was to develop a novel adaptive videogame for training attention and executive functions, with particular emphasis on design features that make the game suitable for brain-damaged patients as a tool to support cognitive rehabilitation. Despite some contrasting findings (Boot et al., 2008; Murphy and Spencer, 2009; Irons et al., 2011), videogames seem to enhance a variety of cognitive skills and they appear to be a promising tool to train cognitive abilities (e.g., Achtman et al., 2008; Basak et al., 2008; Anguera et al., 2013; Franceschini et al., 2013). Moreover, neuroplasticity in the adult brain could be guided with specific training to yield better recovery (e.g., Krainik et al., 2004; Gehring et al., 2008). The rationale for designing a new videogame, despite the great variety of commercial videogames that are currently available, was twofold. First, designing a novel videogame allows the inclusion of specific features in a theory-driven manner as well as to implement a fine control of the difficulty dimensions, including trial-by-trial adaptation to user performance. Second, the graphical user interface of commercial videogames might be too demanding for patients with cognitive deficits in terms of speed, visual complexity, or motor requirements.

Before presenting the videogame, we start with a discussion of the theoretical principles that guided our design choices in terms of structure and features of the game. We then report a modeling study in which we simulated users with different abilities to assess the efficiency of the adaptive algorithm in estimating the "performance space" of the user, which is crucial for the online adjustment of game difficulty. Finally, we validated the game with unimpaired participants (healthy young adults) to ensure that the game involves the activation of the desired cognitive functions as well as to assess the effect of a short training period (<10 h over 2 weeks). Note that the evaluation of videogame training for the rehabilitation of brain damaged patients is left to a future clinical trial.

GAME DESIGN PRINCIPLES

Dysexecutive syndrome and attention deficits are common consequences of traumatic brain injury (hereafter TBI; e.g., Levine et al., 1998; Stuss and Levine, 2002). Indeed, the acceleration-deceleration mechanism of traumatic injury implies that the frontal and temporal lobes are the most frequent damaged sites, with subsequent impairment of a wide range of high-level functions (Povlishock and Katz, 2005). The resulting impairments in attention and executive functions can profoundly affect an individual's everyday cognition, with difficulties in the management of very simple daily activities (Sohlberg and Mateer, 2001). Attention deficits have been found to be significantly correlated with the inability to return to work (Van Zomeren and Brouwer, 1985; Vikki et al., 1994). Because of the related disabilities and the increasing number of people suffering from this pathology, the development of effective rehabilitation strategies should be considered of high priority. Furthermore, the recent finding of Kamke et al. (2012) that increased visual attention demands entail a decrease in motor cortex plasticity strongly supports the notion that attention can be a potent modulator of cortical plasticity.

The design of the game was guided by principles relevant for the rehabilitation of cognitive deficits in TBI patients. The first principle was to enhance mental flexibility, which is the ability to respond to environmental changes in an efficient way. Mental flexibility implies efficient deployment of attentional resources accordingly with the context, as to select and maintain the cognitive set that is appropriate for the current goal. In order to increase mental flexibility, training should engage patients in switching between different cognitive sets. The alternation of different tasks requires reconfiguration of the new task and inhibition of the current active set, that is the set of the previous task (Monsell, 2003). Switching can be predictable or unpredictable (e.g., Andreadis and Quinlan, 2010). If the tasks alternate in a predictable way, participants can take benefit of the information about the switch and consequently prepare the switch endogenously. If the tasks alternate in a random way (i.e., unpredictable switch), switching task requires a faster reconfiguration of the mental set that is exogenously triggered by the task itself. Overall, unpredictable switching is considered more demanding than predictable switching but since TBI patients seem to have problems in the endogenous engagement of attention (Stablum et al., 1994) as well as slow information-processing speed (e.g., Mathias and Wheaton, 2007), they can benefit from training with both types of switching. Therefore, training should initially involve predictable switching and then progress to unpredictable switching.

Patients have also problems with managing two simultaneous tasks (Sohlberg and Mateer, 2001). The multitasking deficit can be ascribed to their slower processing speed (Dell'Acqua et al., 2006; Foley et al., 2010) or to a specific impairment in the ability to divide attention (Serino et al., 2006). There is evidence that dual task training improves the ability to divide attention by speeding up information processing through the bottleneck in the prefrontal cortex (Dux et al., 2009). Finally, increasing attentional load induced by multitasking has been shown to hinder visuo-spatial monitoring in patients with right hemisphere stroke (Bonato et al., 2010, 2012, 2013). Regardless of the specific mechanism underlying the deficit, extensive training with dual tasking can greatly reduce multitasking cost (Van Selst et al., 1999; Schumacher et al., 2001; Tombu and Jolicoeur, 2004). Therefore, a second important principle that should guide the design of game training is to improve the ability to achieve different goals at the same time. Dual-tasking requires to maintain the cognitive sets of both the tasks, dividing attentional resources between the two goals.

Including both tasks switching and dual-tasking within the training may be considered as a reflection of the complexity of daily living. In a more ecological environment, the individual has often to manage with situations that require to quickly change the goals or to pursue two goals simultaneously. Flexible or integrated training regimens, requiring constant switching of processing and continuous adjustments to new task demands have also been claimed to lead to greater transfer (Bherer et al., 2005).

The third principle that should guide the design of a game for cognitive training is to stimulate planning ability. Indeed, disorganized behavior of TBI patients is another aspect of their poor ability to control cognitive resources. They are not able to maintain the intentions in goal directed behavior, likely because the sustained attention system is compromised. This results in a high level of distractibility and a cue-dependent behavior (Levine et al., 2011). Flexibility in planning and strategy selection should be promoted by trial-by-trial changes of the game playground, thereby requiring the gamer to manage a novel situation every time. This implies that achieving the goal would require to choose the adequate strategy, with the interruption of automatic responses and monitoring of the performance, accordingly with the task. Consequently, the gamer would need to plan the correct sequence of actions to achieve the goal and to actively maintain this set of actions.

Patients' performance tends to be more variable and less consistent over time in comparison to healthy controls (Stuss et al., 1989, 1994). A critical challenge is to organize the progression of practice in a way that promotes performance improvement while finding a balance between patient variability and the choice of optimal task difficulty. Moreover, TBI patients are often unaware of their impairments (Prigatano and Schacter, 1991) and their anosognosia is a further challenge because rehabilitation can be seriously hindered by the lack of patient cooperation. Anosognosia predicts recovery from stroke (Gialanella and Mattioli, 1992) and experience-dependent plastic reorganization requires attention to be paid to the activity in question (Recanzone et al., 1993). Therefore, an important principle is to maintain attention and motivation providing sufficient positive reinforcement. Videogames are a useful tool because they are more entertaining than other training programs but in order to maximize the benefit they should be equipped with an adaptive algorithm. Motivation for playing can be maintained by programming the algorithm to adapt the difficulty of the game to a level that is challenging but feasible, for example by keeping the probability of success around 0.75. The ability to complete the task gives a "reward" to the gamer that may enhance his/her motivation. Moreover, the adaptive difficulty is an important aspect in enhancing training effects (Holmes et al., 2009; Brehmer et al., 2012).

Finally, every task should be completed in a pre-determined amount of time, accordingly with the difficulty of the task. The time pressure acts to encourage speeding up of processing, as consistently shown in the literature on videogame playing (Dye et al., 2009b; Hubert-Wallander et al., 2011a).

THE GAME: "LABYRINTH"

OVERALL GAME DESIGN

A little man moves along a maze to reach a goal. The game character is controlled by the gamer through a joystick. The walls that form the maze are variable: both their quantity and their location change at every trial accordingly with the task difficulty. The only constraint in the random distribution of the walls is that the software avoids the appearance of closed areas because this may prevent goal achievement.

The maze difficulty changes accordingly with the type of task. Indeed, the game includes two different tasks, the "Diamond Task" (hereafter DT) and the "Snake Task" (hereafter ST). Overall, every task has eight difficulty levels, across a continuum ranging from the less demanding (level 1) to the more demanding (level 8). In the DT (see **Figure 1**), the easiest maze is the one with as few walls as possible and the number of walls increases in conjunction with the improvement of performance. Conversely, in the ST (see **Figure 2**), the easiest maze is the one with as many walls as possible and accordingly, the number of walls decreases with the improvement of performance.

The goal of the game character depends on the nature of the current task. In the DT, the man has to collect the diamonds that are randomly distributed across the play area. The DT resembles the open-ended version of the Travelling Salesman Problem (TSP), a task that strongly involves planning and is also representative of

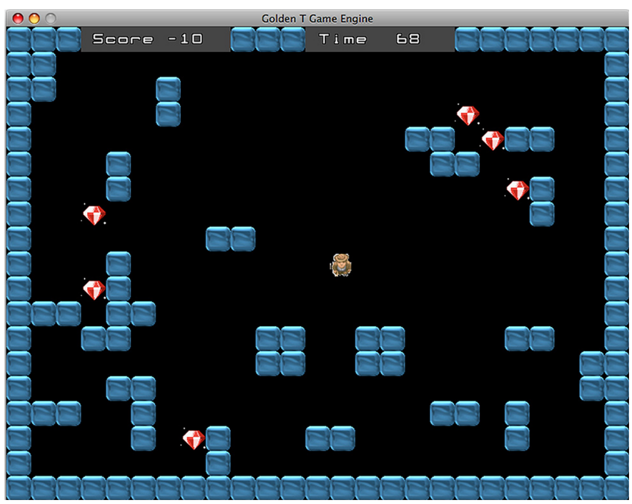

FIGURE 1 | Diamond task. The goal is to collect all diamonds within the time limit.

many real-world situations (Cutini et al., 2008). Given a set of spatial locations represented by points on a map, the task consists in finding an itinerary that visits each point exactly once, ensuring that total traveled distance is as short as possible. While the classic TSP requires to return to the starting point, the open-ended version introduces a distinction between start- and end-point so that participants have to perform an open path instead of a loop. TPS can be solved with multiple close-to-optimal solutions and usually healthy participants change strategy during the pathway to optimize performance. Therefore, the task achievement requires controlling and modifying the plan accordingly with the evaluation of both the current position and the remaining path. Basso et al. (2001) showed that TBI patients tend to use a fixed strategy until the end of the task without considering the alternative options, consistent with the hypothesis that TBI patients are unable to inhibit the current strategy in order to chose a better one (also see Cutini et al., 2008, for a computational model of normal and impaired performance in the TSP). In the DT, the number of diamonds ranges from one, in the less demanding level, to eight in the more demanding level. The achievement of the goal requires the participant to plan a route that allows to collect every diamond within the time limit. Usually the best overall strategy is to follow the shortest path passing through the diamonds.

In the ST, the man has to avoid to be caught by a snake and to reach a "shelter" house that appears at a random location (see **Figure 2**). The range of difficulty is enforced by controlling the running speed of the snake, as well as the time limit for trial completion. The achievement of this task requires a very different strategy compared to the diamond task. The best strategy is sometimes just the opposite: indeed, if the man takes the shortest way to arrive at the shelter house, it is likely that the snake will catch him. Avoiding to be caught often requires to choose a longer route, sometimes moving even in the direction opposite to the house location. Likewise, depending on the location of the house and the disposition of the maze walls, another good strategy may be to stop for a while, in a strategic location, waiting for the snake to take a wrong route. In this way, reaching the house becomes possible provided that the gamer chooses the right timing and moves quickly. Basically, the task requires "to trick" the snake. Therefore, accomplishment of the tasks requires adopting complex strategies involving the ability to plan and sometimes also inhibiting the most "automatic" action.

The DT and ST alternate between each other with a frequency that is adjusted according to the performance score. The difficulty of this "switch condition" has four levels ranging from a completely predictable switching, when one task follows the other, to a completely random switch. The two medium levels involve a switch every two trials and a switch every three trials, respectively. In some trials, the gamer has to perform the two tasks simultaneously (see **Figure 3**). In these trials the participant has to avoid the snake and to collect the diamonds at the same time. Contrary to the standard ST, in this case the shelter house appears only after all diamonds are collected. Overall, the successful performance requires reaching two simultaneous goals: collecting every diamond and avoiding the snake within the time limit. The dual task condition is administered only if the percentage of success is higher than 60%. When the gamer achieves this performance level, the probability to receive a dual task trial is 30%. In this way, the participant can reach enough expertise in the two single tasks before managing the more difficult dual task condition. If the trial is performed correctly the player receives some points, whereas if the participant fails to reach the goal some points are subtracted from the score. Every six trials the gamer receives a feedback concerning his/her performance.

