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Video game experience and its influence on visual attention parameters: An investigation using the framework of the Theory of Visual Attention (TVA)

Torsten Schubert [a,b,*], Kathrin Finke [b,c], Petra Redel [b], Steffen Kluckow [a,d], Hermann Müller [b,e], Tilo Strobach [a,b]

[a] *Department of Psychology, Humboldt-University Berlin, Germany*
[b] *Department of Psychology, Ludwig-Maximilians-Universität München, Germany*
[c] *Department of Psychology, Bielefeld University, Germany*
[d] *Department of Neurology, Friedrich-Schiller-Universität Jena, Germany*
[e] *Department of Psychological Sciences, Birkbeck College London, UK*

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ABSTRACT

Experts with video game experience, in contrast to non-experienced persons, are superior in multiple domains of visual attention. However, it is an open question which basic aspects of attention underlie this superiority. We approached this question using the framework of Theory of Visual Attention (TVA) with tools that allowed us to assess various parameters that are related to different visual attention aspects (e.g., perception threshold, processing speed, visual short-term memory storage capacity, top-down control, spatial distribution of attention) and that are measurable on the same experimental basis. In Experiment 1, we found advantages of video game experts in perception threshold and visual processing speed; the latter being restricted to the lower positions of the used computer display. The observed advantages were not significantly moderated by general person-related characteristics such as personality traits, sensation seeking, intelligence, social anxiety, or health status. Experiment 2 tested a potential causal link between the expert advantages and video game practice with an intervention protocol. It found no effects of action video gaming on perception threshold, visual short-term memory storage capacity, iconic memory storage, top-down control, and spatial distribution of attention after 15 days of training. However, observations of a selected improvement of processing speed at the lower positions of the computer screen after video game training and of retest effects are suggestive for limited possibilities to improve basic aspects of visual attention (TVA) with practice.

1. Visual attention and video game expertise

An interesting research question is to which extent different aspects of visual attention can be improved with excessive and intensive playing of action video games. Several studies have suggested that persons with strong expertise in video game playing are superior in a variety of attention tasks compared to video game non-experts (e.g., Bavelier, Green, Pouget, & Schrater, 2012; Dye, Green, & Bavelier, 2009; Green & Bavelier, 2003), with some of them providing even evidence for a causal relation between video game expertise and the superior attention performance (e.g., Green & Bavelier, 2003, 2006; for a critical perspective, see Boot, Kramer, Simons, Fabiani, & Gratton, 2008).

However, still these existing findings do not allow us to determine the basic mechanisms which might differ between groups differing in their amount of video game expertise. Critically, investigations reporting video-game related differences often rely on incomparable experimental paradigms and theoretical frameworks, which make a clear-cut identification of those mechanisms across studies difficult that might be at the basics of the superior attention performance in the video game experts. The current study aims at specifying such basic mechanisms in visual attention that are related to video game expertise.

Possible candidates for differences in basic mechanisms are, for example, the capacity of visual short-term memory storage (e.g. Achtman, Green, & Bavelier, 2008; Boot et al., 2008; Green & Bavelier, 2003, 2006; Spence & Feng, 2010; Tahiroglu et al., 2010; Trick, Jaspers-Fayer, & Sethi, 2005), the processing speed of visual information (Appelbaum, Cain, Darling, & Mitroff, 2013; Cohen, Green, & Bavelier, 2007; Dye et al., 2009; Green & Bavelier, 2003), the spatial resolution/distribution of attention (Castel, Pratt, & Drummond, 2005; Dye et al., 2009; Feng, Spence, & Pratt, 2007; Green & Bavelier, 2003, 2006, 2007; Riesenhuber, 2004), and the efficiency of attention top-down control (Cain, Prinzmetal, Shimamura, & Landau, 2014; Hubert-Wallander, Green, Sugarman, & Bavelier, 2011). Typically, existing studies on

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* Corresponding author at: Humboldt-University Berlin, Department of Psychology, Rudower Chaussee 18, D – 12489 Berlin, Germany. Tel.: +49 30 2093 4846; fax: +49 30 2093 4910.
E-mail address: torsten.schubert@hu-berlin.de (T. Schubert).

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these mechanisms in video game experts use paradigms targeting different aspects of attention in a highly selective manner but with heterogeneous theoretical and methodological backgrounds. For example, evidence for increased capacity of visual short-term memory storage was demonstrated with the enumeration task (Trick & Pylyshyn, 1994). 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 the number of items correctly within one single focus of attention if no more than 3–4 items are presented, while increasing the visual load above 3 or 4 items (i.e., the number of items shown) gradually decreases the accuracy and/or the time for their estimates. The first observation is usually said to reflect the subitizing span while the observation of a decreasing performance with increasing visual load of more than 3–4 items is assumed to reflect the counting range. The subitizing range is increased in video gamers in contrast to non-video gamers (e.g., Green & Bavelier, 2003, 2006). This has been interpreted to indicate that video gamers can maintain more items in their visual short-term memory and, therefore, have an increased capacity of this storage type.

Video gamers also outperformed non-video gamers in the attentional blink paradigm, requiring the identification of sequentially presented targets in a rapid visual stream (Green & Bavelier, 2003). The correct identification of a second target briefly presented after a first target was improved in video gamers compared to non-video gamers, and this observation is interpreted as reflecting higher visual processing speed. Furthermore, improved spatial distribution of attention in video gamers is often demonstrated with the paradigm of the useful field of view task (Feng et al., 2007; Green & Bavelier, 2003; Wu et al., 2012). In this paradigm stimuli have to be detected at different visual angles (e.g., at 5°, 10°, to 30°) under short presentation time conditions and video gamers show superior performance compared to non-gamers at larger visual angles indicating a larger spatial distribution of attention across the visual field. Interestingly, the resulting visual field in video gamers extends up to 30°, which covers a spatial region larger than most of the computer displays used by video gamers during gaming (Green & Bavelier, 2003).

Finally, studies that investigate the impact of distractors on the processing of pre-defined target stimuli suggest superior control of attention selection in video gamers. In these studies, the presence of a task-irrelevant distractor was found to interfere with target stimulus processing to a smaller degree in video gamers in contrast to non-gamers. This smaller degree of interference is suggestive for video gamers' improved focussing on the relevant visual information in sceneries with high visual load (Chisholm, Hickey, Theeuwes, & Kingstone, 2010; however, see also studies with an increased distractor interference effect on video gamers because of a larger attention focus under conditions of increased visual load, Green & Bavelier, 2003).

While the paradigms used in the studies mentioned above are well suited for targeting individual aspects of visual attention according to selected theoretical frameworks, they are highly diverse with respect to several factors. For example, they require processing of different types of stimuli (i.e. letters, digits, geometric figures, etc.), different basic attention mechanisms, different attention domains, and they often differ in the response demands. Therefore, it is difficult to draw firm conclusions whether extensive action video gaming is associated with a general and broad improvement of visual attention or whether some specific, and if so then, which specific aspects of visual attention are improved in video gamers compared to non-gamers.

2. Theory of visual attention and video game expertise

In the current study, we applied a methodological approach that allowed us to assess several aspects of perception and attention processes within one uniform experimental context that is built upon a cohesive theoretical framework of visual attention. We applied psychophysical assessment tools that are based on the theory of visual attention (TVA, Bundesen, 1990; Bundesen, Habekost, & Kyllingsbæk, 2005; Kyllingsbæk, 2006). These tools deliver, from the same set of trials, a variety of perceptual and attentional parameters that characterize several basic aspects of the individual visual attention performance of participants in a way that is free of possible influences from the motor response system.The latter is important because differences in motor response speed may also obscure differences in attention processes between video gamers and non-gamers (e.g., Castel et al., 2005; Dye et al., 2009).

Visual attention is assessed by several visual attention parameters: perception threshold (t_0), processing speed (C), iconic memory buffer (μ), visual short-term memory storage capacity (K), top-down control (α), and spatial distribution of attention (w_{lat} and w_{vert}). Quantitative estimates of these parameters are derived from modeling participants' performance in two different types of attention tasks, the whole and partial report tasks. In the whole report task participants are presented with 5 letters that are listed in columns either at the left or right side of the display for very short duration (see Fig. 1 for more details). A reproduction function can be obtained individually for each participant and the function exponentially approaches a maximum number of reported letters with increasing time of presentation (see Fig. 2). In the partial report condition participants only need to reproduce the letters of a predefined color that can be accompanied by a distractor letter of an alternative color. The parameters of visual attention can be obtained by applying an independent mathematical fitting procedure to the individual reproduction functions (Bundesen et al., 2005; Kyllingsbæk, 2006).

Using the theoretical framework of TVA has the advantage of a proven and widely accepted theory on attention mechanisms, which can explain obtained differences in the performance between video gamers and non-gamers by referring to basic characteristics of the visual attention system. In detail, TVA has a close relation to the biased-competition view of visual attention (e.g., Desimone & Duncan, 1995). According to this view, visual objects are processed in parallel and compete for selection, i.e. conscious representation. The race between objects can be biased in such a way that some objects are favored for selection, based either on automatic, “bottom-up” or on intentional, “top-down” factors. The selection of an object is synonymous with its encoding into a visual short-term memory storage with limited capacity. The selection probability is determined (a) by an object's processing rate, which in turn depends on its attentional weight, and (b) by the capacity of the short-term memory store. Different TVA parameters model the general processing efficiency of the information processing system (visual perceptual processing rate and visual short-term memory storage capacity), and specific aspects of attentional weighting, namely top-down-control (filtering), and spatial distribution of attention. The validity of TVA and the related assessment tools have already been proved in various contexts. Thus, they were applied in a number of studies to systematically characterize specific groups of younger and older adult patients (e.g., Bublak et al., 2005, 2011; Bublak, Redel, & Finke, 2006; Duncan et al., 1999; Finke et al., 2011; Finke, Bublak, Dose, Müller, & Schneider, 2006; Habekost & Bundesen, 2003; Habekost & Starrfelt, 2009; Redel et al., 2012). Furthermore, it has been shown that the TVA attention capacity parameters react differently to enhancing manipulations, such as alertness cueing (Finke et al., 2012; Matthias et al., 2009), increase of temporal expectancy (Vangkilde, Coull, & Bundesen, 2012) and stimulating pharmacological interventions (Finke et al., 2011).

