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Do enhanced states exist? Boosting cognitive capacities through an action video-game

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ABSTRACT

This research reports the existence of enhanced cognitive states in which dramatic temporary improvements in temporal and spatial aspects of attention were exhibited by participants who played (but not by those who merely observed) action video-games meeting certain criteria. Specifically, Experiments 1 and 2 demonstrate that the attentional improvements were exhibited only by participants whose skills matched the difficulty level of the video game. Experiment 2 showed that arousal (as reflected by the reduction in parasympathetic activity and increase in sympathetic activity) is a critical physiological condition for enhanced cognitive states and corresponding attentional enhancements. Experiment 3 showed that the cognitive enhancements were transient, and were no longer observed after 30 min of rest following video-gaming. Moreover, the results suggest that the enhancements were specific to tasks requiring visual-spatial focused attention, but not distribution of spatial attention as has been reported to improve significantly and durably as a result of long-term video-game playing. Overall, the results suggest that the observed enhancements cannot be simply due to the activity of video-gaming per se, but might rather represent an *enhanced cognitive state* resulting from specific conditions (heightened arousal in combination with active engagement and optimal challenge), resonant with what has been described in previous phenomenological literature as "flow" (Csikszentmihalyi, 1975) or "peak experiences" (Maslov, 1962). The findings provide empirical evidence for the existence of the enhanced cognitive states and suggest possibilities for consciously accessing latent resources of our brain to temporarily boost our cognitive capacities upon demand.

1. Introduction

The existence of optimal experiences, in which specific cognitive processes (e.g., attention, perception) are dramatically enhanced for limited durations has been suggested by phenomenological research (qualitative analysis of narrative data, Csikszentmihalyi, 1990; Maslow, 1999; Wilson, 1972), but overlooked in the domain of experimental psychology. Csikszentmihalyi (1975, 1990, 1997) termed such experiences as *flow*, and Maslow (1962) as *peak experiences* (1965), and they defined them as unique, energized yet effortless, states of consciousness, characterized by a number of qualities, such as the merging of action and awareness (the awareness is entirely focused on the activity, and all distracting stimuli are ignored), the loss of awareness of oneself (as a social actor), intense concentration, and distorted sense of time. These states have been reported during the creative processes of visual artists (Getzels & Csikszentmihalyi, 1976), where they persisted on painting "single-mindedly, disregarding hunger, fatigue, and discomfort" (Nakamura & Csikszentmihalyi, 2002, p. 89) as well as during various gaming experiences, such as basketball, chess, or video-gaming (e.g. Keller & Bless, 2008; Moller, Meier, & Wall, 2010). The critical situational conditions allowing an individual to reach the state of flow in any domain of expertise, identified consistently across the phenomenological research, are: (1) the direct involvement in the activity, so an individual must not just be an observer, but "actively engaged in some form of clearly specified interaction with the environment" (Csikszentmihalyi, 1975, p. 43), and (2) the presence of significant challenge (termed *optimal challenge*), which pushes one's skills to their limit, but not beyond one's capacities (Csikszentmihalyi, 1975).

Despite a wealth of phenomenological reports on the existence of flow or peak experiences, and the circumstances that produce these experiences, there have been only a few experimental studies investigating the existence of enhanced cognitive states, in which a person experiences a temporary boost of cognitive capacities. For instance, Kozhevnikov, Louchakova, Josipovic, and Motes (2009)

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reported the existence of temporary meditative states, in which enhancements on a number of visual-spatial reasoning tasks requiring focused visual attention were observed after specific types of Tibetan meditation (holding the focus of attention on an internally generated image of a Tibetan deity), and persisted for 15–20 min after meditation had ended. May et al. (2011) reported improved performance on the temporal aspects of attention as measured by attentional blink task following “loving kindness” meditation, which involves focusing attention on specific mental images of selected people. Similarly, although the so-called “Mozart effect” (Rauscher, Shaw, & Ky, 1993) was not consistently replicated and was questioned (Chabris, 1999), a more recent study by Ho, Mason, and Spence (2007) observed that listening for 10 min to a Mozart sonata resulted in short-term improvement in the temporal aspects of attention as measured by an attentional blink task. Taken together these studies suggest that certain activities may lead to temporary enhancement of particular type of attention and visual-spatial cognition.

A number of researchers have speculated that action video-gaming (mainly a genre called first-person shooter or FPS) might induce a state of flow (e.g. Cowley, Charles, Black, & Hickey, 2008; Klasen, Weber, Kircher, Mathiak, & Mathiak, 2011; Procci, Singer, Levy, & Bowers, 2012; Sherry, 2004; Weber, Tamborini, Westcott-Baker, & Kantor, 2009) due to a high level of “absorption” (Weber et al., 2009, p. 403), “intense attentional focus” (p. 397), and “merging action with awareness” (Klasen et al., 2011, p. 2). Despite this conjecture, there has been no empirical research conducted to examine the possibility of attaining enhanced cognitive states as a result of video-gaming. Empirical research investigating the influence of video-games on cognition has been focused primarily on the long-term (durable) effects of video gaming (e.g. Castel, Pratt, & Drummond, 2005; Dye, Green, & Bavelier, 2009; Green & Bavelier, 2003, 2006a, 2006b; Li, Polat, Makous, & Bavelier, 2009; see also Mayer, 2014) for a review). These studies report that playing FPS games has a long-term positive effect on several aspects of visual attention, such as enhanced peripheral vision (Green & Bavelier, 2003), target discrimination, identification and contrast (Green & Bavelier, 2007; Li et al., 2009), and multiple object tracking capacity (Green & Bavelier, 2006a; Spence & Feng, 2010).