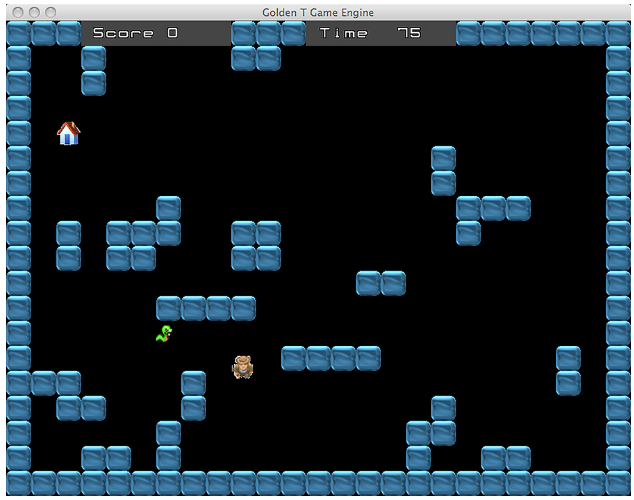

FIGURE 2 | Snake task. The goal is to avoid to be caught by the snake and reach a "shelter" house that appears at a random location.

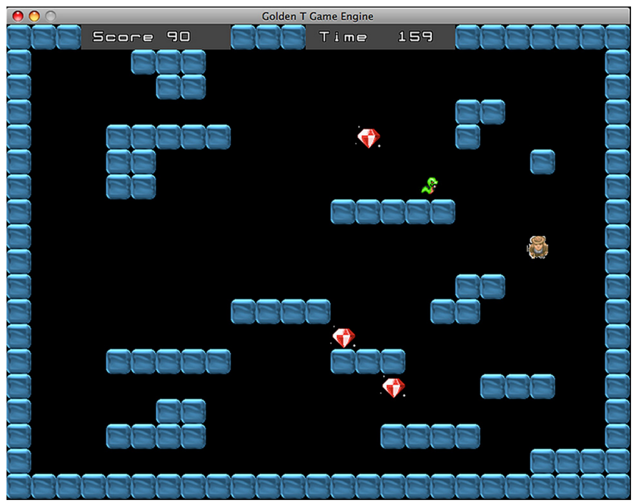

FIGURE 3 | Dual task. In these trials the goal is to avoid the snake and collect the diamonds at the same time. The shelter house appears only when all diamonds have been collected.

ADAPTIVE DIMENSIONS

Following Wilson et al. (2006) we used a multidimensional learning algorithm for continuous, online adaptation of task difficulty to the current performance of the gamer. Adaptation was implemented using three dimensions of difficulty:

(1) Time limit: the time limit to perform the task. The level of difficulty is ranging from 5 to 100 s. It is updated every trial.
(2) Task difficulty: overall it has eight levels but the difficulty depends on the task. In the DT it is related to the number of diamonds that have to be collected (from one to eight), while in the ST it is related to the snake speed. In both tasks the difficulty consists also in the number of walls of the maze (see Overall Game Design). It is updated every trial.
(3) Switch condition: the type of switch, predictable vs. unpredictable. It has four levels (every trial, every two, every three, random). This dimension is updated every 12 trials.

The combination of the three dimensions forms the "training space." This can be described as a cube with the three dimensions of difficulty as sides (Wilson et al., 2006). Every trial corresponds to a point within this cube (with the coordinates defined by the values of the three difficulty dimensions) and every point is associated with a certain probability of success. Higher probability is associated with easy trials and the opposite for the hard trials. Each user will be associated with a different probability of success matrix that defines the individual "performance space". For example, a patient who is more impaired in inhibiting automatic responses and less impaired with speed of processing will have a higher probability of success in the "time" dimension and lower probability of success in the "task difficulty" dimension.

The task of the algorithm is to estimate the performance space of the user accordingly with the current performance. After sampling points within the training space, the algorithm uses the responses of the player to build an interpolated model of the entire performance space. Then, it selects a random point in the space which it estimates to correspond to the level required to maintain performance at 75% of accuracy (**Figure 4**). Moreover, with the game advancing, the algorithm updates the performance space accordingly with the success or failure of the gamer.

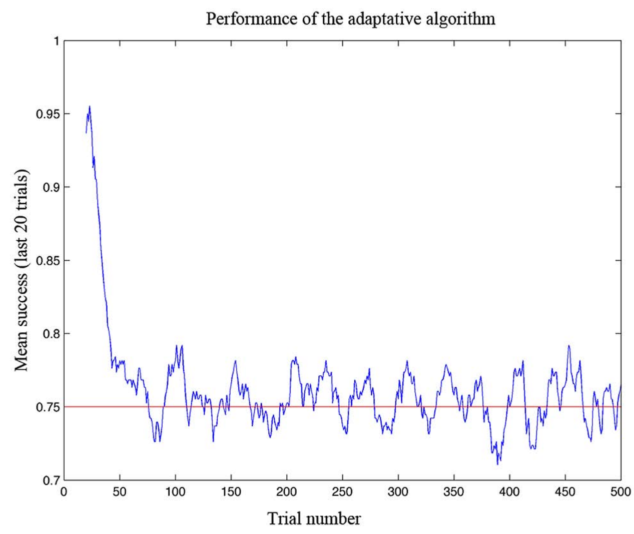

FIGURE 4 | Performance of the adaptive algorithm in ensuring a defined level of success in simulation testing. The graph shows the gamer's success rate (measured as a running average over the last 20 trials) as a function of trial number. Note that the algorithm adapted to the ability of the gamer in less than 100 trials and then kept the success rate at the desired level of 75%.

SIMULATION

In order to test the algorithm, performance in the game was simulated with a Matlab model (http://www.mathworks.co.uk/). The simulator represented the performance space of the gamer at a given moment by a matrix of the success probability, as in the adaptive algorithm. The subject's performance space was characterized by a "performance threshold," that is the set of coordinates which specified the high success zone (in which the probability of success is 100%). Outside the high success zone, the probability of success for a given type of game trial was calculated by determining the distance between its location and the subject threshold and applying a sigmoid function to this distance (Wilson et al., 2006). If the trial location is far from the threshold the probability to be successful at this level of difficulty will be low or zero, whereas if the trial location is close to the threshold the probability to be successful will be high. The "performance threshold" could move up simulating the improvement of performance as a consequence of the training. In the simulator, learning rate (LR) was assumed to be a function of the derivative of the sigmoid (Wilson et al., 2006). For example, if the gamer has a successful performance in a trial far away from the threshold, her performance has a fast LR.

The first simulation was carried out with a virtual gamer who has a fixed level of performance and zero LR. The aim of the simulation was to test if the algorithm was able to develop an accurate model of the gamer ability. In **Figure 5A**, the ability of the algorithm to estimate the performance of four different gamers is represented on a trial by trial basis. At the beginning of the game the algorithm cannot reliably estimate the different performance spaces. After 100 trials, the estimates diverge and then reach the specific level of performance corresponding to the fixed limit set for each simulated gamer. **Figure 6** shows a tridimensional representation of the performance space of three different virtual gamers (with fixed limit of performance).

The second simulation investigated the algorithm's ability to distinguish between gamers with different levels of LR (**Figure 5B**). The performance of the gamer with zero LR does not change over time. Conversely, the slope of the performance of the gamers with higher LRs becomes steeper accordingly with the rate of increase. As shown in **Figure 5B**, the algorithm was able to adjust the rate of increase in difficulty as a function of the LR of the different simulated gamers. **Figure 7** shows the performance space of three different gamers, with different LRs for the three dimensions (i.e., time limit, task difficulty and switch condition). For each gamer, LR for one dimension was set to zero (i.e., the gamer does not learn at all) and the LRs for the other two dimensions were set to 1 (i.e., the gamer learns quickly). It is possible to appreciate how the estimate of the algorithm changes accordingly with the characteristic of the gamer. The probability of success expands rapidly for the two dimensions with high LR, whereas it does not change for the dimension with zero LR.

VALIDATION OF THE GAME WITH UNIMPAIRED PARTICIPANTS

The videogame "Labyrinth" has been conceived as a tool for training specific skills. The goal of the validation study was to test the

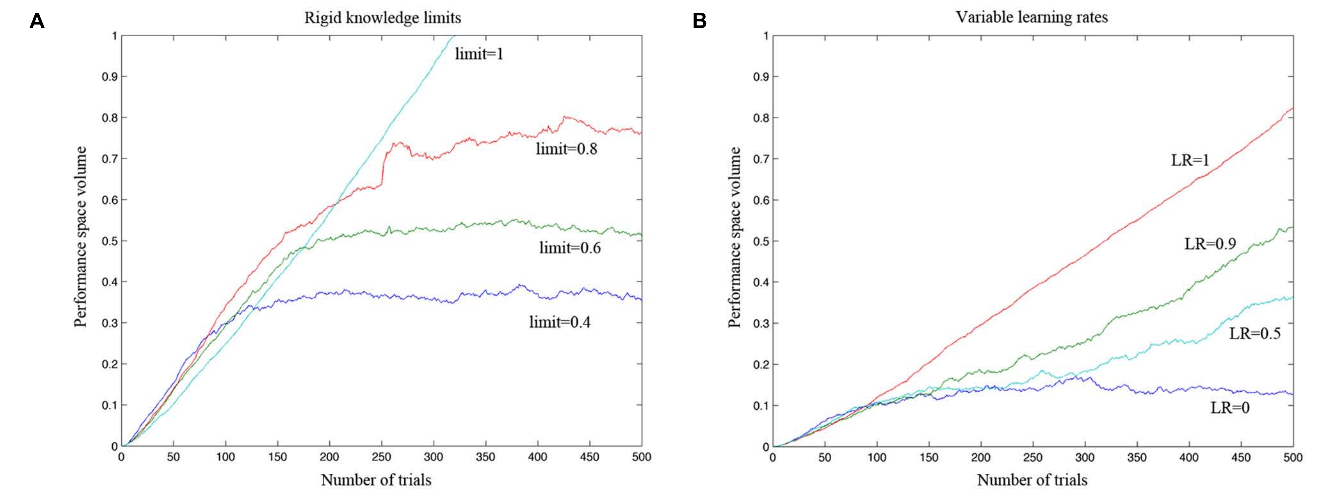

FIGURE 5 | Simulation testing the efficacy of the adaptive algorithm to accurately estimate a model of the gamer ability. (A) The estimated performance space of a virtual gamer who has a fixed level of performance and zero learning rate. The four virtual gamers have different performance limits, ranging from 1 (which implies 100% probability of success in the entire performance space) to 0.4 (which implies 100% probability of success in 40% of the performance space). After 100 trials, the algorithm could estimate fairly well the performance space of the gamer as defined by the simulator and it could clearly distinguish between different gamers with different levels of performance. **(B)** Simulation carried out to test if the algorithm can distinguish between gamers with different levels of learning rate (LR). The algorithm was able to adjust the rate of increase in difficulty as a function of the learning rate of the different simulated gamers.

new videogame with unimpaired participants. A group of healthy young adults was engaged in a training protocol which involved daily 40 min play sessions with the videogame for 2 weeks.

We also sought to establish that the game practice involves the targeted abilities by evaluating the presence of the dual task effect and the task switching effect in the different dependent measures of the game during the first play session. If the alternation between DT and ST works as switch condition we should observe a cost in the participants' performance when one task is followed by the other task relative to when it is followed by the same task (Monsell, 2003). Usually the cost consists in worse accuracy in the new task relative to the repeated one and/or in slower RTs in the new task relative to the repeated one. Likewise, performing the two tasks at the same time should be more difficult than performing a single task, thereby revealing the cost of multi-tasking.