An initial application of TVA-based assessment tools in the context of video gaming was realized in a study of Wilms, Petersen, and Vangkilde (2013). The authors showed larger visual processing speed in video gamers compared to non-gamers with a certain type of TVA-based assessment tools (see below for more details). As a result the authors suggested that, e.g. superior performance in other attention paradigm such as the attentional blink paradigm (Green & Bavelier, 2003) may result from the fact that video gamers process visual information at a higher rate and therefore encode visual information faster into short-term memory.

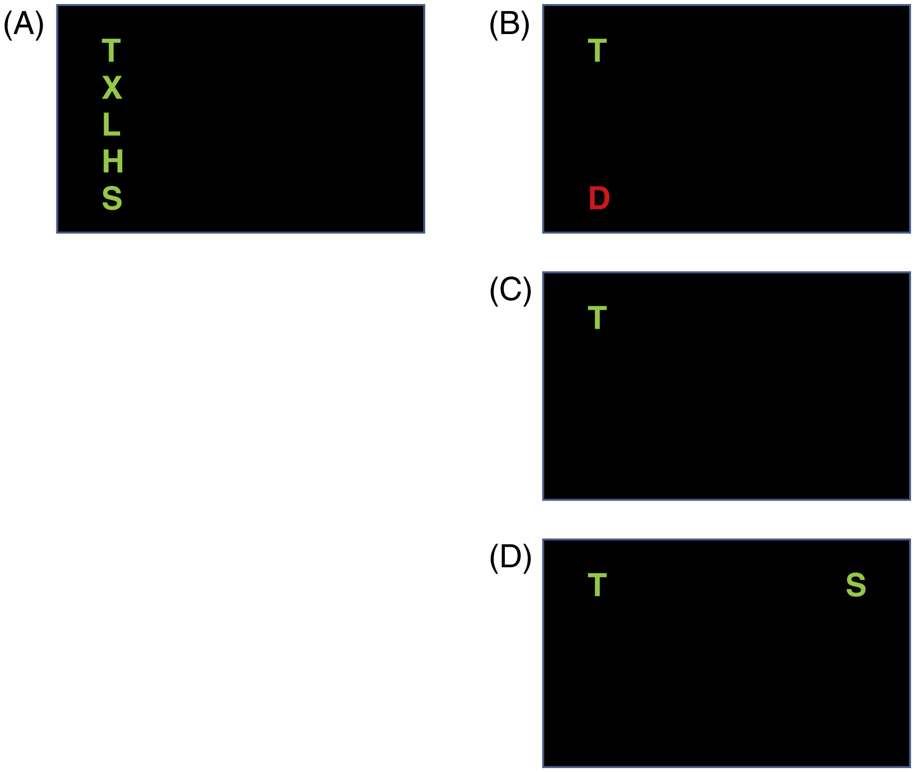

Fig. 1. Examples of displays in the Theory of Visual Attention tests including whole report (A) and partial report (B–D).

Despite the important findings of Wilms et al. (2013) a number of issues remained unresolved and need further investigation. First, Wilms et al. applied a particular TVA procedure, the CombiTVA test (Vangkilde et al., 2012), which is based on an intermingled and random presentation of the whole report and the partial report conditions. That particular version of TVA procedure requires participants permanently to switch between two different task situations, namely the partial and the whole report. As a consequence, the combination of these different report tasks in one experimental setting involves switches and repetitions across tasks in successive trials. This mix of switches and repetitions may have confounded the observed findings of Wilms et al. since task switching ability is enhanced in persons with video game expertise (Colzato, van Leeuwen, van den Wildenberg, & Hommel, 2010; Glass, Maddox, & Love, 2013; Green, Sugarman, Medford, Klobusicky, & Bavelier, 2012; Karle, Watter, & Shedden, 2010; Strobach, Frensch, & Schubert, 2012; Strobach & Schubert, in press). To exclude the potential confound of task switching abilities, the present study, therefore, realizes the whole and partial report trials in separate blocks; this procedure including separate blocks is validated in several studies of Finke and colleagues (Finke et al., 2005, 2006). Second, the study of Wilms et al. does not specify which specific spatial regions benefit from the increased visual processing speed in video gamers. Bublak et al. (2011) showed that the visual processing speed differs across the display positions of the whole report display with remarkably higher processing speed at the upper positions compared to the lowermost positions. According to Bundesen (1990) such position-specific effects may result from differences in basic sensory processing characteristics, such as different retinal acuity at different spatial positions, and from differences in the allocation of attention to the different positions. In normal subjects, this causes high, i.e. most optimal processing speed at upper spatial positions and sub-optimal performance at the lower positions of the display. Since findings of Green and Bavelier (2003) have shown that video gamers have a larger visual field than non-gamers, it is reasonable to assume that the particular portion of the visual field is larger, where video gamers show an increased processing speed compared to non-gamers. Therefore, we expect the benefit of video gamers in processing speed to be manifested mostly at the lower positions of the TVA-display, i.e. on those positions where normal subjects (without special video game experience) show sub-optimal processing speed (Bublak et al., 2011).

3. The present study

In the current study, we conducted two experiments in order to investigate the impact of video game experience on different aspects of visual attention specified with the TVA-based assessment tools. In Experiment 1, we compared visual attention parameters in persons with extensive experience in video gaming (experts) with parameters of persons without (or with a minimum of such) experience (non-experts). In contrast to Wilms et al. (2013) we administered the whole and partial report as separate procedures (to avoid the confounding with task switching abilities). In addition, we measured the influence of potentially meditating variables that may explain possible group differences in TVA performance (see above, Bavelier et al., 2012; Strobach et al., 2012). The potential impact of these variables had not been controlled by Wilms et al. systematically and therefore, its potential confounding influence on visual attention could not be excluded in that study. In particular, we tested (and controlled for) the potentially mediating role of personality trait constructs, social anxiety, sensation seeking, health status, and intelligence on the TVA performance of experts versus non-experts. This control is essential because of the following potential impact of these variables on video gaming: personality traits (e.g., openness, agreeableness) are important determinants of video game choice (Chory & Goodboy, 2011; Hartmann & Klimmt, 2006; Quick, Atkinson, & Lin, 2012; Ventura, Shute, & Zhao, 2013) and, as a result, may (indirectly or directly) influence whether a person has to be categorized as video game expert or not. Furthermore, personality traits may have significant effects on lower-level cognitive processing of visual information (e.g., Granholm, Cadenhead, Shafer, & Filoteo, 2002; Yovel, Revelle, & Mineka, 2005), i.e. letter processing in a global-local

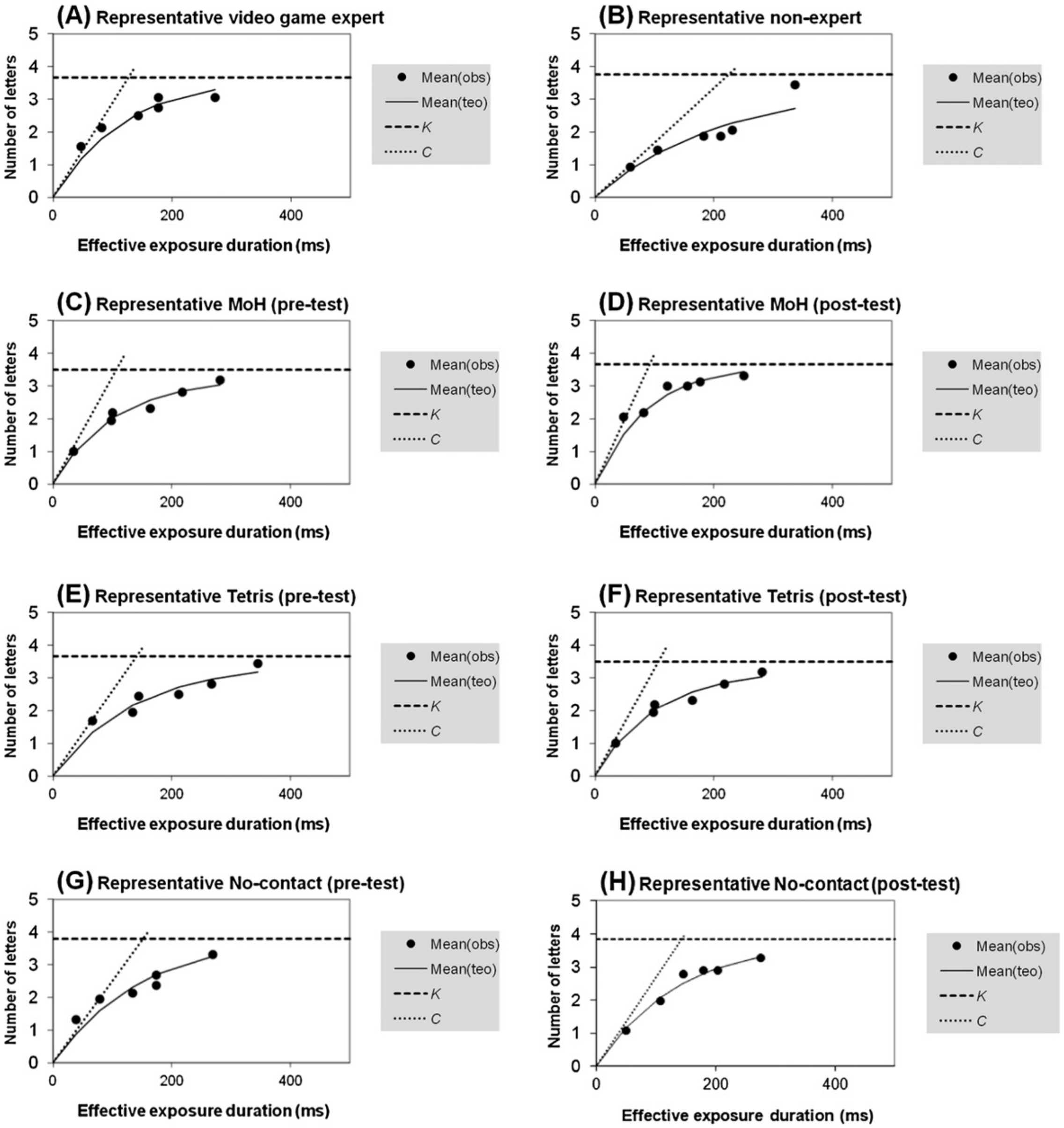

Fig. 2. Whole-report performance of representative participants for each group in Experiment 1: (A) video game expert, (B) non-expert. For Experiment 2, whole-report performance of representative participants for each group during pre-test and post-test: (C) and (D) MoH, (E) and (F) Tetris, (G) and (H) No-contact. The mean number of correctly reported letters (Mean(obs)) is shown as a function of effective exposure duration (in milliseconds [ms]). Solid curves represent the best fits of the TVA (Theory of Visual Attention)-based model to the observed values (Mean(teo)). The resulting estimates of visual short-term memory storage capacity *K* are marked by a dashed horizontal line (asymptote of the curve).

task. Social anxiety has been reported to correlate with the intensity of computer gaming (Walther, Morgenstern, & Hanewinkel, 2012) and the trait social anxiety is correlated with visual short-term memory performance in change detection tasks (Moriya & Sugiura, 2012). Sensation seeking has also been reported to affect the particular choice of video games (Zuckerman, 2006) and it has been found to be related to visual attention, i.e. to affect selective attention in visual search (e.g., Avisar, 2011). Finally, intelligence is positively correlated with a general visual attention performance factor, combining variability across numerous visual attention tasks (Huang, Mo, & Li, 2012).