Out first goal was to examine whether FPS action video-gaming can bring about an enhanced cognitive state, similar to those observed in previous experimental literature (Ho et al., 2007; Rauscher et al., 1993) and meditative experiences (Amihai & Kozhevnikov, 2014, 2015; Kozhevnikov et al., 2009; May et al., 2011). Our second goal was to investigate the physiological correlates of such states. Since several physiological studies have reported that action video-games can elicit temporary autonomic changes (e.g., increase in heart rate, blood pressure and oxygen consumption) characteristic of heightened arousal (Hébert, Béland, Dionne-Fournelle, Crête, & Lupien, 2005; Segal & Dietz, 1991) along with corresponding improvements on attentional tasks (Skosnik, Chatterton, Swisher, & Park, 2000), we hypothesized that arousal might be a critical component of such enhanced cognitive states. Finally, we were interested in examining the cognitive correlates of such states, that is, to explore and specify the particular cognitive processes that are enhanced. Based on the results of previous experimental studies on meditative experiences (Kozhevnikov et al., 2009; May et al., 2011) and the Mozart Effect (Ho et al., 2007)), we hypothesized that the specific cognitive capacities improved during these states are the temporal aspects of attention measured by the attentional blink task, and visual-spatial focused attention. As a control we explored changes in the functioning of *other* attentional networks, which do not require focused visual attention, such as alerting, orienting, and conflict (Posner & Rothbart, 2009), which other researchers (e.g., Weber et al., 2009) have suggested to improve during the flow states induced by action video-gaming.

In order to study these enhanced states experimentally, although one cannot interrupt the activity itself without disrupting the state, our assumption was that it can be studied during its dissipation period.[1] In Experiment 1, we compared the performance of experienced action video-game players on the temporal aspects of attention (attentional blink) immediately after FPS video gaming, and after a rest period. Furthermore, to investigate whether the enhanced states resonated with the phenomenological experience of flow, we interviewed our participants about their experiences and correlated their cognitive enhancement with their scores on a flow questionnaire. In addition, to test the first claim from phenomenological literature (Csikszentmihalyi, 1975) that the enhanced states occur only during direct involvement in an activity, we compared the changes in attentional blink as a result of actively playing an FPS video-game versus merely watching. In Experiment 2, to test the second claim (Csikszentmihalyi, 1975) that the enhancements occur only when there is an optimal challenge-skill balance, we manipulated the skills-demand compatibility between participants' skills and difficulty of the video game. Furthermore, we hypothesized that cognitive enhancements induced by FPS action video gaming are related to changes in the autonomic nervous system. To assess autonomic changes, we used electrocardiographic (EKG) measures that have been shown to be reliably correlated to the activity of the autonomic system (e.g. Amihai & Kozhevnikov, 2014; Camm et al., 1996; Pagani et al., 1986; Pomeranz et al., 1985; van de Borne, Nguyen, Biston, Linkowski, & Degaute, 1994; van Dijk et al., 2013). In Experiment 3, to examine which other cognitive processes may be improved during enhanced cognitive states, we compared the performance of experienced action video-game players on the Attention Network Test (Fan, McCandliss, Sommer, Raz, & Posner, 2002), which measures conflict, orienting, and alerting components of attention, as well as on two visual tasks (visual memory and spatial transformation) immediately after FPS video-gaming versus after a rest period.

2. Experiment 1

2.1. Method

2.1.1. Participants

Thirty-two video-game players (N = 27 males) with 9 months to 16 years of experience in action video-gaming (M*years* = 8.64, SD = 3.96; M*age* = 21.3, SD = 1.31), were recruited from the online portal of the Research Participation (RP) Programme of the Department of Psychology at the National University of Singapore for course credits. The participants were naïve to the purpose of the study.

All participants had normal or corrected-to-normal vision. We required expertise in FPS action video gaming to ensure that the participants would be skilled enough to control the game, which is necessary for the induction of flow according to the phenomenological literature (Csikszentmihalyi, 1975; Seger & Potts, 2012). Thus, we only enrolled players that had spent more than 4 h per week playing video games during the 6 months prior to the experiment, similar to criteria adopted in other studies of expert gamers (e.g. Castel et al., 2005; Green & Bavelier, 2006b). In the current experiment, participants reported an average of 13.26 (SD = 9.57) hours of video game playing per week.