Videogame output is quite different from that of classic experimental paradigms based on choice reaction times. We extracted three different performance measures from the videogame that became the dependent variables of our analyses. The three types of score were:

(1) Success rate: whether the task was completed with success or not, within the time limit;
(2) Overall time: the time taken to complete the task;
(3) Diamond Time (DT): the time to collect the first diamond;

The DT measure is closer to the trial onset than the other two measures and collecting the first diamond is clearly an immediate and objective sub-goal of the task. Therefore, it should be more sensitive in uncovering effects that might be otherwise undetectable.

Note that the first two measures cannot be used to evaluate the effect of training across sessions because the adaptive algorithm keeps the performance level around 75% by continuously changing the different adaptive dimensions. Nevertheless, we assessed the participants' progress across sessions in terms of task difficulty level and time limit (see Adaptive Dimensions above). We predicted a trend toward increasing difficulty level and decreasing time limit across sessions as a marker of improved performance in the videogame during training. Moreover, we assessed the effect of training on dual tasking and task switching performance using the DT measure, because the latter is not influenced by the choices of the adaptive algorithm. The time taken to collect the first diamond was compared between single and dual-task conditions (i.e., dual task cost), as well as between repeated and new task conditions (i.e., task switching cost). We expected a decrease of both costs across training sessions.

METHOD

Participants

Twenty undergraduate students from the University of Padua participated in the study. Their mean age was 20.8 with range of 19–25 years. They had normal or corrected-to-normal vision.

Apparatus, stimuli, and procedure

The videogame "Labyrinth" was installed on the personal computer of each participant. Given that the participants were healthy young adults, we set lower bounds for the level of difficulty (level 3) and the time limit (25 s). The training period was 14 days long. Participants played with the game for 40 min everyday. The duration of the daily training session was enforced by self-termination of the game. The individual performance space estimated by the adaptive algorithm (see Adaptive Dimensions) was saved at the end of the session and reloaded at the beginning of the next session. This ensured that the difficulty of the game was immediately

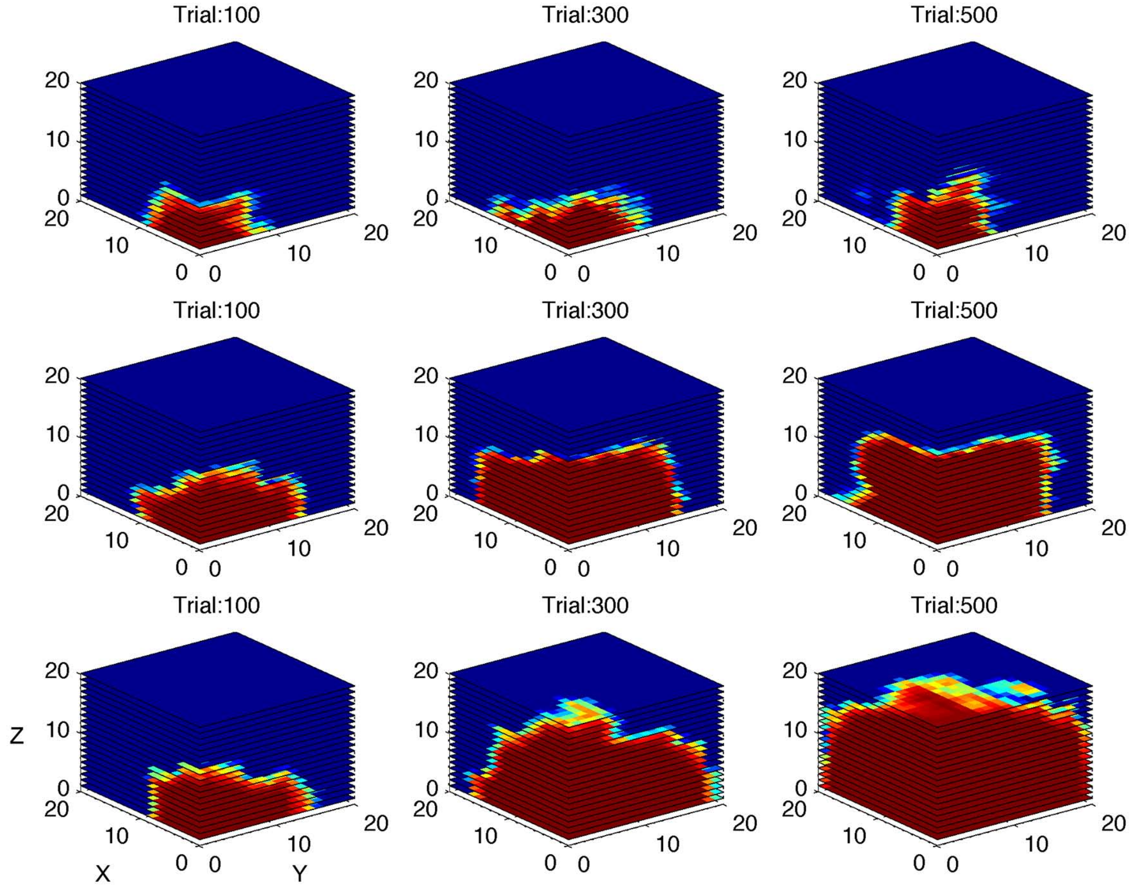

FIGURE 6 | Simulation of gamers with different performance limits. Performance space estimated by the algorithm after 100, 300, and 500 simulated trials, shown as three-dimensional cube, for three different virtual gamers with fixed limit of performance and zero learning rate (top row: limit = 0.4; middle row: limit = 0.6; bottom row: limit = 0.8). The red area represents high probability of success.

restored to the level achieved in the previous play session. Total play time across the 14 sessions was 9 h and 30 min.

RESULTS

First, we analyzed the data collected in the first session of game playing. The aim of this analysis was to assess the presence of the dual task effect and the switch effect. We performed analysis of variance with the type of task as within-subjects factor. The game performance trend across the training sessions was analyzed using mixed-effects multiple regression models (Baayen et al., 2008). Data were analyzed in the R environment (R Core Team, 2013) using ez package (Lawrence, 2013), lme4 package (Bates et al., 2013), afex package (Singmann, 2013), and lmerTest package (Kuznetsova et al., 2013).

Dual task effect

The effect of dual task was assessed on success rate and DT. Overall time was not used because the dual task condition requires an additional time-consuming operation (i.e., reaching the shelter house) with respect to the diamond task.

Success rate. The effect of the type of task, single vs. dual, was significant, $F(1,16) = 311.42$, $p < 0.001$, $\eta^2_G = 0.91$, indicating that in the dual task condition participants were less successful than in the single task condition (see **Figure 8A**). For example, the player was caught by the snake more often in the dual task than in the snake task, $F(1,16) = 33.31$, $p < 0.05$, $\eta^2_G = 0.46$.

Diamond time. The effect of the type of task, single vs. dual, was significant, $F(1,16) = 36.21$, $p < 0.001$, $\eta^2_G = 0.47$, indicating that the time to collect the first diamond in the dual task condition was longer than in the single task condition (see **Figure 8B**).

Task switch effect

Success rate. The effect of the type of task, new vs. repeated, was significant, $F(1,16) = 9.35$, $p < 0.01$, $\eta^2_G = 0.35$, indicating that participants were less successful in trials involving a change of task relative to trials in which the task remained the same, that is a task switching cost (see **Figure 9A**).

Overall time. The effect of the type of task, new vs. repeated, was significant, $F(1,16) = 25.08$, $p < 0.001$, $\eta^2_G = 0.09$, indicating that participants were slower in completing the task for trials involving a change of task relative to trials in which the task remained the same (see **Figure 9B**).

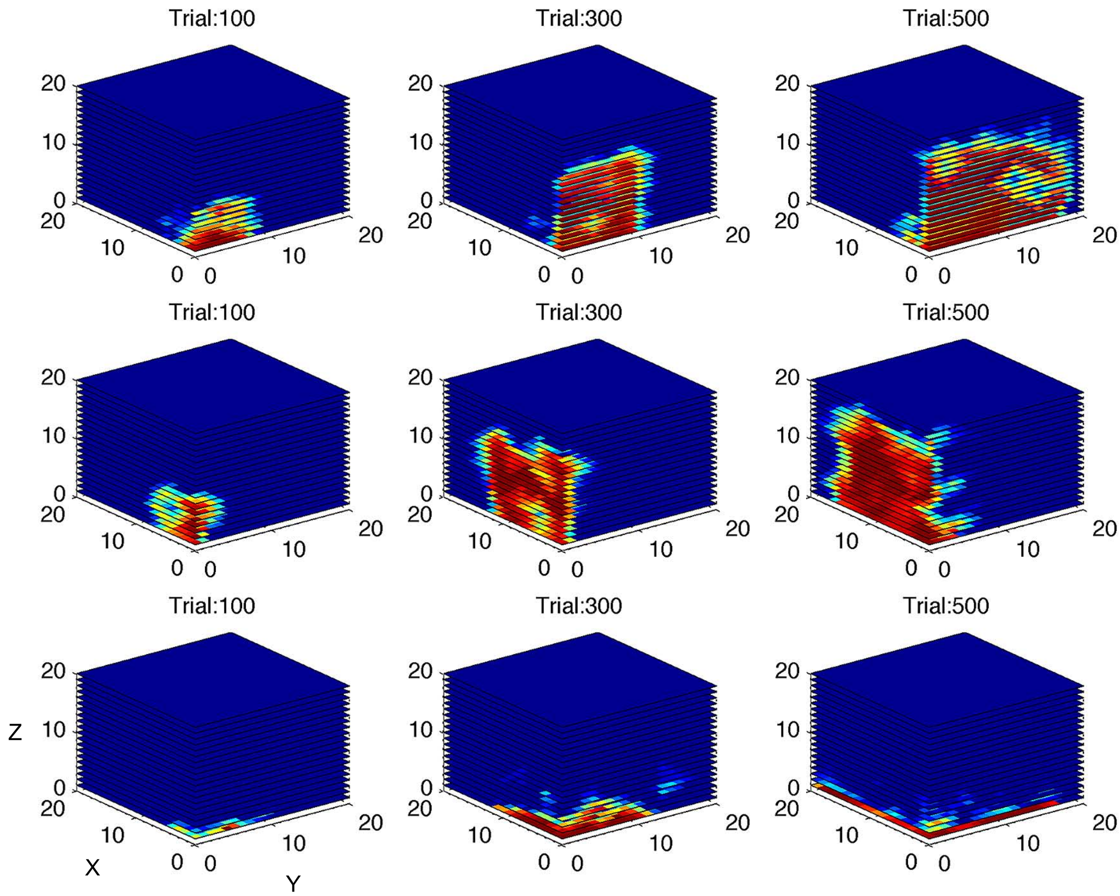

FIGURE 7 | Simulation of gamers with different learning rates. Performance space estimated by the algorithm after 100, 300, and 500 simulated trials, shown as three-dimensional cube, for three different virtual gamers with null initial performance space and different learning rate (LR) for the three dimensions (top row: LR = 0 for X dimension and LR = 1 for Y and Z dimensions; middle row: LR = 0 for Y dimension and LR = 1 for X and Z dimensions; bottom row: LR = 0 for Z dimension and LR = 1 for X and Y dimensions). The red area represents high probability of success. Note that the performance space does not expand through the dimension with zero learning rate.

Diamond time. The effect of the type of task, new vs. repeated, was significant, $F(1,16) = 83.11$, $p < 0.001$, $\eta^2_G = 0.25$, indicating that participants were slower to collect the first diamond for trials involving a change of task relative to trials in which the task remained the same (see **Figure 9C**).

Effect of training

We assessed the presence of a training effect within the game (i.e., performance improvement as a function of training time) in terms of changes in task difficulty level and time limit selected by the algorithm across the 14 sessions. Moreover, we assessed if the dual task and the task switching performance in the DT measure improved during the training. We employed mixed-effect multiple regression models (Baayen et al., 2008). By-subject random intercepts were included in all analyses. For the analyses of task difficulty and time limit we applied a logarithmic link function (Jaeger, 2008) and Poisson variance distribution that is appropriate for counts of events in a fixed time window (e.g., Baayen, 2008). For the DT analysis we performed Type III test calculating *p*-values via the likelihood ratio test in order to assess the significance of the main effects and the interactions of the predictors (i.e., session and condition).