In Experiment 2, we tested whether practice of an action video game can causally lead to changes in TVA parameters in persons who, initially, are non-experts in action video gaming (Boot et al., 2008; Green & Bavelier, 2003, 2007). Evidence for such causal relations is still mixed in literature. While a number of training studies suggested improvements in visual short-term memory storage capacity (e.g., Green & Bavelier, 2003, 2006), processing speed of visual information (e.g., Dye et al., 2009), and spatial resolution/distribution of attention (Feng et al., 2007; Green & Bavelier, 2006), others did not; for instance, the study of Boot et al. (2008) found no or very little evidence for video-game training-induced improvements. Enhanced basic attention skills as measured with TVA tools can therefore either directly result from video game playing and indicate optimization by video game training, or might indicate inherent superior skills (Boot et al., 2008; Green & Bavelier, 2003) in the sense of stable latent attention trait variables that characterize an individual's performance in diverse, attention-demanding task settings (Wiegand et al., 2013). Therefore, in Experiment 2 we assessed TVA parameters in non-gamers after they had practiced different video games that differed in their attentional demands.

4. Experiment 1

The central aim of Experiment 1 was to assess the TVA parameters visual threshold, processing speed, visual short-term storage capacity, visual iconic memory buffer, top-down control, and spatial distribution of attention in whole and partial report experiments (Finke et al., 2005). Based on the findings of Wilms et al. (2013) we assumed that video game experts compared to non-experts would show a larger processing speed, i.e. an increased number of elements processed per second in the whole report. Critically, the advantage should be independent of a number of (mediating) characteristics such as personality traits, social anxiety, health status, intelligence, as well as sensation seeking. Such a test for independence is essential since these variables could represent confounds in the assumed relationships between different groups of participants (i.e., video game experts vs. non-experts) and TVA parameters. Importantly, we expected the lower positions of the computer display to be most sensible for detecting a video-game related difference in processing speed (Bublak et al., 2011; Bundesen, 1990).

4.1. Methods

4.1.1. Participants

Thirty-four students were recruited from different Berlin universities through two types of advertisements in form of flyers or emails. While one type of advertisement promoted a series of experiments for males highly experienced in action video gaming (video gamers), the other type of advertisement promoted this series for males inexperienced in video gaming (non-gamers); so, both types of advertisement were addressed to particular subgroups which potentially equalizes the general level of motivation to conduct the experimental series (for discussions about the pros and cons of this procedure see Boot, Blakely, & Simons, 2011; Green, Strobach, & Schubert, 2014; Schubert & Strobach, 2012). Only males underwent testing because of the relative scarcity of females with sufficient experience in video game playing. The separation of the group of males into two groups, video game experts ($N = 17$, mean age = 24.3 years, $SD = 3.3$) or non-experts ($N = 17$, mean age = 24.6 years, $SD = 3.4$), was validated with an interview about the amount of their video game experience in action games in the last 12 months prior to testing (Green & Bavelier, 2007). To be considered a video game expert, a participant needed to report 10 or more hours a week of action game playing for the last 6 to 12 months; typical games reported were *Call of Duty*, *Counter Strike*, or *Battlefield 3*. The criterion to be considered a non-expert was a report of less than 1 hour per week of action game play for the last 6 to 12 months. All participants had normal or corrected-to-normal vision without red-green blindness. They were German native speakers and naïve about the purpose of the experiment. A handedness test (Oldfield, 1971) indicated that participants in both groups were right-handed. Participants were paid 16 € for participation in this experiment. All participants consented to act as a research participant for the Humboldt University Berlin.

To further characterize the participants, we conducted a paper-and-pencil vocabulary test on (verbal) intelligence (IQ; Wortschatztest [WST]; Anger et al., 1968). Participants were asked to rate their current general health status relative to their age group on a scale of 1 (poor) to 5 (excellent) and to indicate the number of years of formal education they had received. The D2-test measures concentration abilities in individuals. To exclude current and retrospective symptoms of attention deficit-hyperactivity disorder (ADHD), participants answered the Conners' adult ADHD rating scales (CAARS; Conners, Erhardt, & Sparrow, 1999) and the Wender Utah Rating Scale (WURS) (Retz-Junginger et al., 2002; Ward, Wender, & Reimherr, 1993). In Experiment 1 we further assessed the personality traits neuroticism, extraversion, openness, agreeableness, and conscientiousness in the context of the NEO Five Factor Inventory (NEO FFI; Borkenau & Ostendorf, 1993), the sensation seeking sub-scales novelty and intensity using the German version of the Arnett Inventory of Sensation Seeking (AISS; Roth & Herzberg, 2004), as well as the social anxiety trait score of the State-Trait Anxiety Inventory (STAI, Laux, Glanzmann, Schaffner, & Spielberger, 1981). Overall, we found no significant differences between both groups in these measures except increased IQ values of non-experts in the vocabulary test (see Table 1 for further details on these variables).

4.1.2. Apparatus

The TVA experiments were PC-controlled and conducted in a dimly lit room. Stimuli were presented on a 17-inch monitor (1024- by 768-pixel screen resolution; 70-Hz refresh rate). Viewing distance was 50 cm and controlled via chin rest.

4.1.3. Procedure

Each participant completed the whole report and partial report, each lasting ~ 0.5 h, within one testing session, with counterbalanced order across participants. Both reports had basically the same trial event sequence. First, participants were instructed to fixate a central white cross presented for 300 ms. Then, after a gap of 100 ms letters (0.58° high × 0.48° wide) were presented on a black background for a brief predetermined exposure duration. The letters for a given trial were randomly chosen from the pre-specified set {ABEFHJKLMNPRSTWXYZ}, with the same letter appearing only once. The letter stimuli were displayed to either the left or the right of the fixation cross and were either unmasked or masked. Masks consisted of squares of 0.5° filled with a + and an x presented for 500 ms at each stimulus location. Side of presentation changed randomly, so participants did not know in advance in which hemi-field the stimuli would appear. Thus, attending towards one hemi-field in expectation of stimuli, either overtly or covertly, would have no beneficial effect. Each participant received the same displays in a random sequence. Participants were instructed to maintain fixation, before the letters were presented. After presentation, participants had to verbally report all the target letters they were fairly sure they had recognized. Letters could be reported in any order, and there was no emphasis on speed of report. The experimenter entered the reported letter(s) on the computer keyboard and initiated the next trial.

4.1.3.1. Whole report. On each whole report trial, participants were briefly presented with five equidistant red or green target letters arranged in a vertical column left and right of the display center and instructed to report these letters verbally (Fig. 1A). This type of letter presentation in form of columns allows analyzing visual attention performance separately at each position. In particular, visual processing speed can be analyzed on this fine-grained positional level (Bundesen, 1990). The letter arrays were presented for three different exposure durations, and were either masked or unmasked. Owing to visual persistence, the actual exposure durations are usually prolonged in unmasked compared to masked conditions (Sperling, 1960). Thus, by orthogonally combining the three exposure durations with the two masking conditions, six different ‘effective’ exposure durations resulted. These durations were expected to generate a broad range of performance, so that coverage of the whole curve relating report accuracy to effective exposure duration would be possible.

The three exposure durations were determined individually for each participant in a pre-test phase and then introduced into the whole report phase. The individual establishment of presentation durations ensures that each subjects gets his/her individually adjusted presentation time and this allows calibrating the task difficulties of subjects in the whole report condition. In addition, this procedure provides a sufficient number of data points (recall performance at different presentation duration time points), which allows valid estimation of the TVA parameters extracted from the modeled curve relating accuracy of reproduction to presentation duration (for more details see below and Bundesen, 1990; Kyllingsbæk, 2006).

During the pre-test, the individual presentation time was determined at which a participant could report, on average, one letter per trial correctly (i.e., 20% report accuracy) in a series of 24 masked trials (12 for each hemi-field) presented with a fixed initial exposure duration (e.g., 82 ms). This presentation time was then used as the intermediate exposure duration in the experimental session, together with a shorter

Table 1

Measurements specifying video game experts and non-experts (Experiment 1) as well as participants with no practice (No-contact), practice in Medal of Honor (MoH) and Tetris (Experiment 2). Gender distribution, Age, Education, Health status of the participants (for the latter three mean/standard deviation/range). The questionnaires (i.e., WCST) measured IQ, D2 attention and concentration index, subjective retrospective attention-deficit-hyperactivity disorder (ADHD) symptoms (WURS), and range of current ADHD symptoms (CAARS; T values). WST = Wortschatztest/Vocabulary test (sum score); WURS = Wender Utah Rating Scale (Ward et al., 1993) with cutoff score > 34; CAARS = 'Conners' Adult ADHD Rating Scale (Conners et al., 1999); CAARS-subscales: A – inattention/memory problems, B – hyperactivity/restlessness, C – impulsivity/emotional instability, D – problems with self-concept, E - inattentive symptoms according to DSM-IV, F – hyperactive-impulsive symptoms according to DSM-IV, G – total ADHD symptoms according to DSM-IV H – ADHD Index; NEO FFI = NEO Five Factor Inventory; NEO FFI subscales: Neuroticism, Extraversion, Openness, Agreeableness, Conscientiousness; AISS = Arnett Inventory of Sensation Seeking; STAI = State-Trait Anxiety Inventory.