2.2. Materials and apparatus

2.2.1. FPS

The action video game chosen for this study was a first-person

[1] Any state, mental or physical, takes a certain period of time to develop, peak, and dissipate. In physics, an excited state of a system (such as an atom, molecule or nucleus) is any state that has a higher energy (excitation) than the ground state. The lifetime of a system in an excited state is relatively short; the return to a lower energy level is often loosely described as decay, dissipation, or relaxation. Similarly, the state of flow, which has been described as a state that occurs in the course of intense activity, does not end instantaneously after the activity has stopped but it thought to persist for about 15–20 min even after the activity has stopped (dissipation period).

shooter (FPS) game, specifically *Unreal Tournament 2004* (*UT 2004*) by Atari. The player sees three-dimensional graphics on a computer screen from the perspective of his or her avatar in the game. The player must accurately aim his or her weapon and shoot opponents by maneuvering and clicking the mouse. At the same time, the player uses the keyboard to move the avatar in all directions in order to successfully dodge the bullets and proceed through the game's terrain.

We used the 'Single Player' mode of the game, in which the number of enemies and the complexity of the geography increases as the player meets the requirements of each level. To achieve optimal challenge-skill balance, the difficulty was adjusted after each single player level was completed, according to the kill/death (KD) ratio number of kills and deaths in the game) of each participant. Specifically, similar to previous research (Green & Bavelier, 2006a), the level of difficulty was raised when the participant exceeded a KD ratio of 2:1 and was reduced when the ratio went below 1:2. Thus, optimal challenge to skill balance was defined here as maintaining a KD ratio within the interval [1:2; 2:1].

2.2.2. Survey and FFS scale

After the gaming session was over, the participants were asked to complete a 'video game experience survey', and a Flow State Scale (FSS; Jackson & Marsh, 1996) questionnaire to measure the degree of flow experience resulting from playing the video game. The questionnaire was a modified version of the FSS questionnaire designed by Jackson and Marsh (1996). In contrast to the original questionnaire, which included 9 scales related to flow, we used only 4 scales of the FSS questionnaire (N = 16 items), that are particularly relevant for video-gaming: *Action-awareness Merging* (e.g., "I did things spontaneously and automatically without having to think"; alpha-Cronbach = 0.84), *Concentration on Task* ("I was completely focused on the task at hand; alpha-Cronbach = 0.82), *Transformation of Time* ("At times, it almost seemed like things were happening in slow motion"; alpha-Cronbach = 0.82), and *Loss of Self-consciousness* ("I was not worried about my performance during the event"; alpha-Cronbach = 0.81). All items were rated using a 5-point Likert scale from 1 (*strongly disagree*) to 5 (*strongly agree*).

2.2.3. Attentional Blink Task (ABT)

Attentional blink refers to a phenomenon in which a participant exhibits a significant drop in performance when instructed to identify two target letters in a rapid serial visual presentation. Specifically, when two targets are presented within approximately 200–500 ms of one another (e.g. see Dux & Kelly, 2012; Kelly & Dux, 2011), identification of the second target tends to be impaired.

We adopted an ABT task from Raymond, Shapiro, and Arnell (1992) using E-prime 1.0 software. Participants were positioned 63 cm from a Dell 17-inch monitor. They viewed a rapid sequence of letters (approximately 0.82° × 0.82°) on a gray background at the center of the screen (see Fig. 1) and were asked to report: (a) the identity of the one white letter (T1) in a sequence of black letters and (b) whether or not a letter 'X' (T2) was present after the white letter (50% of trials). Each letter appeared for 16.7 ms, followed by an 83.3 ms ISI. The sequence varied in length from 16 to 22 letters, with the white letter appearing unpredictably anywhere from the 7th to the 15th position in the sequence" (Fig. 1).

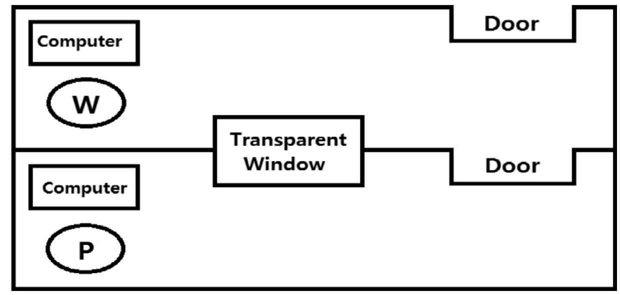

Fig. 2. Schematic drawing of the experimental lab set-up indicating where the players ("P") and watchers ("W") were seated.

In the current experiment, we used four ABT lags (Lags 2, 3, 4, and 7) in which T2 occurred after appearance of T1. At Lags 2, 3, and 4, T2 appeared 200 ms, 300 ms, and 400 ms respectively after the onset of T1, within the range of the attentional blink, whereas at Lag 7, T2 appeared 700 ms after the onset of T1, well outside of the attentional blink window (Shapiro, Arnell, & Raymond, 1997). Overall, there were 96 trials (yielding 12 trials per lag). The primary measure for ABT was accuracy of detection of T2, given that T1 was detected correctly (e.g. Green & Bavelier, 2003; May et al., 2011; Slagter et al., 2007), which is denoted as T2|T1 accuracy.

