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Intensive video gaming improves encoding speed to visual short-term memory in young male adults

Inge L. Wilms [a,b,*], Anders Petersen [c], Signe Vangkilde [c]

[a] Department of Psychology, University of Copenhagen, Denmark
[b] Center for Rehabilitation of Brain Injury, University of Copenhagen, Denmark
[c] Center for Visual Cognition, Department of Psychology, University of Copenhagen, Denmark

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ABSTRACT

The purpose of this study was to measure the effect of action video gaming on central elements of visual attention using Bundesen's (1990) Theory of Visual Attention.

To examine the cognitive impact of action video gaming, we tested basic functions of visual attention in 42 young male adults. Participants were divided into three groups depending on the amount of time spent playing action video games: non-players (<2 h/month, N = 12), casual players (4–8 h/month, N = 10), and experienced players (>15 h/month, N = 20). All participants were tested in three tasks which tap central functions of visual attention and short-term memory: a test based on the Theory of Visual Attention (TVA), an enumeration test and finally the Attentional Network Test (ANT). The results show that action video gaming does not seem to impact the capacity of visual short-term memory. However, playing action video games does seem to improve the encoding speed of visual information into visual short-term memory and the improvement does seem to depend on the time devoted to gaming. This suggests that intense action video gaming improves basic attentional functioning and that this improvement generalizes into other activities. The implications of these findings for cognitive rehabilitation training are discussed.

1. Introduction

It is by now generally accepted that the mature brain may adapt in response to training (e.g. Nudo, 2007; Nudo & Duncan, 2004; Pulvermüller & Berthier, 2008; Sunderland & Tuke, 2005; Taub & Uswatte, 2006; Wilson, 2008) and to changes in stimuli (e.g. Frassinetti, Angeli, Meneghello, Avanzi, & Ladavas, 2002; Redding, Rossetti, & Wallace, 2005; Serino, Bonifazi, Pierfederici, & Ladavas, 2007; Wilms & Malá, 2010). Indeed the conditions of experience-based stimulation which activate plastic processes in a mature brain are fairly well understood (Kleim & Jones, 2008), as are the general response patterns of the neurobiological web of neurons, axons and dendrites to increased or decreased activity (Brown, Kairiss, & Keenan, 1990; Cooper, 2005; Pulvermuller, 1996). However, the extent to which it is possible to actually change or improve basic elements of visual attention and the potential impact of these changes are less well-described.

A series of recent studies has indicated that playing high-action video games (video games in this context refer to games played on gaming consoles and PCs) may alter or improve aspects of the player's visual attention capacity (e.g. Achtman, Green, & Bavelier, 2008; Chisholm, Hickey, Theeuwes, & Kingstone, 2010; Green & Bavelier, 2003; Green & Bavelier, 2006a, 2006b, 2007; Spence & Feng, 2010; Tahiroglu et al., 2010). Since 2003, Green and Bavelier have investigated the effect of long term video gaming on various aspects of visual perception and attention. They have demonstrated that action video gaming modifies visual selective attention (Green & Bavelier, 2003), that video game players (GPs) are faster at locating targets (Green & Bavelier, 2006b) and better at correctly estimating a number of briefly flashed targets (Green & Bavelier, 2006a). In addition, they have demonstrated that experienced GPs show improved spatial resolution allowing them to maintain the same level of performance when reducing the spatial separation between targets (Green & Bavelier, 2007). Others have shown that video gaming improves contrast sensitivity (Li, Polat, Makous, & Bavelier, 2009) and the control of selective attentional switching in avid gamers compared to non-gamers (NGPs) (Karle, Watter, & Shedden, 2010). Green and Bavelier (2003, 2006a, 2006b, 2007) has even demonstrated that NGPs may obtain nearly the same level of proficiency as GPs within areas of perception and attention after playing video games for a fairly brief period of time (10–50 h). However, other

* Corresponding author at: Department of Psychology, University of Copenhagen, Øster Farimagsgade 2A, DK-1353 Copenhagen K, Denmark. Tel.: +45 35324866; fax: +45 35324802.
E-mail address: inge.wilms@psy.ku.dk (I.L. Wilms).

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areas, like change blindness, seem unaffected by training (Durlach, Kring, & Bowens, 2009). Other studies have failed to reproduce difference in temporal attention and useful field of view, suggesting that some of the observed differences in gamers and non-gamers may not be entirely due to gaming (Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Murphy & Spencer, 2009). Also, the ability to inhibit attention to previously attended locations seems similar in gamers and non-gamers (Castel, Pratt, & Drummond, 2005). In general though, not only do action video games increase attention capacity in experienced game players, gaming also seems to improve this capacity after a fairly short training period in people who do not normally play video games.

One method employed by Green and Bavelier (2006b) is a comparison of the performance of game players (GPs) to non-game players (NGPs) in an *enumeration test*. In this experimental paradigm, participants are asked to do a fast estimation of the number of items flashed briefly on a computer screen. Participants are usually able to estimate 1–3 items correctly, but increasing the complexity (i.e., the number of items shown) above 3 items gradually decreases the accuracy of their estimates (Trick & Pylyshyn, 1993, 1994). Plotting the mean accuracy for each display size produces an almost horizontal curve for the first 1–4 items, which then drops with a monotonic decrease indicating that accurate responses depend on a limited resource. The first part of the curve is usually said to reflect the *subitizing range* and the second part the *counting range* implying that dissimilar estimation strategies are used depending on the number of items presented (Trick, 1992, 2005; Watson, Maylor, & Bruce, 2005). According to Trick and Pylyshyn (1994), several theories have been proposed to explain this apparent switch in strategy, some focusing on spatial density, others on pattern recognition and working memory size.

In their 2006 study, Green and Bavelier concluded that playing action video games enhances the number of items that can be apprehended and that this change is mediated by changes in visual short-term memory skills (Green & Bavelier, 2006b; Hubert-Wallander, Green, Sugarman, & Bavelier, 2011). However, as they point out, the differences may be due to other aspects of visual short-term memory. As it is not generally agreed that the subitizing range directly reflects the capacity of visual short-term memory, we wanted to use an alternative test based on the Theory of Visual Attention (Bundesen, 1990; Bundesen, Habekost, & Kyllingsbæk, 2005). This test measures the unspeeded report accuracy as a function of exposure duration. The obtained performance measures can be modeled computationally allowing us to quantify changes in the basic components of visual attention independently from changes and improvements in the motor system. An additional advantage of the TVA-based test is that it allows us to estimate several basic elements of attention from the same set of trials.

By comparing the results from the enumeration test with TVA-based estimates of visual attention, we hope to determine two things: 1) if it is possible to use the enumeration test to estimate the capacity of visual short-term memory and 2) if this estimate compares to the visual short-term memory capacity of the TVA test.

2. Purpose

The purpose of this study was to analyze the effect of playing intensive computer-based action games on basic elements of visual attention capacity using the Theory of Visual Attention (TVA) as a theoretical and computational framework. The intention was to determine if the superior visual performance observed in gamers was due to improvement of visual short-term memory or changes in other aspects of visual attention.