	Experiment 1		Experiment 2		
	Video game experts	Non-experts	MoH	Tetris	No-contact
Gender (N male)	17	17	11	8	10
Age (years)	24.3/ 3.3/ 19–30	24.7/ 3.4/ 19-30	24.8/ 3.3 19-32	26.0/ 3.3/ 21-32	24.5/ 3.0/ 20-29
Education (years)	16.6/ 1.9/ 14-20	17.9/ 3.5/ 13-25	17.7/ 4.1/ 12-33	18.2/ 3.0/ 14-26	16.9/ 2.7/ 13-24
Health status (1- 5)	4.2/ .5/ 3-5	4.2/ .7/ 3-5	4.2/ .7/ 2-5	4.1/ .8/ 3-5	4.2/ 1.3/ 2-5
WST: IQ	107.5	114.1*	110.8	112.9	109.3
D2: Attention and concentration index	202.1	187.1	192.2	217.2	208.8
WURS (score)	24.7	27.7	21.5	23.8	23.3
CAARS (T values)					
A: inattention/memory problems	54.3	53.1	55.9	56.4	57.9
B: hyperactivity/restlessness	44.4	46.8	47.3	49.7	50.8
C: impulsivity/emotional instability	46.8	47.9	50.0	51.8	47.8
D: problems with self concept	46.2	49.9	48.1	49.3	49.9
E: inattentive sympt. DSMIV	59.7	57.5	55.5	56.7	59.3
F: hyperactive impulsive symp. DSMIV	51.4	52.4	48.5	50.9	50.6
G: total ADHD sympt. DSMIV	57.4	56.8	53.1	55.3	56.9
H: ADHD Index	52.1	53.3	54.9	55.8	56.0
NEO FFI (T values)					
Neuroticism	48.8	51.8			
Extraversion	50.7	51.8			
Openness	58.0	58.6			
Agreeableness	50.4	51.2			
Conscientiousness	42.4	46.1			
AISS: Sensation seeking					
Novelty	27.2	28.8			
Intensity	25.8	26.2			
STAI: Social anxiety (only trait; total sum score)	39.3	40.8			

* $p < .05$.

(about half as long, e.g., 47 ms) and longer (about twice as long, e.g., 176 ms) exposure duration (with each exposure duration adjusted to the screen refresh rate). The average "short" presentation time was $M = 44$ ms ($SD = 13$) for video game experts and $M = 65$ ms ($SD = 22$) for non-experts. "Intermediate" presentation times were on average $M = 88$ ms ($SD = 27$) for video game experts and $M = 127$ ms ($SD = 46$) for non-experts, while "long" presentation times were $M = 172$ ms ($SD = 45$) for video game experts and $M = 255$ ms ($SD = 92$) for non-experts. As a result of this procedure the mean presentation times amounted to M = 100 ms and M = 145 ms for video game experts and non-experts, respectively, with significantly shorter presentation times in the first group, $F(2,32) = 10.48$, $p < 0.05$. The whole-report phase comprised 192 trials, separated into four blocks of 48 trials each. Within each block, the 12 different trial conditions (2 hemi-fields × 3 exposure durations × 2 masking conditions) of the experiment were presented equally often and in randomized order.

4.1.3.2. Partial report. During the partial report, either a single target (letter), or a target plus a distractor (letter), or two targets were presented at the corners of an imaginary square with an edge length of 5°, centered on the screen on each trial (Fig. 1B–D). All letters were masked. Two letters were presented horizontally or vertically, but never diagonally. Participants had to report only target letters (red [dark grey] for half and green [light grey] for the other half of the participants).

Equivalent with the whole report, a pretest period was conducted which served to determine the individual exposure durations, aiming for about 80% accuracy in 32 single target trials. In the experiment itself, all stimuli displays were presented for the individually adjusted exposure duration. A mean exposure duration of $M = 88$ ms ($SD = 19$) was used for video game experts and of $M = 134$ ms ($SD = 40$) for non-experts, $t(32) = 4.439$, $p < 001$. The total number of experimental trials was 288, divided into 6 blocks of 48 trials each. Within each block, the 16 different trial types (i.e., 4 single-target, 8 target-plus-distractor, and 4 dual-target conditions) were presented equally often (with 18 trials in total) and in randomized order.

4.1.4. TVA parameter estimates

The individual assessment of performance accuracy across the different whole and partial-report conditions was modeled by TVA-based algorithms using a maximum likelihood method (e.g. Ross, 2000). Detailed descriptions of the model fitting procedure and the software used can be found in Kyllingsbæk (2006).

4.1.4.1. Whole report. An exponential growth function models individual participants' letter report accuracy in relation with its effective exposure duration. This growth function is generated according to a maximum likelihood method on the basic equations provided by TVA (e.g., Bundesen, 1990; Bundesen et al., 2005). The two essential function characteristics are (A) the slope at its origin and (B) its asymptote. These characteristics represent the two TVA parameters processing speed (C) and the capacity of visual short-term memory storage (K), respectively.

In the whole report, stimulus display presentation is determined under masked and non-masked conditions. Under the masked condition, the effective exposure duration is the difference t minus t_0: t is the display presentation time and t_0 the estimated minimal effective exposure duration below which information uptake from the display is assumed to be zero. The non-masked condition is obliged to visual persistence and requires, therefore, an effective exposure duration of μ milliseconds added to the difference of t minus t_0. According to a basic TVA assumption, t_0 and μ are constant across experimental conditions for a given subject (e.g., Bundesen, 1990).

As a result, fitting the whole report raw data thus leads to the estimation of four essential parameters, outlining a participant's exponential growth function: (1) parameter t_0 is the estimated threshold value (minimum presentation time) beneath which no sensory trace is perceived (i.e., probability of report equals zero); t_0 is expressed in milliseconds and reflects the growth function coordinate (t_0, 0); (2) parameter C is an estimation of visual processing speed (rate of information uptake). According to Kyllingsbæk (2006) it can be estimated as the sum of the estimated speed values v_i at each stimulus position 1–5 (from top to bottom at left and right side) and is expressed in numbers of elements processed per second; C reflects the slope of the exponential growth function at its origin (the coordinate [t_0, 0]), based on time-accuracy indices; (3) parameter K is an estimation of visual short-term storage memory capacity (the maximum number of objects that can be represented simultaneously at a time in visual short-term memory) is expressed in number of elements; K reflects the asymptote of the exponential growth function; (4) parameter μ is the iconic memory buffer estimated from the difference in accuracy between unmasked and masked displays and sensory processing; this parameter is expressed in milliseconds.

4.1.4.2. Partial report. The parameter estimates derived from the partial-report task focuses on specific aspects of attentional selectivity: the spatial distribution of attentional weighting w_λ, and the ability to prioritize targets over distractors, top-down control α. Parameter α, reflecting the efficiency of top-down control, indicates whether attentional weights for targets (T) are greater than the weights for distractors (D; averaged across locations) and is defined as the ratio w_D/w_T; in this case, lower α values indicate more efficient top-down control. Unselective processing, by contrast, would give rise to equally weighted target and distractor processing, increasing α to approach one. A value of α greater than one would indicate that the participant actually prioritizes the task-irrelevant distractors.

The lateral spatial distribution of attentional weighting, w_{lat}, is estimated from performance in conditions in which participants have to report stimuli presented either unilaterally, on either visual hemifield, or bilaterally, in the left and the right hemi-field. From the accuracy of target identification, separate attentional weights are derived for the left (w_{left}) and the right hemi-field (w_{right}). The absolute attentional weighting has no meaning; only relative intra-individual values can be compared. Therefore, a laterality index was computed from the raw data of the ω estimates: parameter w_{lat}, reflecting the laterality of the spatial distribution of attentional weights. It is defined as the ratio $w_{left}/(w_{left} + w_{right})$. Hence, a value of $w_{lat} = 0.5$ indicates balanced weighting ($w_{left} = w_{right}$), values of $w_{lat} > 0.5$ indicate a leftward and values of $w_{lat} < 0.5$ a rightward spatial bias, because weights for objects to the left of fixation would be higher than those for objects to the right, or vice versa.

Per analogy to the index for the lateral spatial distribution, w_{vert} reflects the vertical spatial distribution of the attentional weights. It is defined as the ratio $w_{up}/(w_{up} + w_{down})$. Hence a value of $w_{vert} = 0.5$ indicates balanced weighting ($w_{up} = w_{down}$), values of $w_{vert} > 0.5$ indicate an upper and values of $w_{vert} < 0.5$ a lower spatial bias.

4.2. Results

The parameter estimates of both the whole and partial reports obtained individually for each participant allowed for statistical analyses on the group level. In the following we report the results of repeated measures ANOVAs with the between-subjects factor group (video game experts vs. video game non experts) separately for the TVA parameters.

4.2.1. Whole report

Individual, representative exponential growth functions of video game experts and non-gamers are illustrated in Fig. 2A and B, respectively.

4.2.1.1. Visual threshold: Parameter t_0. Fig. 3A illustrates the group means for parameter t_0 and represents the minimum presentation time beneath which no sensory trace is perceived. The figure illustrates a significant difference in this visual threshold parameter: the minimum presentation time is reduced in video game experts in contrast to non-experts, $F(1,32) = 4.962$, $p < .05$, partial $\eta^2 = .13$. This effect cannot be explained by person-related trait factors of participants. The group difference remained significant after the inclusion of the NEO FFI subscales neuroticism, extraversion, openness, agreeableness, and conscientiousness, the sensation seeking sub-scales novelty and intensity, the social anxiety score, the self-rated health status, concentration ability, and verbal intelligence, as covariates into univariate ANCOVAs, all $Fs(1,31) > 4.177$, $ps < .05$, partial η^2s > .13.

4.2.1.2. Processing speed: Parameter C. Fig. 3B illustrates the group means for parameter processing speed C estimated across all positions and shows that video game experts process a significantly higher number of elements per second compared to non-experts, $F(1,32) = 8.204$, $p < .01$, partial $\eta^2 = .20$. In Fig. 2A and B, the higher processing speed is illustrated as a steeper slope of the dotted line in selected examples of experts vs. non-experts, respectively. Again, we tested whether the potentially confounding person-related trait characteristics listed above can explain this effect; we found that the group difference in processing speed remained significant even after the inclusion of these variables as covariates into univariate ANCOVAs, all $Fs(1,31) > 6.953$, $ps < .01$, partial η^2s > .18.