2.2.4. Procedure

First, all participants were administered the ABT as a pretest. After completing the pretest, all participants were randomly assigned to either *Player* or *Watcher* conditions. The players and watchers were positioned in separate rooms (Fig. 2) in order to minimize distraction as well as to ensure an equal distance between the participants and their screens during game play.

While the players played *UT 2004*, the watchers observed the real-time play through an identical display in the adjoining room. The video-gaming duration was 30 min. Immediately after playing/watching *UT 2004*, the participants were administered the ABT a second time (posttest 1), and then again a third time (posttest 2) after 30 min had elapsed from posttest 1 completion.

During the 30 min rest period between posttest 1 and 2, all the participants (both players and watchers) were asked to complete a 'video game experience survey' and the FSS questionnaire. In addition, all the players were interviewed regarding any distinct experiences (e.g. improved concentration, or any changes in perceiving the visual field) that were noticeably different from their perceived 'usual state'.

2.3. Results and conclusions

2.3.1. ABT

First, we excluded two participants (watchers) from all further analyses since they did not show a prominent attentional blink effect,

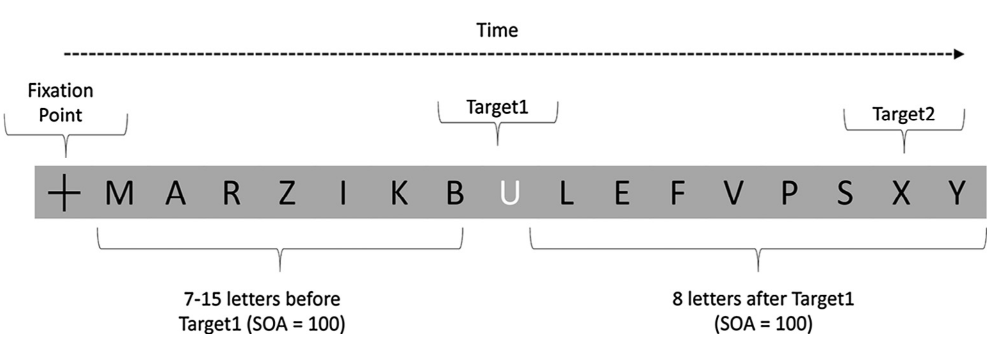

Fig. 1. Illustration of an Attentional Blink Trial. T1 is a white letter embedded in the stimulus stream (A-Z) and T2 is a black *X* presented (50% of trials) at a variable serial position after T1. SOA stands for Stimulus-Onset Asynchrony.

based on the criterion proposed by Martens, Munneke, Smid, and Johnson (2006).[2] Second, three players were unable to achieve a KD ratio between 1/2 and 2/1 at any point during the game (suggesting that their skills did not match the challenge posed by the game, see Green & Bavelier, 2006a), and were excluded from the analysis.

We conducted a 3(Time: pretest/post-test1/post-test2) × 4(Lag: 2/3/4/7) × 2(Condition: Players/Watchers) ANOVA, using T2|T1 accuracy as the dependent variable. As expected, the ANOVA yielded a significant main effect of Lag [$F(3, 75) = 38.56$, $p < .001$, $\eta_p^2 = 0.61$], demonstrating a linear increase in accuracy with increasing lags (Lag 7 > Lag 4 > Lag 3 > Lag 2, $p < .02$ for all comparisons) consistent with previous findings (e.g. Raymond et al., 1992; Shapiro et al., 1997). The main effect of Time was not significant [$F(2, 50) = 2.95$, $p = .06$, $\eta_p^2 = 0.11$] nor was the main effect of Condition [$F < 1$]. However, a significant Time × Condition interaction was observed [$F(2, 47) = 3.74$, $p < .05$, $\eta_p^2 = 0.13$]. Thus, separate follow-up ANOVAs were computed for Players and Watchers separately.

The ANOVA for Players yielded a significant effect of Time [$F(2, 24) = 6.15$, $p < .01$, $\eta_p^2 = 0.34$], and pairwise comparisons showed that T2|T1 accuracy was significantly greater during post-test1 relative to the pre-test ($p = .01$, Mpre = 0.51, SD = 0.23, Mpost1 = 0.62, SD = 0.22), as well as during post-test2 relative to the pre-test ($p = .01$, Mpost2 = 0.59; SD = 0.25), albeit the performance during post-test1 and post-test2 did not significantly differ ($p > .5$). For Watchers, the effect of Time was not significant [$F < 1$], and pairwise comparisons did not reveal any significant differences between the pre-test (Mpre = 0.52, SD = 0.21), post-test1 (Mpost = 0.50, SD = 0.23), and post-test2 (Mpost = 0.53, SD = 0.27, $p > .4$ for all comparisons, see Fig. 3). Thus, only participants who were in the *Players* condition showed significant improvement on the ABT task immediately after the game, while participants who were in the *Watchers* condition demonstrated similar levels of ABT performance before and after the video-game.