Task difficulty. The effect of the session was significant ($b = 0.0021$, $z = 4.59$, $p < 0.001$), indicating that the task difficulty increased (positive beta weight) across the sessions. In the last session, the participants reached a mean difficulty level of 4.67 (SD = 0.14).

Time limit. The effect of the session was significant ($b = -0.0040$, $z = -15.90$, $p < 0.001$), indicating that the time limit decreased (negative beta weight) across the sessions. In the last session, the participants reached a mean time limit of 15.95 (SD = 0.62).

Diamond time: dual task effect. The main effect of session was significant, $\chi^2(1) = 135.71$, $p < 0.001$, indicating that the time to collect the first diamond decreased across sessions. The main effect of condition (single vs. dual) was significant, $\chi^2(1) = 749.41$, $p < 0.001$, indicating that the DT in the dual task condition was longer than in the single task condition. The interaction session by condition was significant $\chi^2(1) = 80.73$, $p < 0.001$,

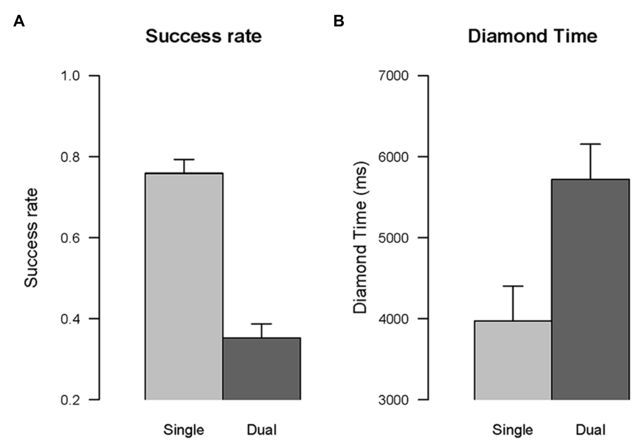

FIGURE 8 | Dual task effect. The comparison between single task and dual task conditions is shown for success rate **(A)**, and time to collect the fist diamond **(B)**. Error bars are within-subjects confidence intervals calculated with the method of Morey (2008).

indicating that the effect of the session was different for the two conditions. The interaction was inspected by changing the reference level accordingly with the desired contrast. The decrease in DT was significant for both conditions, but the reduction was larger for the dual task condition as attested by the larger (negative) beta weight ($b = -8.19$, $t = -3.93$, $p < 0.001$ and $b = -63.35$, $t = -10.98$, $p < 0.001$ for single and dual task conditions, respectively).

Diamond time: task switch effect. The main effect of session was significant $\chi^2(1) = 40.33$, $p < 0.001$, indicating that the DT decreased across sessions. The main effect of condition (new vs. repeated) was significant $\chi^2(1) = 105.98$, $p < 0.001$, indicating that participants were slower to collect the first diamond for trials involving a change of task relative to trials in which the task remained the same. The interaction session by condition was significant $\chi^2(1) = 9.45$, $p < 0.01$, indicating that the effect of the session was different for the two conditions. The interaction was inspected by changing the reference level accordingly with the desired contrast. The decrease in DT was significant for both conditions, but the reduction was larger for the switch (new task) condition as attested by the larger (negative) beta weight ($b = -6.79$, $t = -2.07$, $p < 0.05$ and $b = -19.56$, $t = -7.70$, $p < 0.001$, for repeated and new conditions, respectively).

DISCUSSION

The aim of this experiment was to validate the game "Labyrinth" in a study on unimpaired participants. Playing a game with these characteristics is likely to involve many different cognitive skills, some more basic, and some of a higher level. For example, successful playing requires selecting the relevant information and discarding the irrelevant ones. Playing until the end of the session requires to sustain attention at an adequate level for a relatively long time. Since the game was conceived to tap specific abilities, we first assessed whether playing the game involved these skills. In particular, we assessed whether the participants' performance showed the cost of dual tasking and the cost of task switching to confirm the involvement of divided and alternate attention or flexibility.

The performance of the unimpaired participants in the first play session with the videogame showed the classic cost of dual task across the different performance measures. The success rate was higher in the single tasks than in the dual task condition. The dual task effect was confirmed also in the time dependent variable: the time to collect the first diamond was longer when the gamer

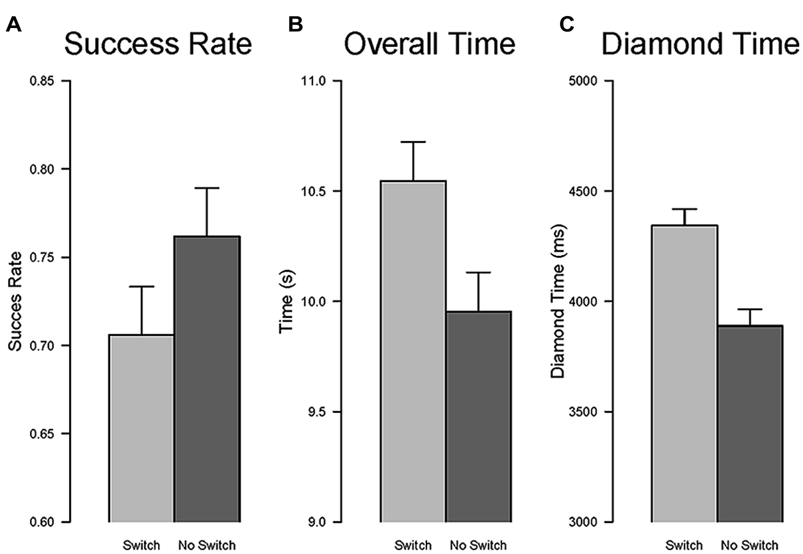

FIGURE 9 | Task switch effect. The comparison between repetition and switch conditions is shown for success rate **(A)**, overall time to complete the task **(B)**, and time to collect the fist diamond **(C)**. Error bars are within-subjects confidence intervals calculated with the method of Morey (2008).

had to collect the diamond and to avoid the snake at the same time compared to when she only had to collect diamonds. Therefore, the results confirm a robust dual task effect, thereby showing that completing the two tasks simultaneously requires to divide attention between the two goals (as well as between diamond and snake stimuli).

The analyses of the three performance measures also revealed a robust effect of task switching. In this case we compared the performance between the condition of repetition, when one task followed a task of the same type (e.g., DT after DT), with the condition of non-repetition, when one task followed a task of the other type (e.g., DT after ST). Success rate was higher in the condition of repetition than in the switch condition, in line with the findings using the classic task switch paradigm (Monsell, 2003). Likewise, the time to complete the task and the time to collect the first diamond showed a switch cost, with longer times for the switch condition compared to the repetition condition. Therefore, changing the task showed the need for reconfiguration or inhibition of the cognitive set of the prior task, thereby involving cognitive flexibility.

Overall, the performance improved throughout the training as indicated by the increase of task difficulty across sessions. This means that the algorithm moved the performance threshold toward more difficult levels because the participants became more skilled in the achievement of the goals. In the same vein, the maximum time allowed to accomplish the task decreased across sessions, indicating that participants became faster in the achievement of the goals. Moreover, using DT as performance index, we found that the cost of dual-tasking as well as the cost of task switching decreased during training. Though the time to collect the first diamond showed an overall decrease across sessions, the improvement was significantly stronger for the dual task condition than for the single task condition, thereby suggesting that players became more efficient in route planning under dual task. In the same vein, the comparison between repeated and new task conditions (i.e., task switching) showed a stronger performance improvement for the switch condition. These results suggest that playing with Labyrinth enhanced the participants' attentional control, at least in terms of the ability to manage multitasking and to quickly reconfigure the task set. This finding is in line with studies showing that extensive dual task training enhances the ability of multitasking (Van Selst et al., 1999; Schumacher et al., 2001; Tombu and Jolicoeur, 2004).

The generalization beyond the task used for training is an important issue in the area of cognitive enhancement and rehabilitation. The training effect should transfer to other tasks to make the training really beneficial. We leave this issue to a follow-up study, but we believe that the characteristics of the game, for example the alternation between tasks as well as multitasking, may stimulate high levels attention functions as opposed to task specialization. Flexibility and control over attentional resources is clearly relevant in a variety of daily-life situations. An investigation of the relationship between videogame play and a comprehensive battery of cognitive / attentional tests would indeed clarify this issue (see Baniqued et al., 2013) and it would explicitly assess transfer to specific skills like task switching and multitasking.

CONCLUSION

There is a growing body of evidence that videogame playing can enhance a variety of specific skills in addition to speeding up information processing (e.g., Hubert-Wallander et al., 2011a). Moreover, gaming seems to promote transfer to more ecological settings and generalization to untrained skills. Here we attempted to design a new videogame including specific features that were conceived to specifically involve attention and executive functions, with the final purpose to use it in supporting the rehabilitation practice of TBI patients. Cognitive deficits following TBI can profoundly affect daily living (Sohlberg and Mateer, 2001) because they often involve executive and attentional functions that are fundamental to control and modulate other more basic abilities. The design of the game was guided by principles relevant for the training of those functions. Therefore, its aim was to enhance mental flexibility (switching between different cognitive sets) and multi-tasking (maintain the cognitive sets of two different tasks and dividing attentional resources between two goals), stimulate planning ability (choosing the adequate strategy, interrupting automatic responses and monitoring performance), and encourage speeding up of processing. Most importantly, the videogame was equipped with a multidimensional adaptive algorithm that provided a continuous, online calibration of the level of difficulty across three different dimensions to the gamer's current performance. We believe that this latter feature is crucial for managing the performance variability of patients. The development of the game included different testing stages. In the first stage, we simulated users with different performance profiles to assess the efficiency of the adaptive algorithm in estimating the user ability. In the second stage of the testing phase, we validated the game with unimpaired participants to ensure that the game involves the activation of the desired cognitive functions as well as to assess the effect of a short training period. Thus, the next step will be to test the videogame in a controlled clinical trial with TBI patients to assess if it is useful for the remediation of attentional and executive impairments.

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Cognitive enhancement through action video game training: great expectations require greater evidence

Joseph Bisoglio[1]*, Timothy I. Michaels[2,3], Joshua E. Mervis[1] and Brandon K. Ashinoff[4†]

[1] Columbia University Medical Center, New York, NY, USA
[2] Manhattan Psychiatric Center, New York, NY, USA
[3] Research Foundation for Mental Hygiene, Nathan Kline Institute for Psychiatric Research, Orangeburg, NY, USA
[4] Department of Psychology, New York University, New York, NY, USA

Edited by:
Walter R. Boot, Florida State University, USA

Reviewed by:
Eric-Jan Wagenmakers, University of Amsterdam, Netherlands
Thomas Redick, Purdue University, USA

***Correspondence:**
Joseph Bisoglio, Columbia University Medical Center, 615W 113th Street #42, New York, NY 10025, USA
e-mail: jb2561@columbia.edu

†Present address:
Brandon K. Ashinoff, Department of Psychology, University of Birmingham, Birmingham, UK.

Action video game training may hold promise as a cognitive intervention with the potential to enhance daily functioning and remediate impairments, but this must be more thoroughly evaluated through evidence-based practices. We review current research on the effect of action video game training on visual attention and visuospatial processing, executive functions, and learning and memory. Focusing on studies that utilize strict experimental controls and synthesize behavioral and neurophysiological data, we examine whether there is sufficient evidence to support a causal relationship between action video game training and beneficial changes in cognition. Convergent lines of behavioral and neurophysiological evidence tentatively support the efficacy of training, but the magnitude and specificity of these effects remain obscure. Causal inference is thus far limited by a lack of standardized and well-controlled methodology. Considering future directions, we suggest stringent adherence to evidence-based practices and collaboration modeled after clinical trial networks. Finally, we recommend the exploration of more complex causal models, such as indirect causal relationships and interactions that may be masking true effects.