4.2.1.3. Position-specific analysis of processing speed. In addition, we analysed visual processing speed separately for each single position 1–5 in the columns at the left and the right sides of the display. These values are illustrated in Table 3. Such a position-specific analysis is possible because the C parameter is calculated as the sum of v parameters at the individual positions according to Kyllingsbæk (2006); the position-specific analysis allows identifying those stimulus positions which benefit most from an increased processing speed on a more fine-grained level of analysis.[1] According to Bundesen (1990) and Bublak et al. (2005) processing speed is usually higher at the upper positions compared to the lower positions and we expected the superiority of the video-game experts to be rather manifested at the lower positions. Accordingly, separate ANOVAs for the C parameters of the right side showed significant differences between video-game experts' and non-experts' processing speed C at position 3, position 4, and position 5 (i.e., 3rd, 4th, and 5th position from top), $F(1,32) = 5.758$, $p < .05$, partial $\eta^2 = .15$, $F(1,32) = 5.544$, $p < .05$, partial $\eta^2 = .15$, and, $F(1,32) = 5.173$, $p < .05$, partial $\eta^2 = .14$, respectively; in all cases, experts' processing speed was higher than that of non-experts (Table 2). There were no differences between groups at position 1, $F(1,32) = 1.156$, $p > .29$, partial $\eta^2 = .04$, and position 2, $F(1,32) < 1$.The position-specific analysis for

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[1] A position-specific analysis is possible for the *general* parameter C because the *general* C is calculated by summing the v values for the individual positions according to the formulae given by Bundesen (1990) and Kyllingsbæk (2006). A position-specific analysis is not possible for the other parameters which are interpolated as common variables for the overall performance of a participant across the whole display. For simplicity we use the symbol C for referring to the processing speed (v) at the individual positions 1–5 from top to bottom at left and right side and specify whether we refer to the processing speed C at a certain position or to the general (aggregated) parameter C.

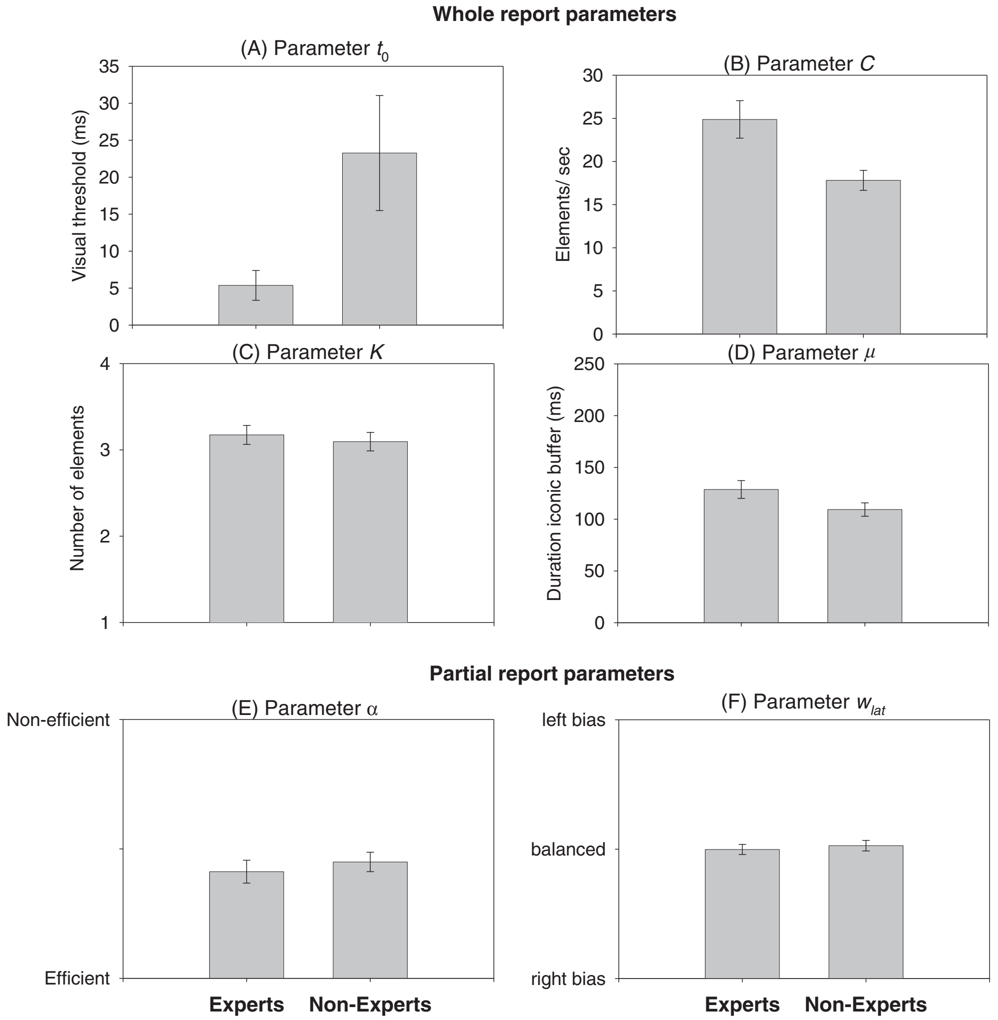

Fig. 3. Means (and standard errors) of visual threshold (t_0), processing speed (C), storage capacity (K), iconic memory buffer (μ), top-down control (α), and spatial distribution (w_{lat}) in video game experts and non-experts in Experiment 1.sec = seconds; ms = milliseconds.

the stimuli at the left side revealed a similar pattern. While we found significant differences between video-game experts and non-experts at position 3, $F(1,32) = 5.611$, $p < .05$, partial $\eta^2 = .15$, position 4, $F(1,32) = 6.991$, $p < .05$, partial $\eta^2 = .18$, and position 5, $F(1,32) = 5.013$, $p < .05$, partial $\eta^2 = .14$ (experts' processing speed higher than that of non-experts), there were no group effects at position 1 and position 2, $F(1,32) < 1$, and, $F(1,32) = 1.358$, $p > .25$, partial $\eta^2 = .04$, respectively. These findings reveal on a more fine-grained level, the distribution of those positions on the visual display in which video-game experts exhibit greater processing speed than non-experts. In particular, these places are mostly located at the lower positions, i.e. starting from position 3 to positions 4 and 5, of the display at the left and right sides.

Table 2
Processing speed (and standard error) for individual left and right side display positions (Position 1–5) separated by group (video-game experts/non-experts) in Experiment 1.

	Left side	Right side
Position 1	6.7 (1.1)/5.5 (0.6)	7.1 (1.1)/5.6 (0.7)
Position 2	6.7 (0.9)/5.5 (0.5)	7.4 (0.8)/7.4 (0.8)
Position 3	7.1 (0.9)/4.4 (0.6)	6.8 (0.8)/4.1 (0.6)
Position 4	2.0 (0.3)/1.0 (0.2)	2.2 (0.4)/1.0 (0.2)
Position 5	1.6 (0.2)/0.9 (0.2)	1.6 (0.3)/0.8 (0.2)

4.2.1.4. Short-term storage capacity: Parameter K. Fig. 3C illustrates the group means for parameter K, representing the short-term memory storage capacity. It shows that the maximum number of elements that can be represented simultaneously in visual short-term memory does not differ between video game experts and non-experts, $F(1,32) < 1$.The observation of a lacking group difference remained constant even after inclusion of all potentially confounding person-related trait characteristics listed above, as covariates into univariate ANCOVAs, all $Fs(1,31) < 2.702$, $ps > .12$, partial η^2s $< .12$.

4.2.1.5. Iconic memory buffer: Parameter μ. As illustrated in Fig. 3D, parameter μ estimations were numerically slightly higher in video game experts than in non-experts, but this difference did not reach statistical threshold, $F(1,32) = 3.271$, $p > .08$, partial $\eta^2 = .09$. Thus, our data provide no evidence for group differences in iconic memory buffering time. Similar to parameter K, the observation of a lacking group difference remained constant after inclusion of the potentially confounding person-related trait characteristics listed above, as covariates into an univariate ANCOVA, all $Fs(1,31) < 4.084$, $ps > .06$, partial η^2s $< .18$.

4.2.2. Partial report

4.2.2.1. Top-down control: Parameter α. Fig. 3E illustrates the group means for parameter α, reflecting the efficiency of top-down control, when participants need to distinguish between the defined target and the distractor. It shows a similar ability to prioritize, i.e. allocate higher attentional weights, to targets compared to distractors in video game experts and non-experts, $F(1,32) < 1$. An inclusion of person-related trait characteristics as covariates into univariate ANCOVAs did not change this pattern, all $Fs(1,31) < 3.307$, $ps > .09$, partial η^2s < .15.

4.2.2.2. Left and right spatial attention distribution: Parameter w_{lat}. As illustrated in Fig. 3F, parameter w_{lat} estimations are similar in video game experts and non-experts, $F(1,32) < 1$. Thus, attention is similarly lateralized to the left and right between groups as indicated by similar proportion of correctly reported "left" and "right" targets within experts/non-experts and between these two groups of participants.

4.2.2.3. Vertical spatial attention distribution: Parameter w_{vert}. In addition, there is also no difference in the strategic allocation of attention to the upper or the lower display parts in the partial report condition between video game experts ($w_{vert} = 0.57$) and non-experts ($w_{vert} = 0.57$), $F(1,32) < 1$. If we had found such a difference between groups then this would have been consistent with an assumption that the experts had by strategy differently allocated attention to the upper or the lower parts of the display than the non-experts.

Similar to the analysis of parameter α, parameters' w_{lat} and w_{vert} differences between the groups remained non-significant after the inclusion of potentially confounding trait factors listed above, as covariates into univariate ANCOVAs, all $Fs(1,31) < 1.855$, $ps > .19$, partial η^2s < .09.