2.3.2. Survey analysis

To explore whether the enhanced attentional states experienced by players share commonality with the flow state as described by Csikszentmihalyi (1975), a qualitative analysis of interviews with the FPS players regarding their experiences during and immediately after video-game playing was conducted. Two independent judges read the transcribed interviews to identify characteristics or “salient themes” (Jackson & Marsh, 1996, p. 79) of the action video-gaming experience. The following major themes were extracted: (1) strong sense of “tunnel” focus, where attention is narrowed to a specific activity so that distractions are ignored, (2) embodiment with a video-game character and its effortless control, (3) overcoming challenges, (4) loss of awareness of immediate physical surroundings, (5) feeling of time slowing down or speeding up, and (6) feeling of excitement/arousal. As shown in Table 1, the phenomenology of action video-gaming shows strikingly similar traits to descriptions of the flow state in phenomenological studies (Csikszentmihalyi, 1990, pp. 49–66).

2.3.3. FSS analysis

We compared self-reports of players and watchers on different dimensions of the FSS questionnaire. Players showed significantly higher scores than watchers on both of the following FSS dimensions: “transformation of time”, Mplayers = 4.23 (SD = 1.17), Mwatchers = 2.57 (SD = 0.5), $F(1, 25) = 23.66$, $p < .0001$; and “loss of self-consciousness”, Mplayers = 3.92 (SD = 1.04), Mwatchers = 3.07 (SD = 0.68), $F(1, 25) = 6.45$, $p < .05$.

[2] The calculation was based on the following formula: [[(T1 accuracy at Lag 2 − T2|T1 accuracy at Lag 2)/T1 accuracy at Lag 2]/2 + [(T1 accuracy at Lag 3 − T2|T1 accuracy at Lag 3)/T1 accuracy at Lag 3]/2] × 100. Participants with a magnitude of less than 10% according to this formula were defined as non-blinkers and the inclusion of these participants would lead to noise in the data.

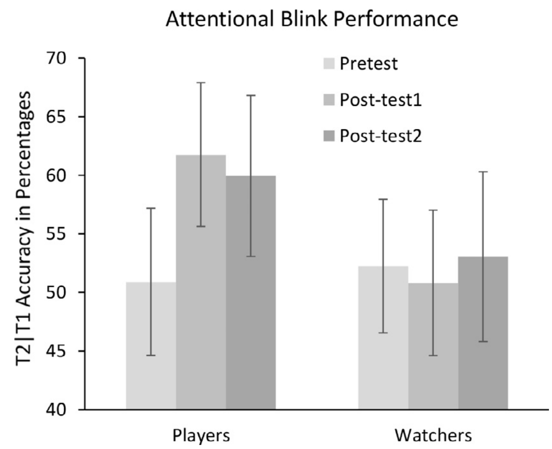

Fig. 3. T2|T1 accuracy for Players and Watchers as a function of time (collapsed across lags), for pretest, posttest 1 and posttest 2. Error bars show ± 1 *SEM*.

In summary, the results of Experiment 1 showed that players' T2|T1 accuracy increased significantly after 30 min of FPS action video-gaming compared to their baseline performance (by 65.3% for Lag2, 40.5% for Lag3, 6.4% for Lag4, and 7% for Lag7). Furthermore, the improvement on the ABT occurred only after active playing, as watchers did not show any significant increases in ABT performance. The results suggest that players experienced a state of enhanced attentional capacities, whereas merely observing real-time action video-gaming was not sufficient for its induction. In addition, analysis of the interviews with players identified themes similar to those characterized as “flow” in earlier phenomenological literature. Interviewed players frequently reported experiencing such phenomena as tunnel focus, arousal, and loss of self-awareness, consistent with descriptions of a flow experience, and reported significantly higher ratings than watchers on such dimensions of the FSS questionnaire such as “Concentration on Task”, “Transformation of Time”, and “Loss of Self-Consciousness”. One possible interpretation of the results of Experiment 1, however, is that the observed attentional enhancements along with participants' reports were merely the result of active video-gaming rather than due to the enhanced cognitive state itself. Moreover, the players' performance on the attentional blink task did not drop significantly after 30 min of rest in comparison to their performance immediately after video gaming. While it could suggest that the observed enhancements are durable, it might also be due to insufficient time for the enhancement to dissipate or be due to efficient learning during the enhanced state. Experiments 2 and 3 were designed to further explore these issues.