Keywords: cognition, action video games, cognitive remediation, neurophysiology, cognitive enhancement

In September 2013, action video game Grand Theft Auto V broke all previous entertainment sales records by grossing $1 billion in just three days (Nayak, 2013). At present, video games yield $20 billion in annual sales and over 50% of Americans report owning a gaming console (Entertainment Software Association, 2013). Beyond entertainment value, video games are also extending into the domain of cognitive therapeutics: Lumosity, the industry leader in game-based cognitive enhancement, has amassed over 40 million users worldwide. These two game types, entertainment versus enhancement, appear qualitatively different. There are some researchers, however, who argue that video games designed for entertainment can facilitate meaningful improvements in cognitive function (Dye et al., 2009; Bavelier et al., 2012a). At present, these claims need to be more rigorously evaluated according to evidence-based practices before scientists endorse any potential therapeutic value.

Are cognitive benefits a direct consequence of video game training? In the only comprehensive meta-analysis on video games to date, Powers et al. (2013) report that playing video games yields a moderately positive effect on cognition. This effect is found in non-experimental studies, $d = 0.46$, 95% CI [0.39, 0.53], where expert video game players are compared to video game novices (hereafter referred to as "experts" and "novices"), as well as in true experiments, $d = 0.45$, 95% CI [0.35, 0.56], where participants train with a video game for a fixed period of time and are compared to their own initial performance or a control group. Yet non-experimental studies, by nature, preclude the possibility of strict causal inference, and a lack of rigorous and standardized methodology in the experimental training studies makes those findings vulnerable to possible confounds.

Powers et al. (2013) examined the specificity of cognitive effects in their moderator analysis. Unlike their primary analysis where they aggregated multiple test outcomes into a single summary effect for each study, their secondary analysis treated studies with multiple test outcomes as if each outcome originated from a separate and independent study. While they noted that this violates the assumption of independence, stating, "analysis at this level was required to test for the effects of most of the moderating variables" (p. 1059), treating multiple dependent outcomes as independent creates two major statistical confounds. One, it artificially inflates the cumulative sample size of the meta-analysis, and therefore overestimates the certainty of any findings, and two, it biases the weight of each study toward those with the greatest number of outcomes (see Borenstein et al., 2009). For example, in their examination of executive function their sample of 13 studies with a cumulative sample of 539, inflated to 89 studies with a cumulative sample of 3,721. Additionally, due to variability in the number of outcomes, some studies (e.g., Lee et al., 2012) were weighted 20 times more than others (e.g., Spence et al., 2009). Multiple dependent outcomes are a common problem in meta-analyses (Dunlap et al., 1996), and while there is no uniform consensus on how to account for them, there are a number of methods available to the researcher, the most common being multivariate methods (see Mavridis and Salanti, 2013). Thus, while Powers et al. (2013) have made a very worthwhile contribution to the field with their primary analysis, the findings reported in their moderator analyses should be interpreted with great caution.

To the extent that video games improve cognitive functioning, the critical next step is to determine what aspects of video games drive cognitive benefits, how this works, and what it targets in the brain. Additionally, different game types may have various effects on cognition or interact with specific domains. While evidence of neuroplastic change is necessary to establish causality, it is not sufficient. We must know what aspects of gameplay drive the change, as well as how and where it manifests in neural circuitry and observable behavior. Examining the literature, Boot et al. (2011, 2013; Boot and Simons, 2012 see also Kristjánsson, 2013) conclude that current research falls short of evidence-based practices. They lay out a series of methodological guidelines for future studies that include training paradigms that utilize randomization, active control groups, and better methods to account for placebo and practice effects They also suggest evaluating behavioral findings in conjunction with neurophysiological evidence in order to track cognitive changes alongside neural correlates.

The current review attempts to qualitatively address the issue of causality by adopting a strict focus on studies whose methodology provides the elements necessary for causal inference. We consider only experimental studies that include some form of training paradigm. We will not consider non-experimental, quasi-experimental studies, or correlational studies in this analysis. Within these studies we give the highest priority to those which include one or more of the following design elements: experimental control in the form of active and/or passive comparison groups, neuropsychological data to assess the transfer of training, and neurophysiological evidence to identify the structural or functional correlates of differences in cognitive performance. Unfortunately, there are few studies that include all of these design elements. Insufficient evidence exists to specify the exact “active ingredient” within video games; therefore we use a broad focus on games with an action component. For the purposes of this review we use a broad definition of the term action so as to not exclude games based on thematic or esthetic design elements. We summarize findings with respect to improvement in three cognitive areas: (1) visual attention and visuospatial processing, (2) executive functions, and (3) learning and memory. Lastly, we illustrate areas in need of further investigation and provide commentary for future directions.

LEARNING AND MEMORY

Perhaps one of the more intriguing mechanisms of cognitive change relates to whether training on action video games can enhance one’s ability to efficiently learn novel tasks. The process of developing skills that facilitate learning in other contexts, referred to as “learning to learn” (Harlow, 1949), may underlie one’s capacity to benefit from training. Although within- and between-group differences may still play a role in learning to learn, Green and Bavelier (2008) argue that well-designed training procedures can facilitate cognitive enhancements that extend beyond specific experiments and conditions. These design principles include the use of shorter training periods, which may allow training effects to generalize more broadly (Karni and Sagi, 1993) and high variability in training strategies to facilitate learning (Schmidt and Bjork, 1992; Green and Bavelier, 2008). Improved learning may not be a specific target of training but rather the by-product of elaborate knowledge structures, complex learning algorithms, and more efficient allocation of attentional resources (Green et al., 2010; Bavelier et al., 2012b).

While attention and executive functions play a key role in learning to learn, it is less clear whether other aspects of cognition, such as memory, contribute toward this process. In particular, findings from training studies examining working memory have been inconsistent. Boot et al. (2008) report no significant between-group differences in any memory abilities post-training. While Basak et al. (2008) report no significant improvement in spatial memory, they do find a group-by-testing-session interaction in working memory. Given that Basak et al. (2008, 2011) did not utilize an active control group, these conflicting results may be due to expectation effects. Oei and Patterson (2013)Oei and Patterson (2013 find no post-training gains in spatial working memory, but do find improvements in working memory measured via a complex span task. Several recent reviews (Shipstead et al., 2012; Melby-Lervåg and Hulme, 2013) indicate that working memory training might improve performance on tasks similar to the training, but generalized skill transfer does not seem to occur. However, these reviews do not focus on action video games, which may provide a unique training experience.

Working memory is unique in that it requires not only maintaining information in short-term storage, but also places heavy demands on attention and continual response inhibition (Baddeley and Hitch, 1974). Behavioral findings of working memory gains may therefore be the result of improvements in other domains, namely attention and executive functioning. Although there are few neuroimaging studies that specifically address post-training working memory enhancement, preliminary data suggest that gains in executive functioning contribute significantly to behavioral findings. Basak et al. (2011) utilized structural MRI to compare brain volumes among older adults who underwent over 20 h of action video game training. The volume of the dorsolateral prefrontal cortex (DLPFC), an area critical to both working memory and executive functions, was correlated with improvements in game performance and with measurements of the rate of learning. This evidence suggests that enhancements in other cognitive domains may underlie working memory gains and provide a basis for understanding why other aspects of memory are unaffected by action video game training.

EXECUTIVE FUNCTIONS

Several recent experimental studies support the idea that training increases various components of executive functioning (e.g., Basak et al., 2008; Green et al., 2012; Strobach et al., 2012). Anguera et al. (2013) reported that older adults without video game experience show enhanced cognitive control after training compared to both active and passive control groups. In terms of neurophysiology, action video game training appears to engage neural structures and circuits that mediate executive functions. EEG studies have shown associations between improved performance in executive function tasks and increases in both frontal alpha (Maclin et al., 2011; Mathewson et al., 2012) and midline frontal theta power (Anguera et al., 2013) after video game training.

In addition to post-training changes in brain function, there is preliminary evidence that training may also lead to structural changes. A recent study reports that compared to a passive control group, participants who trained on *Super Mario 64* for 30 min a day over a period of 2 months showed significant post-training group differences in gray matter volume in the right DLPFC, right hippocampus, and cerebellum (Kühn et al., 2014). While there was no time-by-group interaction for the hippocampus and cerebellum, the right DLPFC showed a significant interaction. The DLPFC is one of the most critical neuroanatomical areas for the executive functions and has been closely linked to the executive component of working memory (Goldman-Rakic, 1995) inhibitory control (Wager et al., 2005a) and shifting (Wager et al., 2005b). Although these results provide some support for structural brain changes post-training, the study lacked an active control group and therefore it is impossible to determine whether the changes resulted from the video game training itself or rather from engagement of any activity over the same period of time. As this is one of few studies to directly examine the effects of video game training on neurophysiology, we have included it in our analysis, despite this methodological flaw.

The relationship between action video game training and cognitive effects, however, may be more complex than a single cause and effect model. A structural imaging study by Erickson et al. (2010), found that pre-training volumes in both the ventral and dorsal striatum were associated with early-stage learning and skill acquisition in a game emphasizing cognitive flexibility, but that only dorsal volume was predictive of continued improvement. This suggests that while immediate learning and skill acquisition is likely related to reward processing and motivation (i.e., ventral striatum), progressive enhancements are a function of procedural learning and cognitive flexibility (i.e., dorsal striatum). Importantly, these findings also highlight the need to investigate how individual differences may be interacting with training to produce differential effects.

VISUAL ATTENTION AND VISUOSPATIAL PROCESSING

The idea that action video games can influence cognition, and specifically attention, is long established (Greenfield, 1994; Greenfield et al., 1994a,b; Subrahmanyam and Greenfield, 1994). A landmark paper by Green and Bavelier (2003) paved the way for numerous behavioral studies concluding that video games modify visual attention and visuospatial processing. Visual attention and visuospatial processing have been grouped together in this review because of their close interaction and potential for bidirectional effects (Yeshurun and Carrasco, 1998, 1999; Carrasco et al., 2004). While these two processes may be independent at the neural level, this distinction is difficult to assess behaviorally. For example, post-training improvements in the continuous performance test (Riccio et al., 2002) or the useful field of vision task (Ball et al., 1993) may be the result of faster perceptual processing, more efficient prioritizing of visual information, or both. Although Green and Bavelier's (2003) paper contained small-scale training studies that supported their conclusions, their subsequent work Green and Bavelier (2006a,b) focused on training novices as a way to identify whether superior attention in expert players was due to the games themselves or pre-existing differences. Novices showed enhancements in selective visual attention after training, suggesting that between-group differences alone could not account for observational findings. Similarly, Wu and Spence (2013) found that while novices initially exhibited poorer visual attention compared to experts, 10 h of training was sufficient to yield improvement. Other studies have produced similar findings (e.g., Feng et al., 2007); results, however, are not entirely consistent (e.g., Boot et al., 2008; Belchior et al., 2013).

Neurophysiological evidence also supports video game training's ability to improve attention and visuospatial processing. Wu et al. (2012) found that participants who exhibited the most improvement on a behavioral measure of attention also showed increased evoked response potentials in late-stage visuospatial processing, compared to those with less attentional improvement and to control participants. These findings are interpreted as gains in the top-down allocation of attentional resources and improved distractor inhibition. Using functional neuroimaging, Prakash et al. (2012) reported that although both controls and training groups recruited attention control areas (such as the ventral medial prefrontal cortex) during task performance, subjects in the training group exhibited reduced activity post-training, suggesting enhanced top-down attentional control. Collectively, these results highlight the possibility that top-down control mediates the relationship between training and enhancements in attentional performance, and further suggest that the magnitude of improvement in attention and visuospatial processing may depend on an interaction between training and training strategy, and between training and individual differences. Future studies should extend upon this work by examining whether reduced activation post-training also correlates with improvements on tasks unrelated to the training paradigm, thus confirming the transferability of efficient neural network processing to non-training paradigms.

DISCUSSION

The proliferation of video games as an entertainment medium provides an opportunity to better understand the plasticity of human cognition as a function of experience. Despite an incomplete understanding of these processes, the use of video games as a tool for cognitive enhancement has outpaced scientific evidence for its efficacy. We reviewed existing research on action video games and their training effects. Behavioral findings from training studies suggest improvements in attention, visuospatial processing, cognitive control and flexibility, but are inconclusive with respect to short-term memory. Enhancements in working memory do occur, although this could be secondary to improvements in attentional and executive resources. In many cases neurophysiological data bolster these behavioral findings through parallel evidence of neuroplastic change and elucidating potential underlying mechanisms related to enhanced cognitive function.