4.3. Discussion

The present data specifies the advantages in visual attention processes in video game experts compared to non-experts by applying the theoretical and methodological framework of TVA (e.g., Bundesen, 1990; Kyllingsbæk, 2006). Replicating the findings of Wilms et al. (2013) the present study shows that video-game experts have a generally increased visual attention speed compared to non-experts. However, the current findings extend the previous observations of Wilms et al. (2013). First, we specified the display position of improved processing speed in video game experts. In particular, video-game experts showed an improved visual attention speed especially at the lower-most positions of the TVA-display. This adds to the earlier findings (Green & Bavelier, 2003, 2006) by specifying that video game experts' visual attention is not only characterized by a larger visual field of view but also by increased processing speed at the lower spatial positions of the peripheral visual field. Importantly, the increased processing speed at lower spatial position seems to not result from a changed visual search strategy in video game experts, where subjects primarily focus on the lower positions and penalize the upper positions of the display. If the allocation of attentional weights on the vertical dimension would have been different between experts and non-experts, then this should be paralleled by differences in the W_{vert} values between groups in the partial report. Thus, the observed difference in C relates to genuinely increased processing speed between groups at the corresponding positions. Second, video game experts showed a shorter pre-attentive visual threshold in form of a reduced minimum presentation time beneath which no sensory trace is perceived as well as an increased visual perceptual processing speed. Additionally, video game experts showed smaller individual display presentation times than non-experts. As the presentation times are adjusted in a way that similar performance is ensured for detecting one of five items correctly (in the whole report condition), this finding suggests faster sensory processing of targets by video game experts. Together, this demonstrates that experts' advantages are not only related to a single parameter but to multiple, pre-attentional and attentional parameters. Third, we demonstrated that the advantages in visual threshold and processing speed are robust even when controlling for numerous external variables such as personality traits, sensation seeking, anxiety, health status, and intelligence. Therefore, potential differences between these personality trait variables cannot explain the observed advantages in the visual attention performance of video game experts compared to non-experts.

5. Experiment 2

In Experiment 2, we investigated whether a relatively short amount of video game practice can causally lead to an improvement of the considered TVA parameters. We trained two groups of initially non-gamers in two games with different demands on attention processes for 15 hours, and tested the practice-related improvements in the TVA parameters in a post-test session compared to their initial performance in a pre-test session. We selected the fast-paced action game *Medal of Honor* (MoH): *Allied Assault* which simulates World War II combat situations. That selection was determined by several reasons. First, derivates of the game are similar to those games played by the video gamers of Experiment 1 and of other studies investigating video gamers and transfer effects after action video game playing (e.g., Boot et al., 2008; Feng et al., 2007; Green & Bavelier, 2003, 2006; Strobach et al., 2012). Second, this game includes an egocentric view of a complex virtual environment with high perceptual demands. The game requires players to successfully localize enemies (enemies can occur almost anywhere on screen, including in the far distance and in the periphery) and to deal with them under high time pressure. Previous research (Green & Bavelier, 2003) suggested MoH to improve a number of visual and attentional abilities, so we expected it to be ideal for testing effects of action video gaming on changes in TVA parameters. A second group of non-gamers was trained in the puzzle game *Tetris*. In Tetris, players rotate and move blocks descending from the top of the screen so that these blocks form lines at the bottom of the screen. This game requires focusing on only one object at a time in a perceptually non-demanding environment (Okagaki & Frensch, 1994; Sims & Mayer, 2002). Tetris, therefore, was not expected to improve attention skills in the way of MoH. Furthermore, it represents an excellent control condition for a possible impact of general effects on the TVA performance, which might be related to different motivation states or expectation effects between groups with different training experience (Green et al., 2014). If 15 hour of MoH practice is sufficient to cause an improvement in basic parameters of visual attention, then this should be observable in selective performance advantages in visual threshold (parameter t_0) and processing speed (parameter C) during post-test when compared to the performance after practicing Tetris. According to the findings of Experiment 1, the lowermost positions of the TVA display are most sensitive for obtaining video-game related differences in processing speed.

Contrary to the hypothesis about a short-termed training-related effect, it might be that the parameters of visual attention distinguishing between video game experts and non-experts in Experiment 1, are not subject to changes of short-termed MoH practice. In that case, we should not find significant training-related influences on the TVA parameters. A third group of non-gamers received no practice between the pre- and post-tests in order to control for possible test-retest improvements in the two groups of trainees.

5.1. Methods

5.1.1. Participants

Sixty-two students of the Ludwig-Maximilians-Universität München and Humboldt-University Berlin were randomly placed into 3 practice groups (Table 1). These students were naïve to the objective of the study as they were recruited via e-mails that included no details about the practice and test sessions. Twenty-one participants practiced MoH (mean age = 24.7 years, $SD = 3.5$), 20 participants practiced Tetris (mean age = 25.0 years, $SD = 4.3$), and 21 participants had no practice at all (mean age = 25.6 years, $SD = 3.5$). Tetris was presented without preview option. All participants were right-handed as measured by the

Edinburgh Handedness Inventory (Oldfield, 1971) and were German native speakers. In an interview, the participants reported no video-game practice in the last 6 months prior to testing. Table 1 presents the participants' demographic data, i.e. gender, age, education, health status, performance in a test on verbal IQ (WST), and concentration abilities (D2-test), which all did not differ between the three groups. For participating in this experiment, we paid 8 € per practice session and 12 € per pre-test/post-test. All participants consented to act as a research participant either for the Ludwig-Maximilians-Universität München or Humboldt-University Berlin.

5.1.2. Procedure

All participants conducted a TVA familiarization session and a TVA pre-test. Participants (of the training groups) then practiced MoH or Tetris for 15 subsequent one-hour sessions that were distributed across 4 weeks and were realized as individual and group sessions while the no-practice group had no contact with the laboratory practice situation during that time. Subsequently, all participants performed a TVA post-test session.

The TVA characteristics were identical to those characteristics in Experiment 1 with the following exception. We administered an initial TVA familiarization session to the participants, in order to introduce the general TVA procedure and material to the participants before the pre-test. This warm-up should minimize the influence of unspecific task-learning effects, which we expected to affect subjects' TVA performance especially during the pre-test but not during the post-test session. Its data was not included in subsequent analyses. This session included two and three blocks of whole-report and partial-report tests, respectively. The individual presentation times were determined separately for the pre- and post-test sessions and remained constant during the corresponding session for each group. For the whole report condition, the mean presentation times amounted to M = 120 ms, M = 128 ms, and M = 132 ms in the pre-test session and to M = 105 ms, M = 120 ms, and M = 132 ms, in the post-test session for the MoH, No-contact, and Tetris group respectively. A subsequent ANOVA with factors group and session revealed a training-specific influence on the presentation times, which was indicated by a significant interaction between the two factors, $F(2,58) = 4.05$, $p < 0.05$, partial $\eta^2 < .12$. Planned pairwise comparisons revealed that the presentation times for the three groups did not differ in the pre-test session (all $ps > 0.3$), while the MoH showed smaller presentation times compared to the No-contact group ($p < 0.05$) and to the Tetris group ($p < 0.05$) in the post-test session. The presentation times of the Tetris and the No-contact group did not differ from each other ($p > 0.24$) during post-test. During the following pre-test and post-test phases, the TVA procedure was identical with Experiment 1.

The presentation times for the partial report amounted to M = 97 ms, M = 94 ms, and M = 110 ms in the pre-test session and to M = 87 ms, M = 86 ms, and M = 110 ms in the post-test session for the MoH, No-contact, and Tetris groups, respectively. This resulted in a significant interaction of session and group, $F(2,59) = 3.913$, $p < .05$, partial $\eta^2 < .12$

5.2. Results

The parameter estimates of the pre- and post-test sessions were obtained individually for each participant and aggregated for statistical analyses on the group level. To test for possible training-related changes we report for each parameter separately the results of repeated measures ANOVAs including group (MoH vs. Tetris vs. No-contact) as a between-subject factor and session (pre-test vs. post-test) as a within-subject factor. The group and session means of these parameters are illustrated in Table 3.

5.2.1. Whole report

Individual, representative exponential growth functions of selected participants of the MoH, Tetris, and no-contact group during pre- and post-test are illustrated in Fig. 2 (MoH: Fig. 2C & D, Tetris: 2E & 2 F, No-contact: 2G & 2H).

5.2.1.1. Visual threshold: Parameter t_0. Parameter t_0 showed no main effects of group, $F(1,59) < 1$, and session, $F(1,59) = 3.105$, $p > .09$, partial $\eta^2 < .05$, as well as no significant interaction, $F(1,59) = 1.149$, $p > .32$, partial $\eta^2 < .04$. Thus, we found no transfer and no practice effects on this parameter.

As of the moderate group sizes, the lacking practice effects between the three groups of participants could be due to a lack of power. Therefore, we conducted a power analysis for parameter t_0 (and for the following TVA parameters) with G*Power (Faul, Erdfelder, Buchner, & Lang, 2009), in order to calculate the required sample size for obtaining a reliable interaction effect between group and practice on the data, which would be indicative for a training-specific improvement of parameter t_0. Given the chosen level of *alpha*, and of the obtained *power* (partial $\eta^2 < .04$) of the factor combination Group x Session, the required sample size for a specific practice effect on parameter t_0 is 2,826 participants. This means that the lacking evidence of group-specific changes is quite robust and not a result of a lack of power.

5.2.1.2. Processing speed: Parameter C. For the mean level of parameter C (i.e., aggregated across all positions), visual perceptual processing speed increased significantly from pre- to post-test, $F(1,59) = 23.693$, $p < .01$, partial $\eta^2 = .29$. There was, however, no significant effect of group or interaction including group, $Fs(1,59) < 1$. The power analysis revealed that the required sample size for a significant practice-specific effect is 7980 participants.

5.2.1.3. Position-specific analysis of parameter C. As in Experiment 1, we conducted a more fine-grained analysis of the training impact on processing speed separately for the individual positions of the computer display, which is represented in Table 4. Based on the findings of a superior performance in video game experts at the positions 3–5 in

Table 3

Pre- and post-test means (and standard errors) of the Theory of Visual Attention parameters processing speed (C), storage capacity (K), sensory processing (t_0), iconic memory buffer (μ), top-down control (α), and spatial distribution (w_{lat}) of participants with no practice (No-contact), practice in Medal of Honor (MoH) and Tetris (Experiment 2).