3. The TVA model

TVA is a formal computational theory in which attention is described as a selection process, that allows us to encode the information currently most relevant for behavior (for a comprehensive account see Bundesen, 1990). According to TVA, visual selection progresses as a parallel processing race in which possible categorizations of the objects in the visual field compete for access to a visual short-term memory (VSTM) with a limited capacity of K objects (K being one of the basic parameters of the model). This limitation entails that only the first K objects finishing the processing race will be selected and encoded into VSTM to become available for later consciousness and action. However, in line with the ideas of Desimone and Duncan (1995), the race is seen as a biased competition in which the chances of finishing first are not equal for all objects and categories. Both the sensory evidence of certain categorizations, attentional weights, and subjective attentional biases influence the probabilities of encoding certain objects and categories.

Encoding into VSTM proceeds in two stages: In the first stage, every object in the visual field is assigned an attentional weight, which reflects the strength of the sensory evidence that the object is relevant. In the second stage, the total processing capacity of the visual system is distributed among the objects in proportion to their attentional weights. The capacity allocated to a particular object determines how fast this object is processed and how likely it is to become encoded into VSTM. In TVA, the total processing capacity of the visual system is assumed to be a constant, independent of the number of objects in the stimulus display. The value of this constant, C (elements per second), is also a basic parameter of the model. In mathematical terms, the processing speed at which an object x in the visual field race toward VSTM is given by:

$$v_x = C\frac{w_x}{\sum_{z \in S} w_z}$$

C is the total processing capacity and w_x is the attentional weight of object x which is divided by the sum of attentional weights across all objects in the visual field, S.

Different parameters quantifying attentional functions can be derived depending on the specific TVA-based experimental paradigm used. We employed the *CombiTVA paradigm* (see Section 4.3.1 and Vangkilde, Bundesen, & Coull, 2011) from which we estimated four distinct components of attention: (1) K, the capacity of visual short-term memory measured in number of letters; (2) C, the speed of visual processing measured in letters per second; (3) t_0, the temporal threshold of conscious perception measured in milliseconds (see Fig. 4 for a graphical illustration); and finally (4) α, the top–down controlled selectivity defined as the ratio between the attentional weight of a distractor w_D and the attentional weight of a target w_T. That is $\alpha = \frac{w_D}{w_T}$. In this definition α-values close to zero reflect efficient selection of targets whereas values close to 1 indicate no prioritizing of targets compared with distractors.

In contrast to most computerized attention tests, TVA-based assessment uses unspeeded, accuracy-based measures, which makes it possible to characterize different aspects of attention avoiding confounding impact from motor components. This is particularly important when investigating effects of training or specific conditions (e.g. brain injury or neuropsychiatric disorders) which might affect both perceptual and motor functioning. TVA has been used to successfully account for a range of behavioral and neurophysiological attentional effects (for a review, see Bundesen & Habekost, 2008), and the theory provides a theoretical and empirical framework for investigating and explaining attention in both normal subjects (Finke, Bublak, Dose, Müller, & Schneider, 2006; Jensen, Vangkilde, Frokjaer, & Hasselbalch, 2012; Vangkilde et al., 2011) and in patients (Bublak et al., 2005; Bublak, Redel, & Finke, 2006; Duncan et al., 1999; Habekost & Rostrup, 2006, 2007; Redel et al., 2010).

4. Method

4.1. Participants

42 young men aged 16–19 ($M_{age} = 17.5$, $SD = 0.15$) were recruited from high schools in the wider Copenhagen area. They were matched on socio-economic factors such as parent education and income, standard of living, and sports activities. All participants had normal or corrected-to-normal vision. Before entering the study, participants above 18 years signed an informed written consent. Parents or guardians were asked to sign the letter of consent for participants under the age of 18. At the day of testing, before the actual tests, all participants filled out a questionnaire about action gaming habits, general computer usage, reading habits, sports activities, drug use and other factors which might influence their visual attention performance. After completing the tests, all participants received a gift card of 350 DKK as a token of appreciation.

The participants were divided into three groups based on their action gaming habits for the past 6 months: *Experienced players* (n = 20) were defined as those playing action games for more than 15 h a month. Only one person in this group specified a minimum of 15 gaming hours per month. The 19 others specified gaming habits ranging from a minimum of 30–120 h per month. *Casual players* (n = 10) played 4–8 h a month and *Non-players* (n = 12) less than 2 h per month. The calculation on action gaming time was done based on two questions, 1) how frequently they played and 2) how long time per instance. In the *non-player group*, seven participants indicated spending less than 2 h a month and five indicated 0 h playing action games. Other studies have specified various criteria for this group ranging from "0 h/week" (Green & Bavelier, 2007) to <5 h/week (Li et al., 2009). As a precaution, all participants were asked to specify the games they play to ensure that gamers did in fact play action video games.

We specifically chose this age group of young males to try to control for as many factors as possible. The total group is therefore very homogenous in terms of socio-economic status, age and other habits than gaming. Since we wanted to detect changes in the performance of elements of visual attention, we aimed for a larger difference in hours played per month for the past 6 months between gamers and non-gamers compared to other studies. However, when comparing our results to those of older studies, it must be pointed out that visual stimulation has intensified compared to a decade ago and that demands on the visual attention system is generally high even in subjects not playing action video games.

4.2. Action video games

Action video games require fast reaction to multiple visual stimuli in a real time gaming environment. Their user interface presents the gamer with a live action movie-type screen play as well as a multitude of support menus which assist the player in switching weapons, locate whereabouts in the game world and get the status of game characters controlled by either the computer or by fellow players. Examples of action games include:

- Counterstrike
- Call of Duty: Modern warfare II
- Left 4 Dead II
- Bad Company II
- Medal of Honor
- Gears of War
- Crysis
- Halo reach
- Red Dead Redemption—expert level

To ensure that the participants' specification on gaming habits, including time played, was related to action games, they were asked to specify a list of their favorite action games.

We included subjects playing action video games on PCs and consoles such as Microsoft XBOX/360 ® and Sony Playstation 3 ®.

4.3. Procedures

The participants underwent three tests: 1) the *CombiTVA test* which measures basic elements of visual attention; 2) an *enumeration test* which measures subitizing ability and to some extent the speed of the visual attention/perception system, and 3) the Attention Network Test (ANT, Fan & Posner, 2004) which measures three hypothetical visual attention networks: alerting, orienting and executive control. All tests were run using CRT displays with a refresh rate of 100 Hz to ensure correct exposure of the stimuli and presented using E-prime presentation software (Schneider, Eschman, & Zuccolotto, 2002). All three tests were conducted in a semi-darkened room to guarantee comparable stimulus contrast levels for all subjects and all tests featured a short practice session allowing participants to become familiar with the tests.

4.3.1. The CombiTVA test

The first test, the Combined Test of Visual Attention (CombiTVA), is a combination of two classical experimental paradigms: the whole report paradigm (Sperling, 1960), in which all (letter) stimuli must be reported, and the partial report paradigm (Shibuya & Bundesen, 1988) in which only stimuli with a certain target feature are to be reported. In the CombiTVA, the participant must report red target letters while ignoring blue distractor letters. This TVA based assessment has been used in numerous studies to investigate the visual attention system and how it may be affected (e.g. Bublak et al., 2005, 2006; Duncan et al., 1999; Finke et al., 2006; Habekost & Rostrup, 2006, 2007; Jensen et al., 2012; Vangkilde et al., 2011).