Boot et al. (2011) suggest adopting an experimental methodology, which mirrors that of clinical trials, including the use of active or placebo control groups, the improvement of reporting practices, and the reduction of demand characteristics. While this review provides support for these suggestions, it also highlights ways in which this approach can be advanced and extended.

While most research has adopted a linear model, this precludes the possibility of indirect causality and assumes that training produces domain-specific enhancements equally across all subjects. More complex causal relations may be elucidated by mediation and moderation analyses, which future studies might explore. Neurophysiological evidence suggests that individual differences may underlie differential training effects (Erickson et al., 2010; Wu et al., 2012), indicating that training may not be equally beneficial for everyone. Future research should also explore individual characteristics as baseline predictors of treatment response.

Action video game studies should also strive to adopt methodologies that boost the signal of any training benefits while simultaneously reducing the noise of placebo effects. This includes adopting a randomized, double-blind, placebo-controlled clinical trial design (Pastore and Scheirer, 1974). Yet additional design considerations can also be utilized to maximize treatment effects. Increasing the signal of cognitive enhancement may be feasible through the adoption of training strategies that enhance complex skill acquisition. For example, regimens that emphasize variable training and sub-part training yield larger improvements over traditional repeated practice measures (Prakash et al., 2012). Clinical trials also benefit from pre-registration, a collaborative research network, and standardized methodology. This practice not only increases accountability, statistical power, and the consolidation of resources but also reduces the variability associated with disparate study designs.

Expectancy effects are another vital consideration in training studies, where active controls may not be enough for causal inference. Boot et al. (2013) survey participant expectations of the potential cognitive benefits of various games they had never played. They find significant differences in such expectations and conclude that unless these differences are accounted for, then causal inferences are potentially unreliable due to possible differential placebo effects. Future studies should standardize training tasks to minimize differences in expected benefits or include manipulation checks so that these differences can be statistically accounted for in analysis.

Additionally, researchers have not yet classified video games in a way that fully accounts for titles that blur genre lines. For example, MarioKart is a racing game in which players use various weapons and abilities to disrupt their opponents' progress. Powers et al. (2013) categorized this as a non-action game, along with other sport and simulation games. Yet MarioKart appears to require many of the same cognitive and motoric demands of a traditional action game like Call of Duty. Even two games that are both readily accepted as first-person shooter games within the action genre, like Doom (1993) and *Call of Duty: Ghosts* (2013), have substantial variance in presentation of visual stimuli and in cognitive load. The multi-faceted nature of video games creates difficulties in appropriately categorizing game titles, and may be contributing to contradictory and confusing results in both the cognitive and neurophysiological studies of video games.

Lastly, it is crucial to consider the potential effects of individual differences. Future research should devote more attention to investigating what factors, if any, are more predictive of cognitive enhancement success. Affective domains such as motivation and reward sensitivity are underexplored, and, apart from a few studies (e.g., Erickson et al., 2010; Basak et al., 2011), baseline differences in brain structure and function may be worthy of greater investigation. Individual differences may be mediating and moderating the effects of video game training, and once identified these indirect effects may account for some of the observed heterogeneity in the literature.

Action video games deliver dynamic, multi-sensory stimulation that requires users to navigate tasks that are equally challenging and entertaining. This medium provides not only a unique tool for investigating human cognition and neuroplasticity, but also the means for potentially counteracting cognitive decline and remediating cognitive impairments. Yet such promise and opportunity must not supersede the need for rigorous and unbiased scientific evaluation. Action video game training may indeed lead to enhancements in attention, visuospatial processing, and executive functioning. However, the magnitude and specificity of these effects remain unclear. Future research should not only adopt methodologies based upon best practices from clinical trials, but also incorporate evidence from both behavioral and neurophysiological approaches.

AUTHOR CONTRIBUTIONS

All authors participated in the literature review, drafted the initial manuscript sections with exception to the discussion, and provided critical revisions on the initial draft. Joseph Bisoglio, Timothy I. Michaels, and Joshua E. Mervis wrote the discussion and all authors contributed revisions to the final version of the manuscript, which all authors approved for submission.

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OPINION ARTICLE
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Action game experimental evidence for effects on aggression and visuospatial cognition: similarities, differences, and one rather foolish question

Christopher J. Ferguson *

Department of Psychology, Stetson University, DeLand, FL, USA
**Correspondence: cjferguson1111@aol.com*

Edited by:
Walter R. Boot, Florida State University, USA

Reviewed by:
James D. Ivory, Virginia Tech, USA

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INTRODUCTION

We are beginning to understand that the social sciences often leap beyond the data, ignore null effects and overstate confidence in cherished beliefs (Ioannidis, 2005; Pashler and Harris, 2012). When perceived health of children is involved, this general effect can be exacerbated into *crusade bias;* the tendency to distort, overstate, or misrepresent research findings to lend a veneer of science to a polemic social agenda. That this occurred in the field of media violence has been well established (Savage, 2004; Sherry, 2007; Ferguson, 2013). But, with media, a parallel process which we might call a *savior bias* also emerges in which the media are considered a remarkable game-changer for reinventing society (e.g., McGonigal, 2011).

In a few short years, research on action games and aggression has gone from an "absolute truth" (e.g., American Psychological Association, 2005) to a full-blown replication crisis. In this essay I examine the degree to which the field of action games and visuospatial cognition may run similar risks. I wish to be clear that, in the debate on visuospatial cognition research, I respect researchers on both sides, and I hope that my comments may be viewed as constructive suggestions for improving the field, rather than merely as criticisms. With that in mind, here are several observations.

SIMILARITIES BETWEEN AGGRESSION AND VISUOSPATIAL RESEARCH

EXTERNAL VALIDITY

Both fields rely heavily on outcome instruments that do not transfer well to the real world. The aggression literature has been seriously plagued by this issue for some time (Savage, 2004; Elson, 2011). Regarding visuospatial cognition, many studies examine the influence of action games on interesting but esoteric laboratory tasks of visual attention and processing (e.g., Green and Bavelier, 2006; Blacker and Curby, 2013). It is not clear that the field has made the next step into demonstrating practical value of these laboratory effects. My concern has been exacerbated by difficulty replicating these findings myself using what I considered measures of visuospatial intelligence closer to what parents or policymakers might be interested in (e.g., Valadez and Ferguson, 2012; Ferguson et al., 2013). In fairness, some research has indicated that surgeons who play action games are better at certain types of surgery (e.g., Rosser et al., 2007). Yet it is not clear that how this research can be generalized to outcomes of practical value has been well-delineated.

ADEQUATE CONTROL CONDITIONS

Many video game studies of aggression introduced systematic confounds due to improper control conditions (Adachi and Willoughby, 2011; Elson et al., in press). Studies of visuospatial cognition acknowledge that action games differ from control games on multiple levels such as cognitive load, pace of action, visual demand, and motor load (e.g., Green et al., 2012). Given that most studies of visuospatial cognition employ action games with violence and control games without, violent content is another differing variable. If scholars wish to identify which variables specifically cause gains in visuospatial cognition, a systematic evaluation of games that are matched more closely on relevant variables would be necessary.

UNCLEAR DEFINITIONS

The aggression literature uses the terminology "violent video game" whereas the visuospatial literature prefers "action game" despite studies in both realms mainly employ first-person shooter games. The terms "violent video game" and "action game" remains vague. Overall "action game" is probably preferable for both fields in avoiding unscientific emotional priming. But neither field has clarified which video games are included in such a category. Related to "violent video games," one scholar recently commented during a murder trial that even games such as *Pac Man* could be considered violent video games (Rushton, 2013). Most would consider this absurd, and this is a serious problem of unclear delineations that potentially invite satire. The concept of action game carries less emotional load but remains unclear. Are action games only first-person shooters (the games typically used in experimental studies) or do racing or other high-paced games count?

Dye et al. (2009) make an admirable attempt at defining action games as requiring "rapid processing of sensory information and prompt action, forcing players to make decisions and execute responses at a far greater pace than is typical in everyday life" (p. 321). Yet such a definition could apply equally well to *Frogger* as it does *Call of Duty.* One of the problems with the concept of "violent video games" is that, according the vague definitions in use, *almost all video games are violent video games*. The concept of action video game would do well to avoid this trap.

A MAJOR DIFFERENCE

Research on new media can often be hampered by the presence of bias among groups of scholars. Scholars who are enamored with the potential of new media may experience *savior bias*. Those who are worried about the potential negative impact of new media may experience *crusade bias* (and see Nature, 2003 for relevant comments). These processes can lead scholars, acting in good faith, to overestimate the strength, consistency, and generalizability of effects.

However, one crucial difference is the presence of societal moral panic and political pressure on the aggression agenda that is not present for visuospatial research. For instance, soon after the tragic 2012 Sandy Hook shooting, debate on video game violence which had subsided following the US Supreme Court Brown v EMA (2011) trial (in which the majority decision was highly critical of video game violence research) resumed with furor. Rep. Frank Wolf, a long-term media critic who also chairs the committee overseeing the funding of the NSF, commissioned a report on media violence and youth violence. The resultant report (Subcommittee on Youth Violence, 2013) worked hard to link media violence to mass shootings despite much evidence to the contrary, by not citing evidence conflicting with the authors' personal views. The only exception was Joanne Savage's work, miscited as supporting links between media violence and violent crime, despite that she concluded the exact opposite (Savage and Yancey, 2008). Whether the fault for this study lies with political pressure of Rep. Wolf, or *crusade bias* (and certainly citation bias) of the report authors, such advocacy-toned reports only damage the credibility of our field.

Similarly, policy statements by the American Psychological Association (2005) and American Academy of Pediatrics (2009) have been criticized for significant distortion and misstatements about the available data, typically in the direction of vastly overstating effects (Ferguson, 2013). Such professional advocacy organizations have produced policy statements by allowing scholars heavily invested in the "harm" position to review their own research and declare it beyond further debate. Given controversies over past policy statements and new research, the APA has agreed to revisit its media policy statements, which is a welcomed move. However, the committee assigned to do so consist of a majority of scholars who had taken public anti-media positions in the past. Of a total of seven, two task force members signed an amicus brief supporting the regulation of violent video games in Brown v EMA (2011), and two others have both worked closely with scholars who had helped write the previous policy statements under contention and made anti-media statements in news interviews in the past (including one who coauthored the NSF report discussed above). This tells us something crucial about policy statements: they often inform us more about the committees that write them than they do about science. Although I don't know the thinking and motives of the APA, the failure of the APA to ensure a neutral review *despite specifically being asked to do so* involves a fundamental failure of the APA policy review process, perhaps due to being overly sensitive to social moral panics and political pressure. As a consequence, a consortium of approximately 230 scholars wrote to the APA asking them to refrain from further policy statements on media and to retire their old and misleading policy statements (Consortium of Media Scholars, 2013). Psychological science must become more informed about how societal moral panics have influenced statements by scholars ranging from the 1950s comic books scare, through participation in the 1980s "Tipper Gore" hearings, to the faulty policy statements of more recent decades.

I wish to remain as positive as I possibly can and infer that these errors are the result of good faith confusion of an advocacy agenda for science. However, it becomes difficult not to see deliberate misinformation in some of these efforts. Citation bias can be a good faith result of familiarity with only certain work, or confirmation bias to which all people are prone (and I claim no exception). However, persistence in citation bias despite a history of the field being warned that it is a problem becomes more difficult to excuse as good faith. Whatever the limitations of the visuospatial cognition research may be, I see no evidence that scholars in this field have confused, purposefully, or accidentally, a cultural agenda with science, nor have I found evidence of misleading claims by scholars in this area. This may be a single difference but a critical one; one that is the distinction between science and pseudo-science.

ONE RATHER FOOLISH QUESTION

Sometimes I hear the question "If action games increase cognition, why can't they also increase antisocial behavior?" This question has common sense appeal, particularly for people in the general populace. But I refer to it as a "foolish question" because it is a question scientists should know better than to ask. That is because the question is a rather obvious logical fallacy, particularly when used to affirm a premise in that it relies on *false equivalence.* The logic of this question is:

If A then B; A; hence C.