3. Experiment 2

The first goal of Experiment 2 was to investigate the physiological correlates of the enhancements observed in Experiment 1. Previous physiological studies have associated the state of flow with temporary changes in the autonomic nervous system (De Manzano, Theorell, Harmat, & Ulen, 2010; Peifer, Schachinger, Baumann, Schultz, & Antoni, 2010), in particular with psychological stress or heightened arousal. To assess the activity of the autonomic system we analyzed heart rate variability (HRV), and specifically, EKG low-frequencies (LF) and high-frequencies (HF) (Camm et al., 1996; Pagani et al., 1986; Pomeranz et al., 1985; van de Borne et al., 1994; van Dijk et al., 2013). Changes in HF are reliably associated with changes in parasympathetic activity, while changes in the low frequencies (LF) are assumed to reflect both sympathetic and parasympathetic activation (Akselrod et al., 1981; Malliani, Pagani, Lombardi, & Cerutti, 1991; Pomeranz et al., 1985). The ratio of LF to HF (LF/HF) have been used to quantify the changing relationship between sympathetic and parasympathetic nerve

Table 1
Main themes extracted from interview with VPGs.

Themes	Number of reports	Examples of participants' reports
Strong sense of "tunnel" focus ("Concentration on the task at hand"; Csikszentmihalyi, 1990, p. 58)	11/12	*"I became so focused in the game that my view narrows down to a tiny spot. And everything becomes clear inside that spot"*
Embodiment with a video game character ("The Merging of action and awareness"; Csikszentmihalyi, 1990, p. 53)	9/12	*"I felt that I was running just like the character inside the game. I totally identified with him"*
Overcoming challenges ("Challenging activity that requires skills"; Csikszentmihalyi, 1990, p. 49)	8/12	*"The game was so challenging that I feel jitters, but I knew I was able to handle it"*
Low awareness of immediate surrounding ("Loss of self-consciousness; Csikszentmihalyi, 1990, p. 62)	8/12	*"I am so focused in the game and I became totally unaware of what's going on outside my focus"*
Feeling of time slowing down during the activity ("The transformation of time; Csikszentmihalyi, 1990, p. 66)	8/12	*"Sometimes in the game, I would experience things moving slower. At those times, I can execute much better moves"*
Feeling of time flying while recalling the activity retrospectively ("The Transformation of Time; Csikszentmihalyi, 1990, p. 66)	6/12	*"The game was so compelling that I totally forgot about the time and I didn't know when to stop"*
Feeling of arousal	8/12	"*At the hyper alert state, there was adrenaline and I was feeling quite jittery. The fast pace ramps up the focus level I think*"

Note. Themes extracted from our interviews with players compared to the corresponding flow criteria.

activities (i.e., the sympatho-vagal balance) (Pagani et al., 1986), although recent studies (Billman, 2013), have challenged this assumption. Our first hypothesis was that arousal, the act of withdrawing from relaxation and stimulating to action (as indicated by decreased parasympathetic and increased sympathetic activities) is a critical physiological prerequisite for the enhanced cognitive states.

The second goal of Experiment 2 was to investigate the importance of optimal challenge as a condition for achieving flow, as has been suggested in phenomenological literature (Csikszentmihalyi, 1975). We assigned participants into three groups: *Under-challenge (UnC)*, *Optimal-challenge (OpC)*, and *Over-challenge (OvC)*, in which they were presented with an FPS game of low, average, or high level of difficulty, respectively. Our second hypothesis was that if in fact the improvements on the attentional blink task observed in Experiment 1 were the result of an enhanced cognitive state, rather than active video-gaming per se, then only OpC group would exhibit these improvements along with associated arousal.

3.1. Method

3.1.1. Participants

Fifty-six participants (N = 39 males) were recruited from the online portal of the Research Participation (RP) Programme in the Department of Psychology at the National University of Singapore for credit reimbursement. The participants were naïve to the purpose of the experiment. Since in this experiment we manipulated the level of videogame difficulty, there were no specific requirements on participants' video-gaming experience, as long as they had some prior and on-going experience and interest in FPS video gaming. Overall, 5 participants reported playing more than 10 h per week, 11 participants reported playing between 4 and 10 h, and 40 participants reported playing between 2 and 4 h of FPS per week.

Upon arrival, participants were randomly assigned to one of the three groups: UnC, OpC, and OvC. In particular, 16 participants were assigned to the UnC group, 22 participants to the OpC group and 18 participants to the OvC group. The three groups did not differ either in years of video-gaming experience [$F(2, 49) = 1.76$, $p = .18$], nor frequency of playing ($F < 1$, $p = .73$).

3.1.2. Materials and procedure

Both the ABT task and the FPS video game (UT 2004 by Atari) were identical to those used in Experiment 1.

First, the experimenter put on the participants the electrodes for EKG recording. Then, the participants were administered the ABT as a pretest, after which they were briefly interviewed about his/her gaming background, and asked to provide demographic information. Second, to get participants accustomed to the particular FPS videogame used in the study, they were asked to play Stage 1 – during which the characters and game setting were introduced – at the "Experienced" level (Level 3) for 5 min. The participants were told that the aim of the playing session was to enjoy themselves, while trying their best in the game. During this period, the experimenter observed the performance of each participant on the computer screen next door that displayed the same graphics as the participants' screen, in order to judge the participant' skills level apropos the group they were assigned. In particular, during this period the experimenter screened the participants to exclude any novices who were unable to play at the "Experienced" level and to identify any extremely skilled practitioners for whom the "Experienced" level was exceedingly easy. As a result of the 5-min screening period, one participant (randomly assigned to the UnC group) was identified as a novice who unable to play at the "Experienced" level, and his data were excluded from all the analyses. Another participant, who exhibited extremely advanced skills during screening, was reassigned from the OvC group to the UnC condition, as it became clear that even the highest levels of the game would not be particularly challenging for this individual. Thus the resulting tallies for each group were as follows: UnC: 16, OpC: 22, and OvC: 17.