The outline of the CombiTVA is presented in Fig. 1. In each trial, the participants must initially fixate on a central cross. After a 1000 ms delay, the participants are exposed to one of three stimulus displays: A) 6 red target letters, B) 2 red target letters or C) 2 red target letters and 4 blue distractors. The stimulus display is terminated by pattern masks presented for 500 ms on all possible target letter positions to control the effective exposure duration of the stimulus displays by preventing further processing based on a potential after image. Following the mask, the participants make an unspeeded report of all the red target letters they are "fairly certain" of having seen during the brief exposure on a blank screen. They respond by typing the letters in any order on a standard keyboard.

Each participant went through 324 trials. The stimulus duration of the six red-target displays varied systematically between 10 and 200 ms for a total of 162 trials. The other two stimulus displays were always presented in 81 trials each for 80 ms. The different trial types were presented in a randomized fashion in 9 separate blocks, each consisting of 36 trials. Participants were instructed to make an unspeeded report of all the red letters they were fairly certain of having seen and aim for response accuracy between 80 and 90%. After each block, participants were informed about the accuracy of their responses. A more comprehensive description of the CombiTVA test can be found in Vangkilde et al. (2011). The TVA model provides an estimate of the limited capacity of visual short-term memory given by the K parameter. However, we acknowledge that there are considerable discussions among researchers as to the nature and scope of short-term memory and that the limited capacity model may measure only certain aspects of this (see Cowan, 2001; Cowan et al., 2005; Luck & Vogel, 1997; Ma & Huang, 2009). Nonetheless, as we were looking for differences in attention parameters across the three subject groups, we believe that it is well justified to use the TVA model for the estimation of parameters under the conditions provided by the CombiTVA test.

4.3.2. The enumeration test

The second test was an enumeration test in which the participants were asked to estimate, as accurately as possible, the number of dots

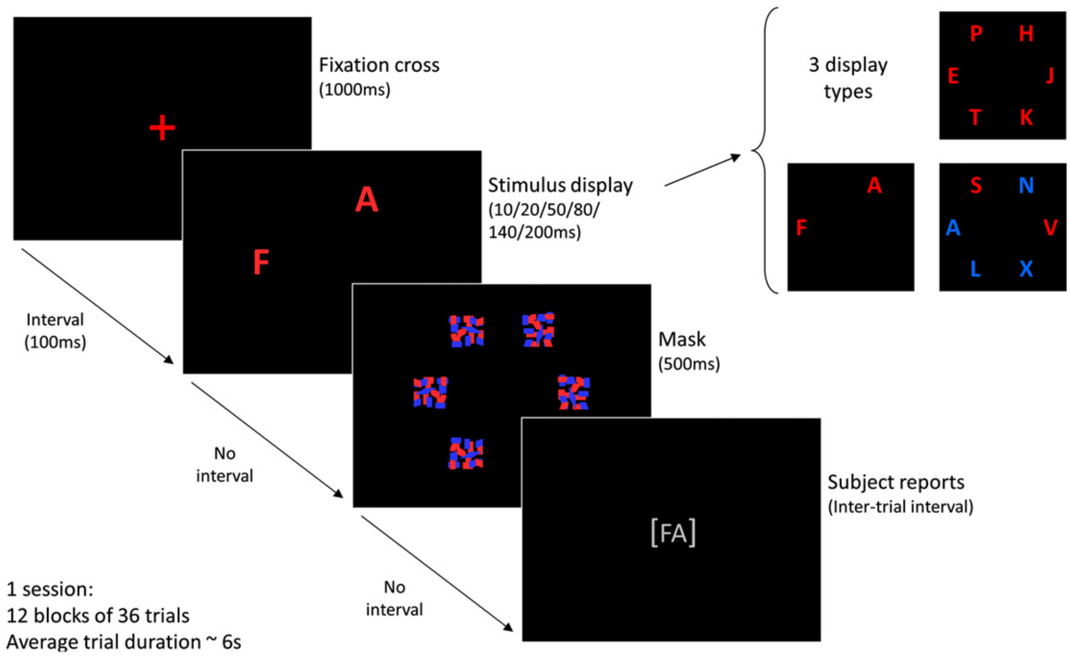

Fig. 1. The CombiTVA test.

briefly presented on a computer screen. In the instructions to the participants, the importance of response accuracy rather than speed was emphasized as we were interested in measuring only the *perceptual* processing elements of visual attention.

Each trial consisted of a sequence of three displays (see Fig. 2). In the first display a fixation cross was shown to position the gaze of the subject; in the second display 1–9 dots appeared in a random pattern on the screen with random distance between the dots to avoid predictable patterns and positions; the third display screen was either blank or featured a mask consisting of a random pattern of black and white squares. The purpose of the mask was to control the effective exposure duration of the stimulus display.

The main session consisted of a total of 540 trials divided into three conditions: 180 masked trials at 50 ms; 180 unmasked trials at 50 ms, and 180 masked trials at 100 ms. The 180 trials in each condition comprised 20 trials for each of the nine display sizes (1–9 dots) in random order. The exposures and masking were chosen to match those of Green and Bavelier (2006b), who employed 50 ms unmasked and 100 ms masked conditions. One concern about the findings of Green and Bavelier was that one of the experiments did not use a mask after exposure. This introduces a possible confound in that the participants are responding to the additional information from the after-image rather than the primary stimulus. We therefore included a set of masked 50 ms stimuli. Furthermore, varying both the exposure duration and masking condition allowed us to use TVA-based computational modeling to estimate a measure of perceptual processing speed comparable to the one obtained from the TVA task (for details see Section 5.3, TVA versus Enumeration).

4.3.3. The ANT test

The final test was the Attentional Network Test (ANT, Fan, McCandliss, Fossella, Flombaum, & Posner, 2005; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Fan & Posner, 2004) which has been used in several studies to assess three different components of attention proposed by Posner and Petersen (1990): Alerting (i.e., achieving and maintaining an alert state), orienting (i.e., selecting information from sensory input), and executive control (i.e., resolving conflict among responses). They suggested that these components were associated with activation in three independent anatomical networks. Later, Fan et al. (2005) conducted a functional magnetic resonance imaging (fMRI) study and provided evidence that alerting was associated with strong thalamic activation and activation of anterior and posterior cortical sites, that the orienting was associated with activation in parietal sites and frontal eye field, and that executive control (or conflict) was associated with activation in the anterior cingulate and several other brain areas.

The ANT was included to verify that our samples of participants were comparable in terms of attentional abilities to those tested in other gaming studies (e.g. Castel et al., 2005; Dye, Green, & Bavelier, 2009; Hubert-Wallander et al., 2011), and to provide measures of attentional capabilities derived from a speeded reaction time-based paradigm.

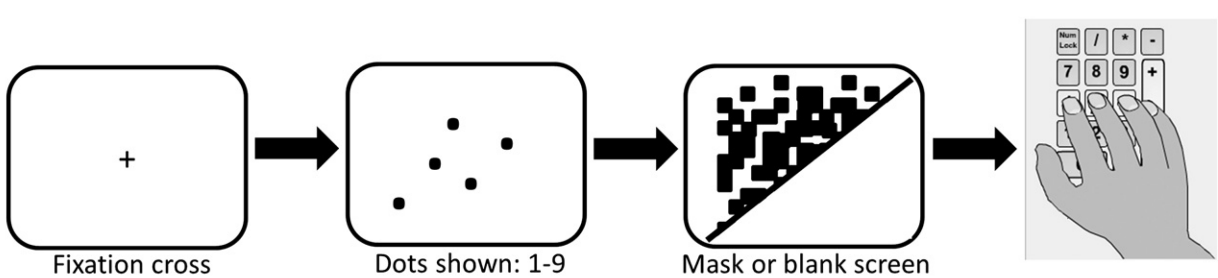

Fig. 2. Trial outline for the enumeration test.