The essence of this question (it is in fact an example of begging the question as the premise of the conclusion is critical to the question itself) is the assumption that B and C (visuospatial cognition and antisocial behavior) are equivalent. If they are equivalent, then action games effect on one should be similar as to the other. However, there is little reason to suspect that the processes that drive visuospatial cognition are equivalent to those for anti-social behavior and many reasons to suspect otherwise. Visuospatial cognition involves a straightforward cognitive practice effect, requiring no fundamental changes in personality or motivation. By contrasts advocates for action game influences on antisocial behavior have specifically posited exactly those fundamental changes to personality or motivation. For instance, Anderson and Dill (2000) suggest "If repeated exposure to violent video games does indeed lead to the creation and heightened accessibility of a variety of aggressive knowledge structures, *thus effectively altering the person's basic personality structure*, the consequent changes in everyday social interactions may also lead to consistent increases in aggressive affect" (p. 788, Italics added for emphasis). Given that the theoretical mechanisms for these two processes differ, there is no reason to assume equivalence.

Further on a more basic level, media effects are not "one size fits all" (a similar question based in false equivalence is the comparison of fictional media effects to advertising). Each individual hypothesized effect must be studied independently. Assumptions that seeing one effect must mean that all effects are true are likely to lead to gross errors and distortions within the field. In the end visuospatial cognition effects may or may not be true, and aggression effects may or may not be true, but these two sets of hypotheses must be tested independently.

CONCLUDING REMARKS

Studies of video game effects over the past few decades have labored under the cloud of social narratives regarding video games' place in society. Outcomes related to video game influences on visuospatial cognition (Boot et al., 2011) and aggression (Adachi and Willoughby, 2012) have received criticism for their methodological limitations and, perhaps, tendency to overspeak the data. Such criticisms are likely to be disappointing for researchers in the field, but they can also serve for impetus for better studies. Criticism and skepticism is an essential part of the scientific process. Fields that embrace this as part of the natural scientific process will survive. Those that do not will collapse under the weight of their own ideology.

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Just how expert are "expert" video-game players? Assessing the experience and expertise of video-game players across "action" video-game genres

Andrew J. Latham[1,2]*, Lucy L. M. Patston[3] and Lynette J. Tippett[4,5]

[1] Department of Philosophy, The University of Sydney, Sydney, NSW, Australia
[2] Brain and Mind Research Institute, The University of Sydney, Sydney, NSW, Australia
[3] Department of Osteopathy, UNITEC Institute of Technology, Auckland, New Zealand
[4] School of Psychology, The University of Auckland, Auckland, New Zealand
[5] Centre for Brain Research, The University of Auckland, Auckland, New Zealand
*Correspondence: alat6470@uni.sydney.edu.au

Edited by:
Walter R. Boot, Florida State University, USA

Reviewed by:
Walter R. Boot, Florida State University, USA

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Video-game play (particularly "action" video-games) holds exciting promise as an activity that may provide generalized enhancement to a wide range of perceptual and cognitive abilities (for review see Latham et al., 2013a). However, in this article we make the case that to assess accurately the effects of video-game play researchers must better characterize video-game experience and expertise. This requires a more precise and objective assessment of an individual's video-game history and skill level, and making finer distinctions between video-games that fall under the umbrella of "action" games. Failure to consider these factors may partly be responsible for mixed findings (see Boot et al., 2011).

ASSESSING VIDEO-GAME EXPERIENCE AND EXPERTISE

Current cross-sectional research investigating video-game play has relied on self-reports in order to distinguish expert video-game players (VGPs) from non-VGPs. Participants who report playing "action" video-games (e.g., Bialystok, 2006; Dye et al., 2009; Dye and Bavelier, 2010) for multiple hours per week, 6 months to a year prior to testing (e.g., Green and Bavelier, 2003; West et al., 2008; Hubert-Wallander et al., 2011) are classified as expert VGPs. Those who report no video-game play in the same period are classified as non-VGPs. Current criterion, however, fail to appreciate the significant difference between VGPs who have played for 5 h per week over the past 6 months and those who have played for 20+ h per week over the past 10 years (whom, in addition, would be classified as non-VGPs if currently abstaining from video-game play).

The purpose of cross-sectional research is to test the limits to which perceptual and cognitive processes may or may not be impacted by video-game play, while training studies using appropriate controls establish causal relationships between those differences and video-game play (see Boot et al., 2013). Unfortunately, the assumption that recent video-game experience reflects expertise is mistaken. There is no guarantee that VGP participants used in most current research papers possess either the experience or expertise necessary to be classified as expert VGPs. Similarly, there is no guarantee that individuals classified as non-VGPs, in their past, do not possess the relevant experience or expertise that would qualify them as expert VGPs. The misclassification of expert VGPs, non-VGPs or both, may be the basis of null results in the video-game literature (e.g., Murphy and Spencer, 2009; Irons et al., 2011), and other studies that have not been published.

A few early studies classified participants as expert VGPs and non-VGPs based on performance in a screening video-game (Greenfield et al., 1994; Sims and Mayer, 2002). As long as experimenters are able to set the appropriate performance threshold this is a valid method of classification. There is, however, a simpler method, used in other areas of expertise research (i.e., musical performance) that assigns expertise on the basis of professional attainment (i.e., highest instrument grade attained) and some objective assessment of their skill (i.e., achievement, awards or rankings). Similar measures of expertise are often freely available to video-game researchers on the internet and VGPs' in-game statistics. Level of professional attainment in video-game play can be assessed through placings in open tournaments and leagues, and qualifying, or being invited, to compete in closed tournaments and leagues. Like other competitions, video-game contests occur at a local, regional, national and international level, with each subsequent level representing higher levels of attainment.

Objective measures of video-game expertise are commonly available in the form of skill ratings and ladder rankings (based on the ELO system used in Chess) found in-game or online. For example, *Guild Wars 2* and *World of Warcraft* maintain ratings and rankings of individual players and teams. Some video-games do not assign exact ratings or rankings, but instead assign a token which represents skill level. For example, *Counter Strike: Global Offensive* assigns players one of 18 emblems ranging from Silver I to The Global Elite. Meanwhile, in *Starcraft II*, players are divided into different competitive tiers. The top 200 players on a server are in the Grand

Master League, followed by the next 2% in the Master League and next 18% in the Platinum League. This is followed by Diamond, Gold, Silver, and Bronze, respectively. Finally, in some video-games, such as *Defense of the Ancients II*, ratings and rankings are maintained openly by online communities (e.g., *joinDota*, *GosuGamers*).

While video-game experience is not well suited to assigning expertise, it can highlight the qualitative and quantitative features of video-game engagement that may underlie expertise and its development. For example, Ericsson et al. (1993) used a diary study with musicians and found expert musicians engaged in more "deliberate practice" than non-experts. Deliberate practice refers to structured task rehearsal for the sake of improving performance, and is contrasted with "play" which is task immersion for the sole purpose of enjoyment. While many people play video-games, very few deliberately practice them. Engaging in deliberate practice is almost certainly also a characteristic feature of video-game expertise, however, video-games' success may come from an ability to blur the lines between deliberate practice and play.

Other relevant features of video-game experience include length of experience and the age at which they began gaming (e.g., Latham et al., 2013b). Unfortunately, potential variability in video-gaming histories increases the complexity of both variables. As a result, length of experience and age began might also be better understood in terms of play and deliberate practice. For example, a VGP may begin regular play during childhood, play more regularly and begin deliberate practice during adolescence, and then cut back to irregular play during tertiary study. Expertise-related changes are likely to reflect not just the accumulation of video-gaming experience but the nature of that experience as well, especially during formative years. The human brain is most malleable during childhood and adolescence (Freitas et al., 2011), thus perceptual, cognitive and neural changes resulting from intensive training (be it video-game, music or some other expertise) may be more likely during this period.

TEASING APART MAJOR "ACTION" VIDEO-GAME GENRES

Video-game researchers have largely restricted interest to the link between "action" video-game play and, perceptual and cognitive performance. The term "action," however, actually refers to a vast array of different video-game genres. Early video-game researchers noted the significance of video-game type, showing that while spatially-orientated video-games enhanced visual cognition, non-spatially orientated games did not (e.g., Subrahmanyam and Greenfield, 1994; De Lisi and Wolford, 2002). Surprisingly, the importance of video-game genre has only recently been made apparent with real-time strategy (RTS) games shown to extend beyond the traditional results of enhanced visual cognition to improve higher order cognitive abilities, such as working memory and cognitive flexibility (e.g., Basak et al., 2008; Glass et al., 2013).

Briefly we highlight four major subgenres that support international competition. These genres are: first-person shooters (FPSs), RTS, action RTS, and massively multiplayer online role-playing games (MMORPG). It is important to note that the complexity of these genres is greater than can be highlighted here (i.e., team roles, play-styles, meta-game), which may help shape specific perceptual and cognitive demands. In addition, there are many other "action" video-game subgenres (i.e., driving, sport) with unique demands and potential to provide different sets of enhancements to players.

In RTS games players take control of a race, continually create, and utilize worker units to obtain resources, create, and expand a base, and create and improve combat units. Using combat units, players must destroy opponents or force them to concede. Countless combinations of build orders and unit combinations exist, which must be performed, controlled and adjusted in real-time against opponents. Success is reliant on the ability to assess, update and plan the most efficient series of mechanical responses. During professional *Starcraft II* play, players commonly execute up to 250 actions per minute, increasing to over 300 during combat. Other RTS games can have additional layers of complexity through the alternative victory conditions. For example, in *Civilization V* players can actively obtain victory through science, culture and diplomacy. Given these demands it is unsurprising RTS games may emphasize and enhance executive processes.

The term "action," when used by researchers, however, has typically referred to FPSs. Players aim a targeting reticule at opponents and click in order to eliminate them. Success is dependent on the ability to make rapid visual judgments and responses. Although the executive demands are lower in FPSs than in RTS games, the demands on speed and accuracy of visual abilities are far higher. Many FPS games are objective and team-based (i.e., *Counter Strike: Global Offensive*) and include vehicles (i.e., *Battlefield 3*). However, even with these additions, success is still highly dependent on the speed and accuracy of basic visual and motor processes.

Action real-time strategy (ARTS) games arose from RTS games whereby players control a single unit with a handful of unique abilities called a "hero." Often there are hundreds of unique heroes to choose from (e.g., *League of Legends* has 115 heroes and *Defense of the Ancients II* has 102). In a game, two teams of five players fight alongside waves of computer-controlled units in order to destroy the opponent base. Eliminating enemy heroes and units confers experience and currency. Experience allows heroes to gain levels which make them more powerful and grant skill points which are used to learn and improve skills. Currency is spent on items that either make a hero more powerful and provide additional skills, or supports the team by granting map vision, temporary invisibility, or revealing hidden units.

The competitive player-vs.-player element of many massively MMORPG shares some similarities with ARTS games. Players control a hero who has a whole pool of unique abilities to choose from rather than only a handful. Furthermore, "talent systems" allow players to customize their hero according to their specifications. However, unlike ARTS games, skills, talents, and items are selected prior to competing. With large pools of heroes, items, and abilities, the numerous possible combinations make each game played potentially unique. Success in ARTS and MMORPGs is reliant on ability to rapidly assess opponent hero roles and actions from visual cues. The specific perceptual and cognitive demands are roughly an intermediary between the RTS and FPS genres.

While there is undoubtedly a large overlap between the skills required to succeed across video-game genres (e.g., the ability to perform precisely timed bi-manual movements in response to complex visual cues), each genre typically has unique perceptual and cognitive demands necessary for success. Specific enhancements may result from these demands. Distinctions between genres are, therefore, of particular importance to researchers conducting training studies and those who wish to target specific abilities.

Researchers investigating expert VGPs typically provide lists indicating the "action" video-games participants report playing, with little appreciation given to the breadth of genres shown. Breadth itself may be another characteristic trait of experts, as the unique capabilities trained by specific tasks in a domain are likely to be advantageous to general performance within the domain as a whole. For expert VGPs, the unique capabilities trained by specific genres are likely to benefit video-game performance in general, and those with greater breadth may also tend to show greater expertise. As a result, the genre of video-games played needs to be considered in conjunction with video-game experience (see Assessing video-game experience and expertise).