Third, after playing for 5 min, the participants were reassigned to a new game level, according to their experimental manipulation group. In the UnC group, participants were assigned to a lower level of game difficulty, usually "Average" (Level 2) or "Novice" (Level 1). In the OpC group, participants were assigned to "Experienced" (Level 3) or "Adept" (Level 4) levels. Participants in OvC group were assigned to the highest levels of difficulty, usually "Expert" (Level 5) or "Inhumane" (Level 6). All participants played the videogame for 30 min, with the UnC and OpC groups starting at the highest level of difficulty for their group (level 2 for the UnC, level 4 for the OpC group), and lowest level of difficulty (level 5) for the OvC group. During this play, the level of difficulty was readjusted after the end of the first match (about 15 min into the play period) for participants who were not able to achieve the specific KD ratio for their assigned group. Specifically, the difficulty level was decreased if the KD ratio went below 2:1 for participants in the UnC group, and it was increased if KD ratio went above 1:2 for participants in the OvC group, following criteria specified in previous research (Green & Bavelier, 2006a). Participants in the OpC group were expected to maintain a KD ratio between 1:2 and 2:1, and the level of difficulty for this group was raised when a participant exceeded a KD ratio of 2:1 and reduced when the ratio fell below 1:2. Thus, the KD ratio was maintained in the following intervals: UnC [2:1, $+\infty$], OpC [1:2, 2:1] and OvC [0, 1:2]. If a participant was unable to achieve the KD ratio required for his/her assigned group at any point during the game (i.e., either at levels 6 or 5 for OvC, 4 or 3 for OpC, and 2 or 1 for

UnC), the participant's data were excluded from all analyses.

Finally, after the playing session, each participant was given a 2-min self-report questionnaire, consisting of 4 questions, in which they were asked to assess the level of the challenge and its match to their skills on a 0–5-point scale (total score of 20). This was followed by an additional ABT session (post-test1), followed by 30-min rest period, after which the participants performed the ABT for the third time (post-test 2). The whole experiment lasted about one and a half hours in total and the participants were debriefed after the experiment.

3.1.3. EKG recording and protocol

Although various measures (e.g., blood pressure, oxygen consumption, load on the heart, as well as galvanic skin response) have been used to quantify changes in the autonomic system, we chose to use EKG as it is both non-invasive and less sensitive to environmental conditions such as humidity and temperature. Additionally, since the EKG electrodes were placed on the participants' torsos, the signal was less susceptible to motion artifacts induced by arm movement during the game.

In the current experiment, the participants had their EKG measured throughout the entire experiment. EKG was recorded using the BioTrace + Software recording system (Mind Media B.V.), and was sampled at 256 Hz, and a high-pass filter of 0.1 was applied to the data. The measures were taken via two electrodes, one placed on the right collarbone and another below the left rib cage, and referenced to the left collarbone.

3.1.4. Heart rate variability analysis

HF were computed using Welch's periodogram method (FFT spectrum), and were measured in absolute power (milliseconds squared). The HF frequencies we analyzed were 0.15–0.4 Hz, and the LF frequencies were 0.04–0.15 Hz, the ranges most commonly used in EKG analysis (Berntson et al., 1997; Bigger, Fleiss, Rolnitzky, & Steinman, 1992; Billman, 2013; Molgaard, Hermansen, & Bjerregaard, 1994; Stein et al., 1993). The HF and LF changes due to videogame playing were calculated as the percent difference between the first and final 5 min of video-game playing, and the ABT performance change was calculated as the percent difference between post-test1 and pre-test performance on lags within the attentional blink window (i.e. 2, 3, and 4).

3.2. Results and conclusions

Three participants were excluded from all analyses because they were unable to achieve the KD ratio required for their group at any point during the game. Two additional participants, who were "non-blinkers" and did not show an attentional blink effect, were also excluded from the analysis. Finally, one participant in the UnC group was excluded from all analyses as an outlier, since this participant showed improvement on ABT (ΔABT = 0. 26) greater than 3SD above the UnC group mean (ΔABT = −0.02, SD = 0.11). Thus, the final data analyses below include 49 participants: 14 in the UnC, 20 in the OpC, and 15 in the OvC group.