In each trial, participants had to determine the direction of a central arrow, which may appear above or below a fixation cross. The target arrow is either accompanied by neutral, congruent, or incongruent flankers, and the arrow may or may not be preceded by alerting or spatial cues (see cue-stimulus configuration in Fig. 3). The ANT comprised three blocks of 96 trials each which varied with regard to *cue* type (no cue, central cue, double cue, or single cue) and *flanker* type (neutral flankers, congruent flankers, incongruent flankers). Sixteen trials had neutral stimuli, sixteen had congruent stimuli and sixteen had incongruent stimuli.

4.3.4. Questionnaire

In addition to the tests, each participant filled out a questionnaire about gaming habits such as how often they played video games and the type of action video games played. We also asked for information about other activities which could potentially influence visual attention such as medical history, sports habits, drug usage, drinking habits, general PC usage, and reading habits.

5. Results

The participants were divided into three groups (experienced, casual, and non-players) based on the average time spent per month playing action video games. One subject was excluded from the experienced group due to a misunderstanding of task requirements.

5.1. CombiTVA results

The number of correctly reported letters in each trial constituted the main dependent variable in the CombiTVA test. The performance of the participants across the different test conditions was fitted by a maximum likelihood procedure using the LibTVA toolbox for MatLab (Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011). In the specific model used, it is assumed that the storage capacity of visual short-term memory (K) is drawn, trial by trial, from a probability distribution characterized by 5 free parameters (i.e., the probabilities that $K=1, 2, \ldots, 5$, respectively). These five probabilities sum to a value between 0 and 1, and the remaining probability, up to a value of 1, is accounted for by the probability that $K=6$. Hence the K value reported in the next section is the expected K given the particular probability distribution. In a similar fashion, the perceptual threshold, t_0, is assumed to be drawn, trial by trial, from a normal distribution with a given mean and standard deviation (2 free parameters). In contrast, the speed of visual processing, C, is a constant (1 free parameter). Though subjects are instructed to distribute their attention equally on the six possible stimulus positions, we cannot be sure that they distribute attention uniformly. Therefore, attentional weights (w values) are estimated individually for targets at each location (5 free parameters, as the sum of the 6 attentional weights is fixed at a value of 1). Finally, top–down controlled selectivity is modeled by a single free parameter, α, which is defined as the ratio of the attentional weight of a distractor at a certain spatial location to the attentional weight of a target at the same location. These assumptions result in a TVA model with 14 free

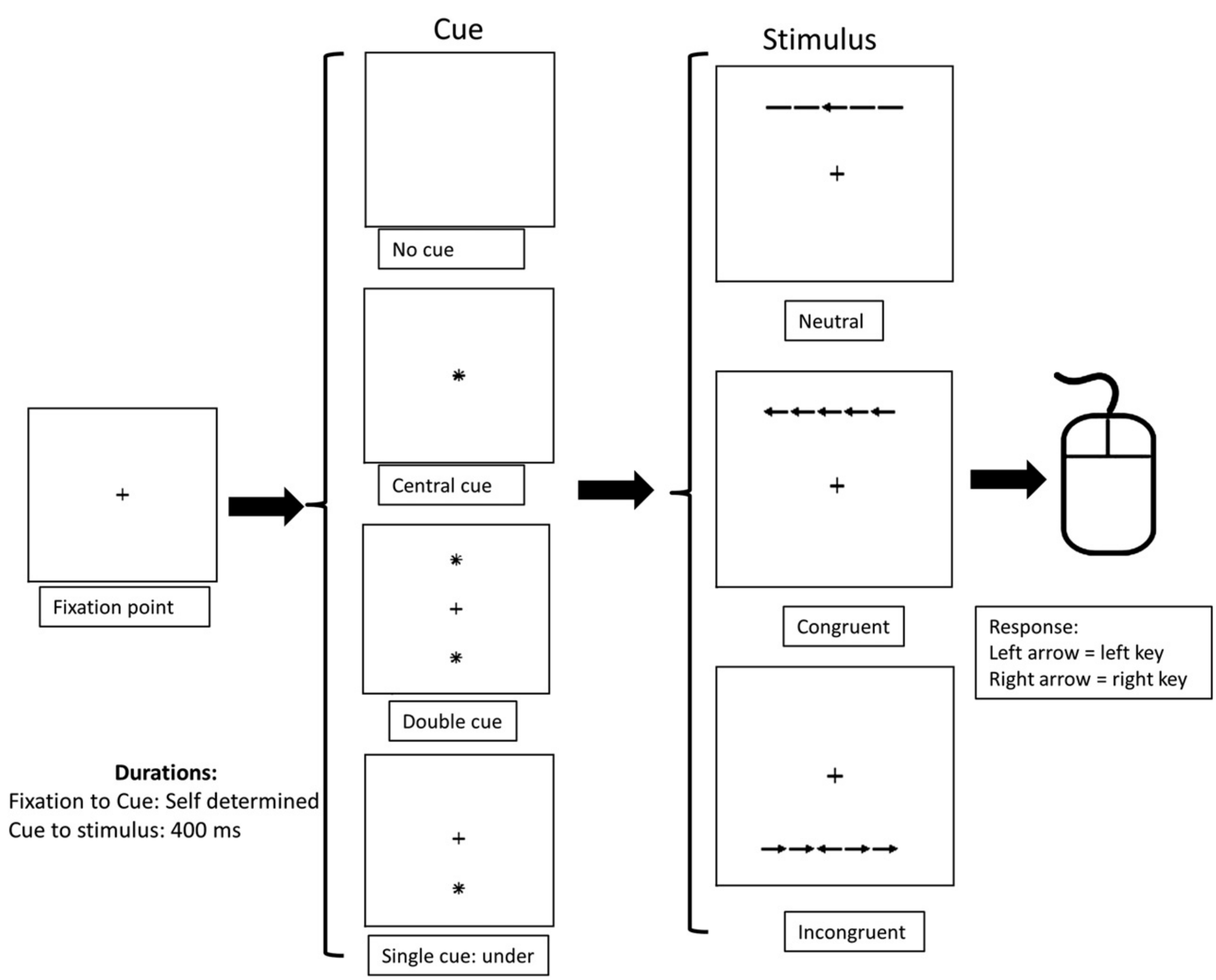

Fig. 3. The version of the Attentional Network Test (ANT) used in this study.

parameters. This may raise concerns about overfitting which can be addressed by analyzing the standard-errors of the estimated parameters (see Dyrholm et al., 2011). However, no standard-errors were found below 3% of the estimated parameters making it unlikely that the model has overfitted the data.