	MoH		Tetris		No-contact	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Whole report						
Parameter t_0	4.6 (2.2)	2.4 (1.2)	7.1 (2.9)	4.4 (2.3)	6.5 (1.5)	7.1 (2.6)
Parameter C	27. 8 (2.1)	31.9 (2.1)	22.1 (1.4)	25.6 (1.5)	24.4 (1.4)	26.7 (1.6)
Parameter K	3.3 (.1)	3.5 (.1)	3.3 (.1)	3.3 (.1)	3.2 (.1)	3.3 (.1)
Parameter μ	107.7 (6.0)	106.0 (7.6)	113.3 (8.5)	108.0 (7.6)	119.6 (7.4)	110.2 (9.8)
Partial report						
Parameter α	.44 (.04)	.45 (.04)	.46 (.03)	.45 (.03)	.46 (.04)	.43 (.04)
Parameter w_{lat}	.51 (.02)	.48 (.02)	.51 (.01)	.50 (.01)	.52 (.02)	.51 (.01)
Parameter w_{vert}	.57 (.02)	.59 (.02)	.57 (.01)	.55 (.02)	.59 (.02)	.62 (.02)

Experiment 1, we collapsed the data of each participant for these 3 positions and analysed the data separately for the right side and the left side. On the right side, this analysis demonstrated a significant interaction between group and session, $F(2,59) = 3.857$, $p < .05$, partial $\eta^2 = .12$, if we conducted a two-factorial ANVOA with the within-subject factor session (pre-test vs. post-test) and the between-subjects factor group (MoH vs. Tetris vs. No-contact). Multiple comparisons of the C values with t-tests revealed that the significant Group × Session interaction resulted from the significant training-related increases of processing speed on these low display positions in the MoH group, $t(20) = 3.825$, $p < .001$, and in the Tetris group, $t(19) = 2.152$, $p < .05$, while there was no training-related change of parameter C in the No-contact group, $ts(20) < 1$. Importantly, the increase of processing speed from pre-test to post-test was larger in the MoH group (increase in $C = 1.2$) compared to the Tetris group (increase in $C = 0.4$), $t(39) = 2.07$, $p < 0.05$. Thus, these analyses indicate a training-related improvement of the processing speed with MoH experience (as well as with Tetris) at the lower positions (3–5) of the display. Similarly to Experiment 1, we did not find hints for video game specific advantages at the upper positions of the right side. The corresponding interactions between session and group were not significant for the separate and combined analyses of C parameters at the positions 1 and 2, $Fs(2,59) < 1$. For the left side, the position-specific analyses did not provide hints for training-related improvements of parameter C at the lower positions (collapsed across 3 to 5), $F(2,59) < 1$, and the upper positions 1 and 2 (separate and collapsed), $Fs(2,59) < 1$ (see Table 4). We did not find other significant effects.

5.2.1.4. Short-term storage capacity: Parameter K. Short-term storage capacity generally increased from pre-test to post-test, $F(1,59) = 5.569$, $p < .05$, partial $\eta^2 = .09$. This increase was the same for all three groups, as there was no significant interaction between group and session, $F(1,59) < 1$; the three groups did not differ in K, $F(1,59) < 1$. Thus, there were no MoH-specific practice effects on visual short-term storage capacity. The power analysis revealed a required sample size for a significant practice-specific effect of 6,708 participants.

5.2.1.5. Iconic memory buffer: Parameter μ. The three groups did not differ in the size of the iconic memory buffer μ, nor are there any effects of session and of the interaction between session and group, all $Fs(1,59) < 1.852$, $ps > .18$, partial η^2s $< .03$. The required sample size for a significant specific practice effect is 17,163 participants.

Table 4
Processing speed (and standard error) for individual left and right side display positions (Position 1–5) separated by Group (MoH, Tetris, and No-contact groups) and Pre-test vs. Post-test in Experiment 2.

	Left side		Right side	
	Pre-test	Post-test	Pre-test	Post-test
MoH group				
Position 1	9.7 (1.2)	10.8 (1.3)	9.2 (1.0)	9.5 (1.1)
Position 2	8.9 (0.7)	9.4 (0.8)	10.3 (0.8)	11.0 (1.0)
Position 3	5.3 (0.6)	6.2 (0.5)	5.8 (0.6)	7.3 (0.7)
Position 4	1.7 (0.3)	2.3 (0.3)	2.0 (0.3)	3.4 (0.5)
Position 5	1.4 (0.4)	2.0 (0.4)	1.4 (0.3)	2.0 (0.3)
Tetris group				
Position 1	6.3 (0.7)	7.7 (0.7)	7.3 (1.1)	8.2 (1.0)
Position 2	5.9 (0.6)	7.0 (0.6)	7.5 (0.5)	8.8 (0.7)
Position 3	5.3 (0.6)	5.8 (0.7)	5.6 (0.7)	6.2 (0.8)
Position 4	1.6 (0.3)	1.9 (0.2)	2.1 (0.3)	2.3 (0.3)
Position 5	1.2 (0.2)	1.5 (0.3)	1.3 (0.3)	1.8 (0.4)
No-contact group				
Position 1	8.5 (1.0)	9.6 (1.2)	8.0 (0.9)	9.0 (1.1)
Position 2	6.6 (0.6)	7.4 (0.8)	8.5 (1.0)	9.6 (1.1)
Position 3	5.4 (0.8)	5.6 (0.9)	5.3 (0.6)	5.3 (0.7)
Position 4	1.6 (0.3)	1.9 (0.3)	2.1 (0.4)	2.3 (0.4)
Position 5	1.3 (0.3)	1.4 (0.3)	1.4 (0.3)	1.5 (0.3)

5.2.2. Partial report

5.2.2.1. Top-down control: Parameter α. No main factor and interaction proved significant when analyzing the parameter for top-down α, $Fs(1,59) < 1$. The required sample size for obtaining a significant practice-specific effect is $N > 20{,}000$ participants.

5.2.2.2. Spatial attentional distribution: Parameters w_{lat} and w_{vert}. We did not find significant main effects or interaction effects when analyzing w_{lat}, $Fs(1,59) > 3.140$, $ps > .08$, partial η^2s $< .05$. This means that attention is similarly lateralized in MoH, Tetris, and No-contact groups as indicated by similar proportion of correctly reported "left" and "right" targets within their pre-tests and their post-tests. The required sample size for obtaining a significant practice-specific effect is 9,657 participants.

The observed w_{vert} values amounted to 0.57, 0.57, and 0.59 in the pre-test sessions and to 0.59, 0.55, and 0.62 in the post-test session for the MoH, Tetris and the No-Contact group, respectively. A subsequent ANOVA showed no significant main or interaction effects, $Fs(1,59) < 1$, $ps > .2$, which indicates that the strategic distribution of attention at the vertical dimension was not different between groups and not modulated by training. The required sample size for obtaining a significant practice-specific effect is 18,415 participants.

5.3. Discussion

By and large, the present training experiment demonstrated no video game practice-specific effects on a variety of TVA parameters. In more detail, there were no differential effects of MoH and Tetris practice in contrast to no-practice on the TVA parameters visual threshold, storage capacity, iconic memory buffer, top-down control, and spatial laterality. Thus, the present data shows that 15 hours of practice with MoH or Tetris are not sufficient to causally change these TVA parameters. The validity of this conclusion is emphasized by the findings of the corresponding power analyses, which ruled out that the lack of training-specific effects results from a moderate sample size of the present study.[2]

However, with respect to the parameter of visual attention speed the findings are more puzzling and need to be discussed in a more differentiated way. While the analysis of the aggregated C parameter showed no reliable video-game-specific effects at a general level, a more fine-grained analysis provided hints that subtle training-related improvements can be detected at selected positions (i.e., the lower right positions) of the TVA display. This observation points to the possibility that appropriate practice indeed leads to specific improvements of selected TVA parameters. This conclusion is additionally supported when considering the individual presentation times for the visual search display in the whole report condition. The analysis revealed that the individual display presentation times in the TVA task were influenced by video game practice. While the presentation times of the three training groups did not differ before training, we found significantly shorter presentation times in the post-test session for the action video game compared to the Tetris group, which did not differ from the control group. Since the establishment of calibrated presentation times for the search displays aims to equalize the difficulty levels across

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[2] An alternative way to assess the lack of an interaction between group and session on TVA parameters than the power analyses is to apply Bayesian-like inference testing. Accordingly, we tested the posterior probability ($\Pr(h_0|D)$) of assuming a non-interactive, additive factor combination model versus a model that assumes a significant interaction between both factors. As one indicator for the posterior probability of the additive model in contrast to an interactive model we calculated the Bayesian information criterion (BIC) between both models (Glover & Dixon, 2004; Wagenmakers, 2007). This approach showed "positive" evidence in favour of the additive against the interaction model in case of the parameters C, K, μ, α, W_{lat} and W_{vert}, all $\Pr s(h_0|D) > 0.75$, and "weak" (but sufficient) evidence in case of t_0 $\Pr(h_0|D)) = 0.7$. Together this supports the conclusions of the power analyses and confirms that it is plausible to assume additive effects of group and session on these parameters. For details about the verbal labels of the posterior probability values see Raftery (1995, Table 6; Wagenmakers, 2007, Table 3).

subjects (Bundesen, 1990), the findings of Experiment 2 suggest that subjects benefit from action video game training for the target processing in the TVA procedure.

The assumption that practice is of use for improving TVA parameters is also supported by the fact that we found a non-specific practice effect on the parameters processing speed *C* and short-term memory storage capacity *K* across all three training groups (see also McAvinue et al., 2012). This indicates that repeated performance with the paradigm can lead to improvements of the specific mechanisms that are involved in the current TVA task and underlines the possibility of practice-related changes of the underlying mechanisms. We will come back to these practice effects in the General discussion.

6. General discussion

What specific aspects of visual attention are superior in persons with video game expertise in contrast to non-gamers? We approached this question by using elaborated TVA-based tools that allow an assessment of several parameters of visual attention under consistent experimental conditions. In essence, we found video game expert advantages in visual sensory threshold and visual perceptual processing speed. Importantly, we assessed the potential mediating influences of differences in person-related characteristics. We found that TVA advantages were not moderated by NEO-FFI personality traits, sensation seeking, verbal intelligence, social anxiety, or health status. Thus, the current findings are suggestive for robust advantages in attentional skills in video game experts. Additionally, the intervention experiment of the present study showed that video-game practice of 15 hours can causally improve several selected aspects of visual attention skills (see below) but evidence for video-game practice effects on the general level of TVA measures was rather limited.