Understanding the extent to which video-game play can shape perceptual and cognitive abilities requires testing expert VGPs. Current research, however, mistakenly classifies participants as expert VGPs using only a limited assessment of recent video-game experience, hindering progress in the field. While knowledge of a participant's video-game experience is incredibly useful, it cannot be used to definitively assign expertise. Proper classification of expertise requires the use of professional attainment, objective performance measures, or both. Once expertise has been correctly assigned, differences in experience between experts and non-experts may highlight factors, or combinations of factors, that promote the development and maintenance of expertise. Perhaps more significantly, it may reveal the key/s to shaping perceptual and cognitive processes.

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Uncovering mechanisms in video game research: suggestions from the expert-performance approach

Tyler J. Towne*, K. Anders Ericsson and Anna M. Sumner

K. Anders Ericsson Laboratory, Department of Psychology, Florida State University, Tallahassee, FL, USA
**Correspondence: towne@psy.fsu.edu*

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Árni Kristjánsson, University of Iceland, Iceland

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In the United States, video game playing is an immensely popular form of entertainment; the majority of adults will have had some experience with video games during their lives (Rideout et al., 2010). As the popularity of video games in entertainment has increased, so has interest in exploring the potential effects that video games may have on learning and generalizable cognitive ability. Educators have begun to seek a way to use video games as a tool to motivate students to learn academic skills (Blumberg, 2014). Despite general enthusiasm for video games as an avenue for training, there are shortcomings in the methodology commonly used to demonstrate the advantages of video game experience (See Boot et al., 2011; Kristjánsson, 2013). Additionally, few studies have sought to evaluate video game skill in the context of established research on skill acquisition in more traditional domains. This paper attempts to connect research on expertise with the claims being made in video game studies. Particularly, we discuss how the expert-performance approach can be used to describe video game performance and the mechanisms that are responsible for increases in skill as well as for potential transfer. We will also discuss how the design of traditional "casual" video games may be inconsistent with principles of skill acquisition through deliberate practice that has been documented in many other domains (Ericsson et al., 1993; Ericsson, 2006a).

USING THE EXPERT PERFORMANCE APPROACH TO EVALUATE SKILL AND TRANSFER IN VIDEO GAMES

The expert-performance approach necessitates that researchers proceed through a series of steps. The first step requires demonstrating that some individuals are able to perform on a reproducibly superior level than others, when presented with a standard domain-representative task. For example, studies have demonstrated that after video game training, typically lasting 10–40 h, non-gamers show reliable individual differences in performance when they play the game "Space Fortress" (Green and Bavelier, 2006; Basak et al., 2008). One problem with analyzing these individual differences in total score on the game is that, based on the selection of the first few actions, participants will encounter very different problem spaces and thus their outcome scores are not comparable. For example, the differences in total score could depend on differences in strategies, speed and accuracy, perceptual-motor implementations, or other general abilities.

The methodology of the expert-performance approach remedies this issue by identifying a number of situations from a game environment where one would present participants with the task of executing an immediate short sequence of actions. This method (Ericsson and Smith, 1991; Ericsson, 2006b) was derived from de Groot's (1978) work in chess where he presented players with challenging chess positions and required that they select the best subsequent move. By using a standard representative task, it becomes possible to compare individuals of different skill levels within a narrowly defined problem space. Additionally, by limiting analyses to a small subset of these representative tasks, it becomes theoretically easier to understand the structure and underlying mechanisms supporting subjects' performance. This approach has been used to describe mechanisms of skill in soccer (Ward et al., 2013), snooker (Abernethy et al., 1994), SCRABBLE (Tuffiash et al., 2007), and typing (Keith and Ericsson, 2007), among others. Video game environments can be limited in such a way that small snapshots of video game performance can be isolated from the larger game in order to present players with consistent scenarios such that differences between more and less skilled subjects can be identified.

Once performance on a set of representative tasks has been measured, the expert-performance approach attempts to trace the processes mediating the superior performance. The most influential method involves collecting concurrent and retrospective verbal report data (Ericsson, 2006b) from participants during performance on representative tasks. The methods of concurrent and retrospective verbalization draws on fundamentally different cognitive processes for their generation than the less successful traditional interviews with experts to extract rules for expert systems (Ericsson and Simon, 1993; Fox et al., 2011). For example, Moxley et al. (2012) analyzed think aloud protocols of chess players selecting moves to assess intuition's role in generating superior moves by highly rated players. There has also been studies collecting think aloud verbalizations while playing entire games (Blumberg et al., 2008; Blumberg and Randall, 2013).

Significant work has been done designing experimental manipulations that interfere with task performance to test hypotheses about the mediating processes revealed by verbal reports. For example, individuals with exceptional memory have had their memory performance reduced to the level of college students by manipulating the material and conditions of memorization (Ericsson and Polson, 1988; Ericsson et al., 2004; Hu et al., 2009; Hu and Ericsson, 2012). Based on verbal reports collected from representative situations in particular video games, it should be possible to generate experimental manipulations that would interfere with the processes reported by systematically changing the game environment. Finally, one would attempt to trace the development and acquisition of the various mechanisms that are found to mediate the superior performance and assess the role of prior deliberate practice and innate talents in their development.

By using the expert-performance approach to systematically evaluate the nature of skill in video games, researchers can begin to make more specific hypotheses about the mechanisms that account for findings of generalizable transfer. By using this approach in other domains, studies have found that skills previously explained by generalizable mechanisms are instead the result of the accumulation of highly domain-specific cognitive structures (Ericsson et al., 1980, 2004; Ericsson and Kintsch, 1995). Additionally, the expert-performance approach will allow video game researchers to objectively quantify skill by implementing the use of standard representative tasks, where traditionally, they have relied on a gamer vs. non-gamer distinction (cross-sectional) or total game score (longitudinal) when making claims about the cognitive advantages of skilled video game players.

VIDEO GAMES AS TRAINING TOOLS

Studying video game performance is particularly appealing to researchers because, traditionally, games have been explicitly designed to keep players' attention, maintain an enjoyable level of challenge, and lead to continued improvements across many hours of play to give a sense of accomplishment. We are particularly interested in contrasting skill acquisition in popular video games to more traditional domains where effective practice activities have been identified. Studies have discovered a pattern of behaviors, known as deliberate practice, in areas such as music, chess, and sport that are highly predictive of skilled performance (Ericsson et al., 1993). Deliberate practice is defined as the engagement, with full concentration, in a training activity designed to improve a particular aspect of performance with immediate feedback, opportunities for gradual refinement by repetition, and problem solving.

Effective practice activities should be designed to foster continued development. In areas such as driving, typing, and recreational sports, an adequate level of performance is reached, productions are automated, appropriately challenging situations are not sought, and improvement is arrested (see **Figure 1**). In competitive games, such as baseball, chess, and soccer, the level of challenge typically increases as the participating individuals improve their skill. One of the key characteristics of traditional video games is that the difficulty level of a game is adjusted as the player masters a given level and progresses to the next. This adaptable level of difficulty gives the player an appropriate sense of challenge and interest and the change in difficulty is often associated with the introduction of new and unfamiliar environments.

Many solitary videogames will allow the player to pursue a path until they are not able to handle a situation, at which point they are reset to the beginning of the current level. In the past, this meant that players would spend much of their time re-tracing steps until returning back to the challenging situation, an act unrelated to skill acquisition. More recent games have built in mechanisms to "save" a game before reaching a challenging point so that the mastered parts of a level would not need to be retraced. It would therefore be interesting to analyze the amount of time that a player engages in activities successfully (positive feedback), as well as how often they fail (negative feedback), and the associated competitive outcomes.

Ericsson et al. (1993) found that individuals enjoyed successfully playing music, soccer and baseball games, and chess matches. However, the time spent in these types of successful performances were not associated with engagement in activities that are designed to maximize learning. To apply what we know about deliberate practice to video games, one would have to look for specific challenges encountered in games where players have the option to replay these situations either through a "rewind" or "save" mechanism. Players would then be able to replay the challenge repeatedly until they feel they had mastered the situation.

When Ericsson et al. (1993) studied how highly skilled individuals spent their time improving their skills, they engaged in exactly this type of deliberate practice. A music student encountering a problem with one section of a piece of music would not simply rehearse the piece again and again, he or she would focus on the difficult part and repeatedly work on

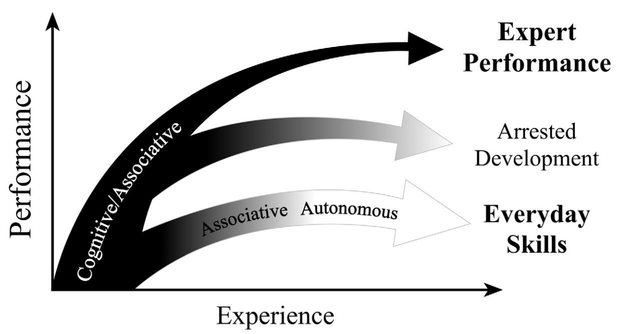

FIGURE 1 | An illustration of the qualitative difference between improvement of experts and those engaging in a domain recreationally. The goal for casual players is to quickly reach a satisfactory level that is stable and "autonomous," at which point, positive feedback is a much more common than negative feedback. In contrast, expert performers counteract automaticity by developing increasingly complex mental representations to attain higher levels of control of their performance. Therefore, they remain in the "cognitive" and "associative" phases. Some experts will, at some point in their career, stop engaging in deliberate practice and prematurely automate their performance. (Adapted from "The scientific study of expert levels of performance: General implications for optimal learning and creativity" by K. A. Ericsson in High Ability Studies, 9, p. 90. Copyright 1998 by European Council for High Ability).

mastering just that section before returning to the entire piece. Similarly, skilled chess players study positions from games of chess masters to find the best move. Once they have generated their best move for the position they can compare their move to the chess master's selected move during that game. This gives immediate feedback instead of completing a chess game across several hours and then trying to identify where they could have selected a better move.

Deliberate practice requires that individuals engage in training at the limits of their ability, where they often fail. It is not as enjoyable as tasks, like play, where performance can be generated easily and effortlessly. One method to make the activity attractive is to mix a short duration of deliberate practice (10–15 min for beginners) with the majority of time being spent on play. Many video games are structured in a similar manner by having the player spend most time on already mastered activities until they reach challenges, but after a few they are sent back to familiar territory.

Video games offer researchers an opportunity to study skill development in a relatively well-controlled environment, where they can manipulate specific parameters of the game. It is relatively easy to maintain a minimum level of experimental control and log data in such a way that specific behaviors can be isolated and related to subsequent performance gains. However, it is difficult to draw generalizable conclusions about the nature of skill development when examining games in which positive feedback outweigh the instances of negative (i.e., casual games).

CONCLUSIONS

We believe that applying the expert-performance approach to skill in video game environments is essential for understanding the mechanisms of superior performance as well as the shared components that may eventually account for discovered correlations between video games and general ability measures. Furthermore, we believe that it is unlikely that classic game environments are optimally designed to foster continued improvement in an ecologically valid way.

Many of the video games that have been proposed in the literature as vehicles for academic and real-world improvement are those such as Space Fortress, Medal of Honor, Rise of Nations, and Tetris that seem to be highly self-motivating, primarily because they give more positive feedback than informative negative feedback. We argue that meaningful improvement is only achieved through principles of deliberate practice, which include negative feedback (i.e., failures), and that many traditionally studied games do not adequately incorporate these components. Superior skill is the product of many years and decades of intense training under conditions that are very different from those in a typical video game. If meaningful real-world tasks were designed like a casual or recreational video game environment, it is unlikely that individuals would improve beyond a relatively low and automated state, which is the observed outcome of extended experience in most professional environments (Ericsson, 2006a). As with any proposed training regimen, video game training must be systematically evaluated against alternatives. Our assertion is that the very components of video games that make them uniquely motivating, are antithetical to the deliberate practice. Additionally, only through systematic detailed descriptions of individuals' behavior and acquired skills can we begin to hypothesize about the role that acquired performance in video games might benefit cognitive development in schools and everyday life.

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