Panel A of Fig. 4 shows the performance of the three participant groups (mean number of correctly reported letters) at the different exposure durations in the six-target whole report conditions. Panel B shows the mean number of correctly reported letters for the two-target whole report displays versus the partial report displays with two targets and four distractors. Performance was clearly diminished when distractors were added to the displays indicating that selection in the three gamer groups is not perfect. Furthermore, both panels present the model corresponding to the mean of the model parameters for each group. The individual model parameters (K, C, t_0, α) and the overall error rate are summarized in Table 1, which also shows goodness of fit to the individual data. As can be seen from Table 1, the model explained almost all of the variance in the performance of the participants for all three groups. The mean estimates for the attentional parameters were also very similar across the gaming groups, and accordingly one-way ANOVAs with Gamer type as between-subject factor revealed no significant effects of group affiliation for any of the measures in Table 1 (all $Fs<1.56$). However, speed of visual processing (C) was faster in the experienced gamer group than in both the casual and non-gamer groups. Comparing the average number of hours spent playing a month with the individual estimates of processing speed revealed that playing time was strongly associated with faster information processing, $r(39)=.44$, $p=.004$. In the estimation of action gaming time per participant, we have used a conservative estimation. We have verified that using an average estimation produces similar results. The data on this can be acquired from the authors. Even though our study confirmed the relationship between faster processing speed (C) and better short-term memory capacity (K), specifically $r(39)=.43$, $p=.005$, found in previous studies (Jensen et al., 2012; Vangkilde et al., 2011), there was no correlation between the short-term memory capacity and number of hours spent playing action video games, $r(39)=.22$, $p=.21$. Nor were the K estimates associated with any of the other background factors like drinking habits, drug use, sports, reading habits or medical history. These findings support the notion that the short-term memory capacity is not influenced by the number of hours spent playing video games, while the speed of processing visual information seems to be positively influenced by increased playing time.

Table 1
Attentional performance and goodness of fits for the three gaming groups.

Parameter	Experienced ($N=19$)		Casual ($N=10$)		Non-players ($N=12$)	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
t_0	19.1	(11)	21.2	(8)	22	(9)
C	70.2	(30)	60.5	(23)	53.9	(18)
K	3.73	(.79)	3.95	(1.07)	3.44	(.90)
Alpha	.59	(.30)	.60	(.25)	.54	(.27)
Error rate	.21	(.08)	.25	(.08)	.21	(.06)
Var%	93.64	(3.32)	93.13	(3.64)	93.10	(3.58)

Note. Units for the individual parameters are: t_0 (ms), C (letters/second), K (letters), α ranges from perfect selection at 0.0 to non-selectivity at 1.0. Var%: Percentage of variance in the observed individual mean scores accounted for by the maximum likelihood fits.

5.2. Enumeration results

Two measures were used to evaluate the results from the enumeration test: the error rates which indicate the ratio between incorrectly estimated number of dots and the number of trials, and the reaction time which measures the time from stimulus exposure to response on the numeric keyboard.

5.2.1. Error rates

Error rates were analyzed in a mixed ANOVA with the three different exposure durations (50 ms unmasked, 100 ms masked, or 50 ms masked) and number of dots (1–9) as within-subject factors and gamer type (experienced, casual, or non-players) as between-subject factor (see Fig. 5, upper panels). The ANOVA revealed the expected main effect of the number of dots, indicating that the error rate increased with the number of dots on the screen, $F(8, 304)=326.82$, $p<.001$, $\eta_p^2=.90$. In addition, a significant main effect of exposure duration was found, $F(2, 76)=324.23$, $p<.001$, $\eta_p^2=.90$, reflecting that least errors were made in the 50 ms

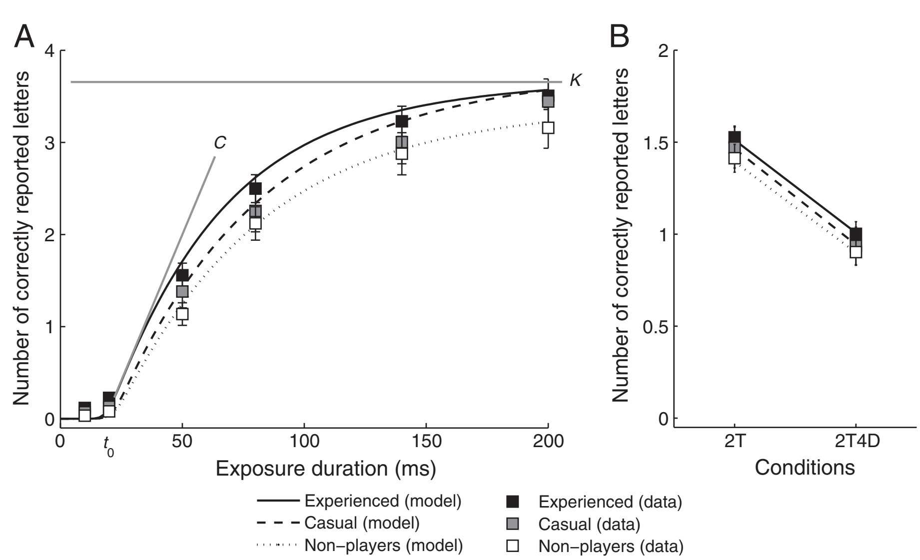

Fig. 4. *Results of the TVA task.* Squares represent the mean number of correctly reported letters for each gamer type (experienced, black squares; casual, gray squares; and non-players, white squares) as a function of exposure condition (10, 20, 50, 80, 140 and 200 ms) in panel A and target–distractor condition (two targets, 2T, versus two targets and four distractors, 2T4D) in panel B. Error bars represent standard errors of the means. Lines show the model corresponding to the mean of the model parameters for each gamer type (experienced, solid lines; casual, dashed lines; and non-players, dotted lines). In addition, the parameters t_0, C and K are illustrated in panel A: t_0 is the exposure duration at which the number of correctly reported letters starts to rise above 0 (i.e., the perceptual threshold), C is the slope of the curve at t_0 (TVA assumes an exponential increase in the number of correctly reported letters), and K is the asymptotic level of the number of correctly reported letters if the exposure duration is increased to infinity.

unmasked condition and most errors were made in the 50 ms masked condition. However, most interesting to the current study, no main effect of gamer type was found, $F(2, 38) = 0.51$, $p = .60$, $\eta_p^2 = .03$. Thus, experienced gamers did not perform better or worse than casual gamers or non-players. The ANOVA also revealed a significant interaction between exposure and number of dots, which might reflect a difference in the subitizing range between exposure durations, $F(16, 608) = 28.49$, $p < .001$, $\eta_p^2 = .43$.

5.2.2. Reaction time

Reaction times were analyzed in a mixed ANOVA corresponding to the setup of the error rate analysis (see Fig. 5, lower panels). Similar to the error rates, there was no main effect of gamer type on reaction times, $F(2, 38) = 0.79$, $p = .46$, $\eta_p^2 = .04$, but significant main effects of both exposure duration and number of dots, $F(2, 76) = 17.93$, $p < .001$, $\eta_p^2 = .32$ and $F(8, 304) = 152.09$, $p < .001$, $\eta_p^2 = .80$, respectively. Although reaction times did not differ in the three gamer groups, reaction times were different for the three exposure durations such that the slowest responses were found in the 50 ms unmasked condition and the fastest responses were found in the 50 ms masked condition. As expected, reaction times were affected by the number of dots presented on the screen: the measured reaction times became progressively slower, the more dots were presented. Again, the ANOVA on reaction times revealed a significant interaction between exposure time and number of dots, reflecting a possible reaction time difference in the subitizing range across exposure durations, $F(16, 608) = 21.7$, $p < .001$, $\eta_p^2 = .36$. Actually, this corresponds to Green and Bavelier's (2006b) suggestion, that what is improved by video game play experience is not actually the capacity seen in the subitizing range but skills involved in the more serial counting component such as the ability to read-off the stimuli longer from the memory or to cycle through them faster.