6.1. TVA parameters and previous findings on attention in video game experts

The present findings extend the pioneering findings of Wilms et al. (2013), who showed a higher processing speed in video game expert compared to non-experts with a different type of TVA-based assessment tools than the current study. First, we were able to associate the increased processing speed to particular display positions. These positions are rather located in the lower part of the display and demonstrate the video-game experts' advantage when visual attentional processing becomes more difficult. Note that increased difficulty of visual attentional processing at lower display position is implied by the observed reduction of parameter *C* from position 1 to position 5 as found in the current study and by others (Bublak et al., 2011). Thus, the current findings suggest that video game expertise benefits the attentional processing especially at those spatial positions of the visual field, at which the attention processes are mostly deteriorated in normal people without specific experience in attention training. Importantly, the position-specific improvement is not due to a strategic change of the attention allocation to the lower positions of the display by penalizing the upper positions. If video-game experts had focused their attention especially on the lower positions to the detriment of the upper positions, then this should have led to differences in the vertical distribution of attention, which is indicated by w_{vert} parameter of the partial report condition and which did not differ between video game experts and non-experts. Thus, the processing speed in video game experts is high across the whole display including the upper and the lower positions, but the advantage compared to non-experts is more likely to be observed at the lower positions, because here there is more room for improvement because of the relatively low values of the non-experts.

Second, we demonstrated advantages of video game experts in further critical TVA parameters. Video game experts process attended material not only with an increased speed, but they even start processing the presented information more early after the onset of presentation, i.e. at a lower sensory threshold. Third, we showed the robustness of these improvements by controlling for a number of mediating variables (e.g., personality traits). Importantly, visual threshold and processing speed as measured with TVA-based whole report (and un-speeded responses) are "pure" perceptual measures which are not confounded with motor speed factors (that could potentially also differ between video game experts and non-experts, see Castel et al., 2005; Dye et al., 2009). Thus, according to the present findings it is possible to unequivocally relate the changes in TVA parameters to differences in early attention processing, which does not exclude the additional existence of differences at later motor stages.

Differences in visual threshold and processing speed can explain superior performance of video game experts in various attention tasks that rely on fast encoding of visual information. Critically, this also holds true for tasks that have mainly been interpreted to assess processing capacity (e.g., Achtman et al., 2008; Boot et al., 2008; Spence & Feng, 2010), temporal resolution (Donohue, Woldorff, & Mitroff, 2010; Green & Bavelier, 2003; Mishra, Zinni, Bavelier, & Hillyard, 2011), and spatial distribution of attention (e.g., Castel et al., 2005; Dye et al., 2009; Green & Bavelier, 2003, 2006, 2007; Okagaki & Frensch, 1994). Therefore, the critical common mechanisms that lead to the superior performance of video game experts in these tasks seem to be a combination of a higher speed of visual processing (which is in accordance with Wilms et al., 2013) and shorter minimal exposure duration needed to start perceptual processing. For example, a lower visual threshold and an increased processing speed may allow focusing on an increased number of objects within a certain time period before information decay starts. In this way, an increased number of objects can be attended simultaneously or in rapid succession within a single episode (e.g., Achtman et al., 2008). Furthermore, a higher processing speed might enhance the temporal resolution of attention (e.g., in tasks of the attentional blink type, Green & Bavelier, 2003) because it enables an earlier switch from a previously relevant target to an upcoming target. Finally, an increased processing speed might enable earlier switches from a focally attended object towards alternative locations, leading to better results in tests of the spatial distribution of attention (e.g., Feng et al., 2007). Thus, we conclude that a variety of advantages of video game experts in contrast to non-experts found in diverse task settings can result from more fundamental differences in threshold and processing speed that are relevant for successful performance in each of these tasks.

6.2. TVA parameters and intervention effects

Experiment 2 investigated the effects of different types of training interventions (i.e., MoH, Tetris, no-contact) on the TVA measures in order to test a possible causality between attention superiority and video gaming. The data need to be discussed in a differentiated way because several TVA parameters did not change as a result of 15 hours action game playing (i.e., MoH) or puzzle game playing (i.e., Tetris) while others did. The first holds for the visual threshold, storage capacity, size of the iconic memory buffer, top-down control, and spatial distribution, while the parameter processing speed improved at selected spatial positions (see below).

The lacking significance of a training-related influence on the general TVA parameters (see above) was not because of a power problem, and therefore it might be that robust transfer effects on general TVA parameters, might need more intensive video-game practice than that in the current study. It might be that the total amount of 15 hours of practice as applied in the current study was not sufficient to cause robust video-game specific training effects on the assessed TVA parameters. In the literature on video-game practice effects, the amount of time of lab-based video game practice in non-experts ranges between ten and 50 hours (e.g., Dye et al., 2009). Note that Green and Bavelier (2006) needed 30 hours of training in order to get reliable training effects on the useful field of view task. Thus, the present practice amount is a rather moderate one and effects of long-term practice such as realized in video game experts of Experiment 1 seem qualitatively and structurally different from short-term practice effects as realized due to MoH practice over a few days (Kristjánsson, 2013). A further aspect which may have counteracted the manifestation of training-related transfer effects on mean TVA parameters is related to the fact that subjects had performed a warming-up session before the pre-test session in Experiment 2. This may have caused the good starting pre-test values in selected TVA parameters such as visual threshold and processing speed in the untrained subjects of Experiment 2, which do not significantly differ from those of the (highly experienced) action video game experts in Experiment 1 (all ps > .10). Therefore, we cannot exclude that the additional warm-up experience has caused possible floor effects for the visual threshold and processing speed parameters in Experiment 2 and that possible training effect are rather underestimated with the current experiment.

This assessment is additionally supported by the fact that several findings of Experiment 2 indeed point to causal effects of practice on basic characteristics of visual attention as assessed by TVA methodology. Experiment 2 showed training-related improvements of the processing speed for selected spatial positions of the TVA display after MoH training compared to Tetris and no training. In particular, such improvements occurred for the right medium and lower positions of the display and we emphasize that these are the positions where VGP experts showed a higher processing speed than non-experts already in Experiment 1. This indicates that excessive experience with video game playing increases the spatial area from which we encode visual elements in a relatively fast manner into a stable conscious representation in visual short-term memory. Similarly to the findings of Experiment 1, the findings of Experiment 2 indicate that this does not result from a changed visual search strategy, where subjects are primarily focusing on selected lower (right) positions by penalizing the upper positions of the display. If such a strategy change would have been acquired by subjects during training, then it should be paralleled by changed W_{vert} values, but this had not been the case in Experiment 2. In contrast, subjects after MoH training show high values of processing speed at all positions of the computer screen whereas the difference to the values of the other groups reaches significance only for the medium and lower (right) positions. Note that the Tetris training group showed increased processing speed values at these positions after training as well, but this increase was smaller than in the MoH group.

The findings specify the results of earlier studies of Green and Bavelier (2003, 2006) who showed that video game playing may lead to an increase of the visual field of view. The current findings extend these observations by specifying that the field of view in video game players is not simply enlarged but that the visual attention processes of video game players are even faster when gating the sensory traces to the attentional focus at a larger space.

We can only speculate, why we found the particular right medium and lower position advantage in processing speed especially pronounced for the action video game training. One possible reason might be related to the fact that in the current version of the action video game MoH many fast changes of information occurred in the right lower corner of the computer screen; here the player's ammo and weapon information is located, which often changes during the game and this might also add to the enhanced processing speed. This may have enhanced processes involved in the fast re-direction of attention at these positions or simply the related neural substrate reflecting these spatial positions (Bundesen, 1990). However, one has to be cautious in relating the observed advantage to that characteristic of the game display because the other three corners contain important pieces of information, too. A decisive solution of this issue would require the continuous measurement of player's eye movements during the game and/or a systematic manipulation of the game display, which should be subject of future research.

A further observation underlines the view that video-game training influences basic visual attention processes in the TVA framework. The presentation times for the displays are influenced from action video gaming. While the minimum presentation times necessary to process at least one of five items correctly did not differ between the training groups before training (pre-test), action video game training led to a decrease of the presentation times compared to other trainings like Tetris. This shows that different types of speed characteristics of the visual attention mechanisms as measured with TVA may be subject to improvements that are caused by action video game training.

Further practice effects relate to the observation that repeated testing may lead to significantly enhanced estimates of selected TVA parameters (Kyllingsbæk, 2006). We observed such retest effects as a main effect of session on the parameters *C* and *K* regardless of the intervention condition (i.e., across the MoH, Tetris, and no-contact groups) in Experiment 2. Comparable effects were already documented by McAvinue et al. (2012) who also found unspecific intervention effects of other practice types (across an active self-alerting practice group, a passive self-alerting practice group, and a no-contact group). Finke et al. (2005) showed that a substantial increase of whole report trials leads to a significant enhancement of processing speed *C* estimates, while visual-short term memory storage *K* parameter estimates remained constant. According to Bundesen (1990) such improvements of processing speed due to repeated practice may result from an improved strengthening of the category relationship between the current types of letter stimuli and their category representation in long-term memory. The repeated processing of the current set of letter stimuli, which is highly unfamiliar to the participants at the beginning of the experiment, probably, leads to such a strengthening of the category relations between the current set of letters and the corresponding long-term categories.

While the observation of retest effects points to task-specific learning, the observed position-specific effects on processing speed and the effects on the presentation times indicate more general improvements of basic visual attention mechanisms due to action video game training (Schubert, Strobach, & Karbach, 2014).

6.3. Summary

Altogether, the present study demonstrated the usefulness of the TVA parameter-based assessment of multiple aspects of visual attention in order to describe the differences in visual attention performance of persons with high amount compared to low amount of video game experience. On the basis of our findings we suggest that the critical combination of decreased visual sensory threshold and faster visual perceptual processing speed is the common underlying mechanism that (A) explains findings of superior performance in a large variety of attention tests found in numerous studies on video game experts, and (B) is rather independent of person-related variables (e.g., personality traits or sensation seeking tendencies). While the results of an intervention study showed that 15 days of MoH training are hardly enough to causally change basic TVA parameters in a general sense, a more fine-grained analysis provided hints that this training can lead to improvements of the visual processing speed especially in the lower parts of the visual field. Together with the observed training-related decreases of the necessary display presentation times this indicates that different speed characteristics of the visual attention mechanisms are subject to improvements caused by action video game training. Further experimentation is necessary to investigate the possible impact of the amount of practice and of the specific content of trained experience on the TVA parameters.

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