In summary, we found the fastest and least correct responses in the 50 ms masked condition, while the longest and most correct responses were observed in the 50 ms unmasked condition. This finding is not surprising: In the 50 ms masked condition, participants cannot benefit from after-image information on the number of presented dots after the 50 ms presentation time and thus responded fast but less accurate. In contrast, participants continued to accumulate visual information beyond the 50 ms presentation time in the unmasked condition and thus may have delayed their response to optimize performance.

5.2.3. Breakpoint analyses

To obtain a quantitative measure of the breakpoint between the subitizing and counting ranges, we fitted a bilinear model to the individual error rates using the least squares method. That is, accuracy data for each subject was modeled as an intersection between two linear components; the first component was constrained to have a slope very near zero (maximum increase of 3% per dot) while the second linear component was allowed to vary without restrictions of the slope. The output of the model was the slopes of the two lines and the accuracy breakpoint, similar to the modeling included in the study of Green and Bavelier (2006b).

A mixed ANOVA with exposure duration as within-subject factor and gamer type as between-subject factor was used to analyze the individual breakpoints. Similar to the previous analyses, no main effect of gamer type was observed, $F(2, 38) = 0.90$, $p = .42$, $\eta_p^2 = .05$, whereas a significant main effect of exposure was found, $F(2, 76) = 45.95$, $p < .001$, $\eta_p^2 = .55$. We did not find any correlation between hours spent playing and the breakpoint for any of the exposure durations (50 ms unmasked: $r(39) = .03$, $p = .87$; 50 ms masked: $r(39) = .22$, $p = .16$; 100 ms masked: $r(39) = .09$, $p = .56$).

Interestingly, when comparing the breakpoints for the 50 ms unmasked condition to the results from Green and Bavelier (2006b), we found that our non-players ($M = 4.72$, $SD = 1.43$) were not significantly different from their experienced video game players tested under the same condition (VGPs; $M = 5.0$, $SD = 0.72$; $t(23) = 0.63$, $p = .54$), but performed significantly better than their non-players (NVGPs; $M = 3.0$, $SD = 1.08$; $t(23) = 3.42$, $p = .002$). Across all three

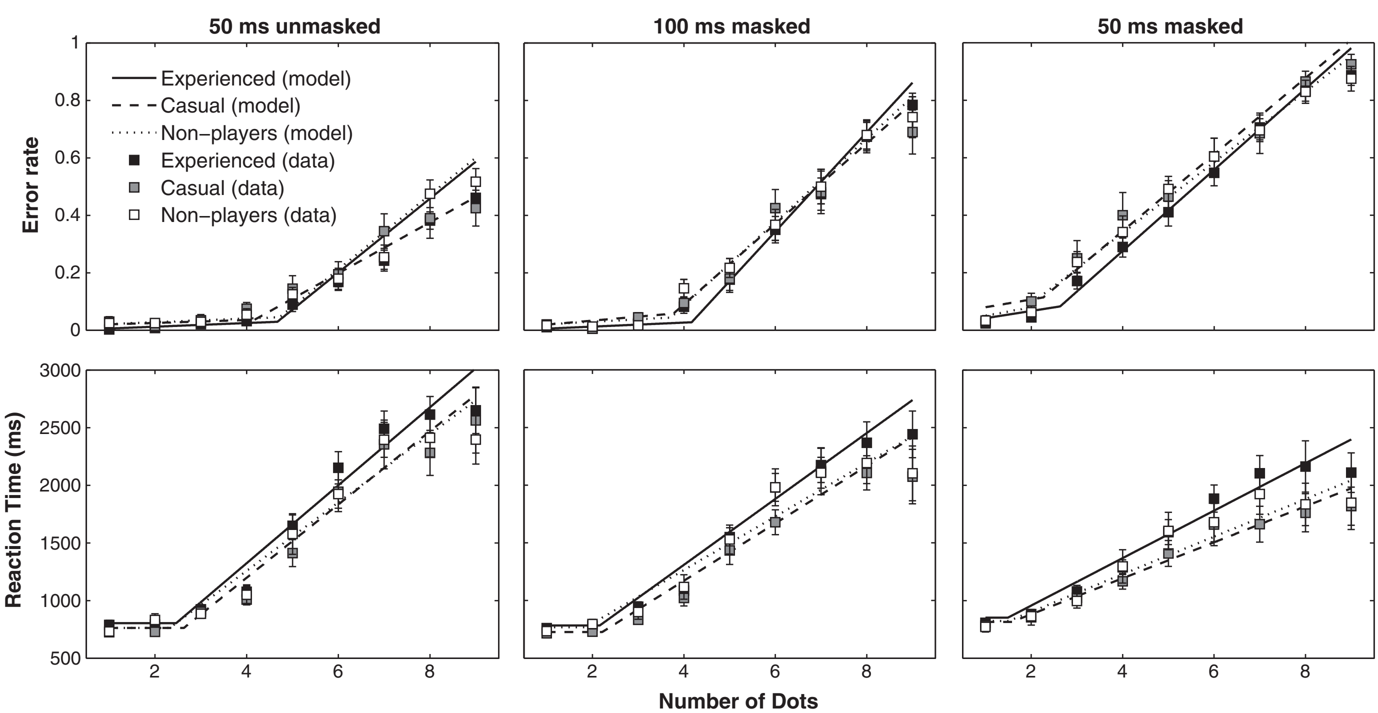

Fig. 5. *Results of the enumeration task.* Mean error rates and mean reaction times as functions of number of dots (1–9) for each gamer type (experienced, black squares; casual, gray squares; and non-players, white squares) depending on exposure condition (50 ms unmasked, 100 ms masked, and 50 ms masked). Lines show the resulting mean of fitting the bilinear model to the individual subject data (experienced, solid lines; casual, dashed lines; and non-players, dotted lines). Error bars represent standard errors of the means.

exposure conditions, our participants performed the same number of trials as did the ones from Green and Bavelier's study. Thus, when comparing our 50 ms unmasked condition with their full study, the number of trials per data point is only one third in our study. This discrepancy may explain why the mean breakpoint for our non-players shows twice the standard deviation compared to both VGPs and NVGPs. However, there are no trends in our data to suggest that the three groups we tested would perform significantly different if more trials had been run. Furthermore, we would not expect our non-players to perform markedly worse with more trials.

The quantitative measure of the breakpoint between subitizing and counting was also applied to the reaction time data, and a mixed ANOVA with exposure duration as within-subject factor and gamer type as between-subject factor was used to analyze the breakpoints. This ANOVA similarly revealed a significant main effect of exposure duration, $F(2, 76) = 21.40$, $p < .001$, $\eta_p^2 = .36$, but no main effect of gamer type, $F(2, 38) = 0.36$, $p = .70$, $\eta_p^2 = .02$. As for the accuracy measures, none of the breakpoints for the three exposure durations correlated with the number of hours spent playing (correlations ranged from −.07 to .06 and were non-significant, $p > .68$).

5.3. CombiTVA versus enumeration

The breakpoint between subitizing and counting has been hypothesized to be a measure of short-term memory capacity. However, we found no correlation between the short-term memory estimates from CombiTVA (K) and the breakpoints estimated from the accuracy data from the enumeration task. This questions whether the enumeration task and CombiTVA measure the same aspect of the visual short-term memory.

Instead, we found a significant correlation between the visual processing speed, C, estimated from the CombiTVA paradigm and a comparable C-estimate from the enumeration task ($r(39) = .32$, $p = .04$). The latter individual C-estimates were found by fitting TVA to the mean accuracy for each of the three exposure durations (i.e., 50 ms unmasked, 100 ms masked, and 50 ms masked) in the same way as when TVA is used to estimate parameters from the single stimulus recognition paradigm (see Bundesen & Harms, 1999). That is, we temporarily neglected the impact of short-term memory capacity and treated each stimulus display as a single stimulus disregarding display size. In contrast to the standard fitting of TVA-based single stimulus recognition paradigms, the low number of exposure durations made it impossible to estimate the visual threshold, t_0, and it was therefore fixed to zero. Furthermore, a visual decay parameter, μ, was introduced to account for the prolonged effective exposure duration in the unmasked condition (see Bundesen, 1990).

The significant correlation between the C-estimate from the CombiTVA and C-estimate from the enumeration task gives us reason to believe that the breakpoint estimate from the enumeration task does not depend on short-term memory capacity alone but is also influenced by visual processing speed. This may be the reason why we did not find a correlation between K and the accuracy-based breakpoints estimated from the enumeration task.

On the other hand, this may also suggest that the C-estimate from the enumeration task is probably not as precise an estimate for visual processing speed as the C-estimate from the CombiTVA. This may explain why we did not find a significant difference between the C-estimates based on the enumeration task in the three gamer groups in a one-way ANOVA, $F(2, 40) = 0.75$, $p = .48$, nor a significant correlation between these C-estimates and the number of hours spent playing video action games, $r(39) = .13$, $p = .43$.

In conclusion, the negative findings from the enumeration task may be caused by the standard analysis of the enumeration test not being able to tease apart independent estimates of short-term memory capacity and visual processing speed as distinctly as in the CombiTVA paradigm.

5.4. ANT results

The ANT test did not produce evidence for a difference between the three gamer groups. Reaction times (RT) and accuracy (ACC) were analyzed by conducting two separate mixed ANOVAs with warning type (orienting cue, double cue, central cue, no cue) and congruency (congruent, neutral, incongruent) as within-subject factor and gamer type (experienced, casual, non-players) as between-subject factor. In the analysis of reaction times, only correctly reported trials and trials with a reaction time within 3 standard deviations of the mean in each condition were used. Due to an unusually high number of errors, one of the non-players was excluded from the analyses of reaction times and accuracy. Neither of the ANOVAs showed any main effect of gamer type, RT: $F(2, 37) = 1.36$, $p = .27$, $\eta_p^2 = .07$; and ACC: $F(2, 37) = 1.14$, $p = .33$, $\eta_p^2 = .06$, respectively. However, the average reaction times of the experienced group were significantly faster than both those of the casual and non-playing groups: in a binomial test 12 out of 12 mean reaction times were faster for the experienced group compared with the two other groups, $z = 3.46$, $p < .001$.

Furthermore, the ANOVAs revealed that both the congruency of the stimuli, RT: $F(2, 74) = 354.56$, $p < .001$, $\eta_p^2 = .91$; ACC: $F(2, 74) = 67.43$, $p < .001$, $\eta_p^2 = .65$, and the warning type, RT: $F(3, 111) = 198.49$, $p < .001$, $\eta_p^2 = .84$; ACC: $F(3, 111) = 3.68$, $p = .014$, $\eta_p^2 = .09$, significantly affected performance. This reflected that responses to incongruent stimuli were slower and less accurate than to congruent stimuli, and that orienting cues led to the fastest responses whereas the no cue condition led to the slowest responses of the four warning types (cf. Fig. 6). Although the main effect of warning type on accuracy was significant, the effect size was small and the mean data showed no clear interpretable pattern besides a slight increase in error rate for the experienced gamers in the incongruent trials especially with center cues. However, an additional mixed ANOVA testing the contribution of warning type and gamer type, respectively, to performance accuracy in the incongruent condition showed no main effect of gamer type, $F(2, 37) = 1.10$, $p = .345$, $\eta_p^2 = .06$.

Finally, the ANOVAs revealed a significant congruency × warning type interaction, RT: $F(6, 222) = 7.49$, $p < .001$, $\eta_p^2 = .17$; ACC: $F(6, 222) = 3.43$, $p = .003$, $\eta_p^2 = .09$, as alerting cues (center or double cues) containing no spatial information slowed down reaction times and impaired accuracy much more than orienting cues and no cue in the incongruent stimulus condition.

Overall these findings are in accordance with findings reported by Fan et al. (2002) even though our participants had an overall lower reaction time ($M = 448$, $SD = 46$) and error rate ($M = 0.95$, $SD = 0.03$) across all gamer types compared to the overall reaction time ($M = 513$, $SD_{\text{pooled}} = 50$; $t(78) = 6.05$, $p < .001$) and error rate ($M = 1.91$, $SD_{\text{pooled}} = 0.41$; $t(78) = 14.31$, $p < .001$) reported by Fan et al. (2002). This difference could arise from a lower mean age in our sample (17.5 years) compared with the mean age of 30.1 years in the sample by Fan et al.

Based on the reaction time data, the alerting effect ($RT_{\text{no cue}} - RT_{\text{center cue}}$), the orienting effect ($RT_{\text{center cue}} - RT_{\text{orienting cue}}$), and the conflict effect ($RT_{\text{incongruent}} - RT_{\text{congruent}}$) were calculated reflecting the attentional components suggested by Posner and Petersen (1990). Fig. 7 shows these effects for the three gamer types. A one-way ANOVA for each of the three effects showed no significant difference between the gamer types confirming our previous ANT findings; alerting: $F(2, 37) = 1.23$, $p = .31$, $\eta^2 = .06$; orienting: $F(2, 37) = 0.30$, $p = .75$, $\eta^2 = .016$; conflict: $F(2, 37) = 1.53$, $p = .23$, $\eta^2 = .08$. The average alerting effect ($M = 43.6$, $SD = 18.8$) and conflict effect ($M = 93.5$, $SD = 28.6$) across gamer type were not different in magnitude from the scores reported found by Fan et al. (2002), specifically $M_{\text{alerting}} = 47$, $SD = 18$, $t(78) = 0.83$, $p = 0.41$; and $M_{\text{conflict}} = 84$,

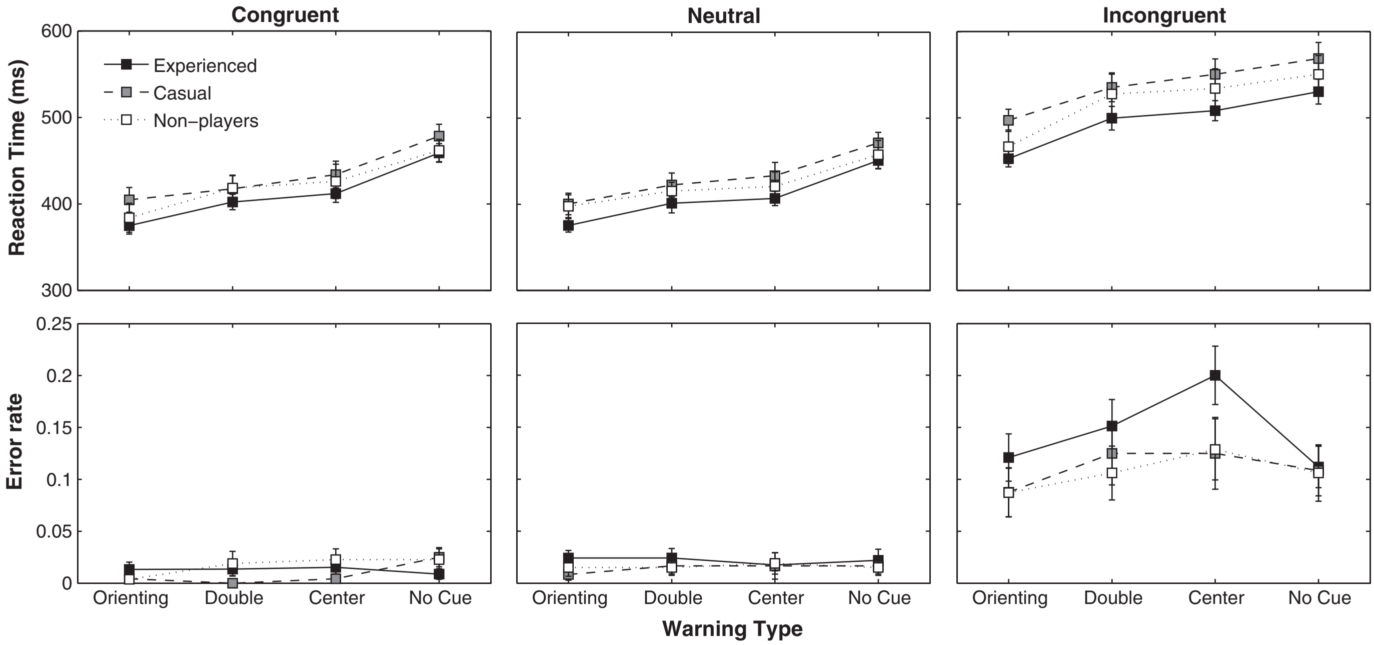

Fig. 6. *Results of the ANT task.* The mean reaction times and error rates for each gamer type (experienced, black squares; casual, gray squares; and non-players, white squares) depending on warning type (orienting, double, center, or no cue) and congruency (congruent, neutral, or incongruent). Error bars represent standard errors of the means.

$SD=25$, $t(78)=1.58$, $p=.12$. However, the orienting effect across gamer type ($M=41.4$, $SD=16.4$) was significantly different from the orienting effect reported by Fan et al.: $M_{\text{orienting}}=51$, $SD=21$, $t(78)=2.28$, $p=.03$.

6. Discussion

The similarity between the tests we have included in the present study and the tests performed in the original gamer studies by Green and Bavelier (2003) gave us the opportunity to compare the integrity of the groups now and then. In our tests even the casual and non-game players perform at a level comparable to the performance level of the expert gamers found in the 2003 study. We speculate that this might be due to young people being more exposed to the use of computers and other electronic devices today than a decade ago. Also, the fast pace and cut scene action of most movies, music videos and action televisions series may pose as implicit training of at least certain elements of visual attention corresponding to a training that was previously obtained primarily by intensive video game playing. This could contribute to a smaller difference between the performances of our gamer groups than what has previously been reported.

The superior visual performance of experienced game players on some cognitive measures has been suggested to arise from a short-term memory improvement induced by playing action video games. Specifically, this argument has been based on an improved subitizing range reflected by the enumeration test. However, there seems to be some uncertainty as to what is being measured by this test. In our study, we included an enumeration task with identical experimental conditions to those used in previous studies but we did not find any relation between hours played and the size of the subitizing range. Using TVA-based modeling to derive an estimate of visual processing speed from the enumeration task, we found a correlation between the two estimates of

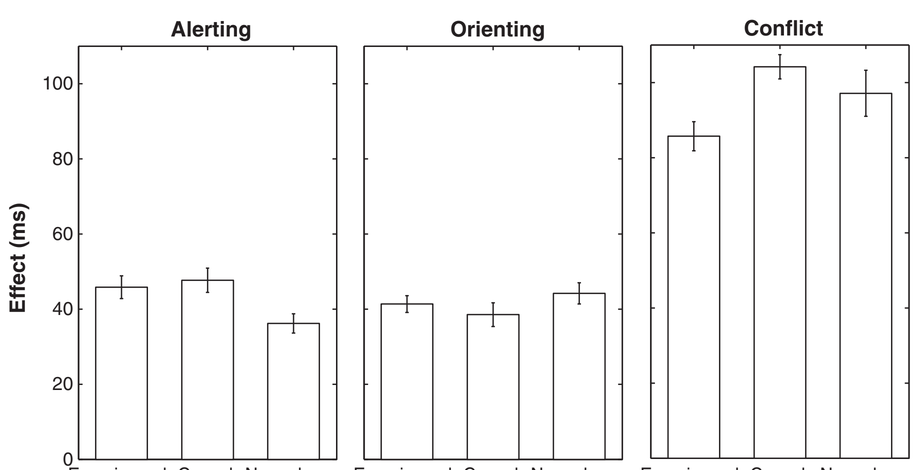

Fig. 7. *Attentional network scores from the ANT task.* Alerting, orienting, and, conflict effects for each gamer type (experienced, casual, and non-players). Error bars represent standard errors of the means.

visual speed obtained from the CombiTVA and the enumeration task, respectively. This would support that the enumeration task does measure an important perceptual process, namely the encoding speed into short-term memory. Even though we did not replicate the previously reported finding of enhanced subitizing range, our results suggest that the basic component of visual attention which is modulated by video gaming is the speed of information processing. A similar conclusion was reached by Green and Bavelier (2012) and Green, Pouget, and Bavelier (2010) based on two discrimination tasks in which they varied the stimulus exposure duration. They found that the increase in performance as a function of exposure duration was well-described by a delayed exponential function and that it was the slope of the function (the speed of information processing) and not the time at which performance raised above chance level or the asymptotic performance that differed between gamers and non-gamers. Correspondingly, we found that it was the C parameter (the speed of information processing) and not the t_0 parameter (the perceptual threshold) or the K parameter (the asymptotic performance) that differed between groups in the TVA-based test. In addition to this perceptual effect, our findings on the ANT task at least hint that the motor speed is also generally enhanced by video action gaming.

7. Conclusion

Brain plasticity is very much the key component in future attempts to overcome deleterious effects of aging, illness and brain injury. Some of the interesting questions in this context are whether basic elements of perception are susceptible to training induced enhancements and how well such changes generalize to other activities. One way to investigate this was to measure these elements in participants who had voluntarily exposed themselves to hours of intensive training. By using three tests all measuring different aspects of visual attention and memory, we tested the hypothesis that visual short-term memory would be one of the elements susceptible to improvement from training.

In conclusion, intensive video action gaming seems to improve one general parameter of visual attention, viz. the encoding speed to short-term memory. We did not observe any changes in the capacity of visual short-term memory, nor did we observe any changes in the visual attention threshold. Ideally, these findings should be replicated in a study where a group of non-players received intensive training.

Broadly translated our findings indicate that action gaming activities placing a heavy demand on visual attention do in fact improve one basic aspects of attention, the encoding speed, suggesting that experienced gamers are able to utilize the limited capacity of short-term memory faster and more efficiently. This is an important finding in the understanding of the flexibility of visual attention as well as to future implementations of rehabilitation efforts in patients with attention deficits.

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