To ensure that the assignment of the participants to the three groups corresponded to the intended level of challenge, we compared the participants' assessments of perceived challenge and its match to their skills. There was a significant difference between the three groups in their perceived level of challenge: $F(2, 49) = 19.3$, $p < .001$. Consistently with the experimental manipulation, UnC group participants reported the least degree of challenge (M = 10.9, SD = 1.50), in comparison to the other two groups ($p < .05$), while OvC group participants reported the highest degree of challenge (M = 15.9, SD = 1.89; $p < .01$). The OpC group participants (M = 13.7, SD = 2. 87) reported significantly higher challenge than the UC group participants ($p < .05$) but lower than participants from the OvC group ($p < .001$).

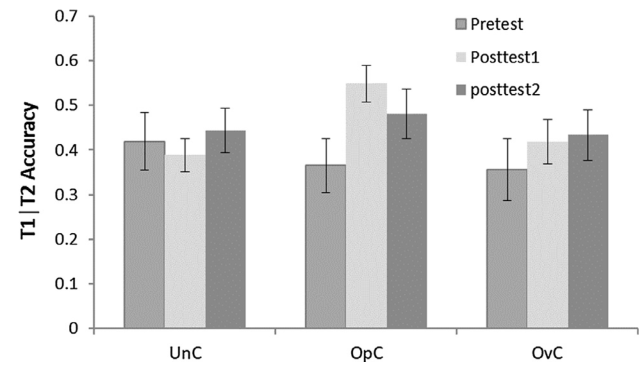

Fig. 4. Performance on ABT pre-test, post-test 1, and post-test 2 by Group.

3.2.1. ABT performance

We conducted a 3 (Time: pretest/post-test1/post-test2) × 4 (Lag: 2, 3, 4, 7) × 3 (Group: UnC, OpC, and OvC) ANOVA using T2|T1 accuracy across lags 2, 3, 4, and 7 as the dependent variable (see Fig. 4).

As expected, the ANOVA yielded a significant main effect of Lag [$F(3, 47) = 18.55$, $p < .001$, $\eta_p^2 = 0.60$], demonstrating a linear increase in accuracy with increasing lags (Lag 7 > Lag 4 > Lag 3 > Lag 2). The main effect of Group was not significant $F(2, 46) = 0, 41$, $p = .67$), however, there was a significant effect of Time, $F(2, 465) = 11, 41$, $p < .01$, $\eta_p^2 = 0.24$). Also, there was a significant interaction between Time and Group, $F(4, 92) = 7.11$, $p < .001$, $\eta_p^2 = 0.24$).

The follow-up ANOVA for the UnC group yielded a non-significant effect of Time, $F(2, 26) = 1.361$, $p = .022$. The UnC group did not show significant improvements in their ABT performance either from the pre-test to post-test1 (Mpre = 0.44, SD = 0.24; Mpost1 = 0.40, SD = 0.24; $p = .12$) or from the post-test1 to posttest2 (Mpost2 = 0.47, SD = 0.27; $p = .11$). The ANOVA for the OpC group yielded a significant effect of Time [$F(2, 38) = 14.38$, $p < .01$, $\eta_p^2 = 0.43$], and pairwise comparisons showed that T2|T1 accuracy was significantly greater during post-test1 relative to the pre-test (Mpre = 0.42, SD = 0.25, Mpost1 = 0.55, SD = 0.19, $p = .001$, see Fig. 4), as well as during post-test2 relative to the pre-test (Mpost2 = 0.48, SD = 0.27, $p < .01$). The performance of the OpC group slightly decreased from post-test1 to post-test2, but the change was not statistically significant ($p = .10$). Finally, for the OvC group, the effect of Time was not significant [$F(2, 28) = 2.71$, $p = .08$, $\eta_p^2 = 0.16$]. The OvC group showed a slight, but non-significant improvement in T2|T1 accuracy from the pre-test to post-test1 (Mpre = 0.38, SD = 21, Mpost1 = 0.42, SD = 0.22, 35.6% vs. 41.8%, $p = .07$), and no significant changes from post-test 1 to post-test 2 (Mpost2 = 0.43, SD = −0.22, p = .66).

Thus, only the OpC group showed a significant improvement on the ABT task after playing the FPS videogame, while the participants in other groups demonstrated similar levels of ABT performance before and after the video game. Similar to the results of Experiment 1, performance of the OpC group on the ABT task did not drop significantly after 30 min of rest.

3.2.2. HRV analysis

First, for each group, we computed the changes in LF and HF, as percentage difference in the LF and HF values, for the last 5 min of video-game playing in comparison to the first 5 min. Due to the noise in EKG recording, LF data for one participant from the OvC group were discarded.

The OvC group showed no significant changes in HF ((M = 5.60, SD = 43.64), $t(14) = 0.49$, $p = .6$ or in the ratio ΔLF/HF (M = 2.95, SD = 13.23), $t(14) = 0.87$, $p = .4$. However, the increases in LF (M = 49.54, SD = 64.54) were significant, $t(14) = 2.97$, $p = .01$), indicating unchanged parasympathetic activity and increased sympathetic activity (Toledo, Gurevitz, Hod, Eldar, & Akselrod, 2003). The

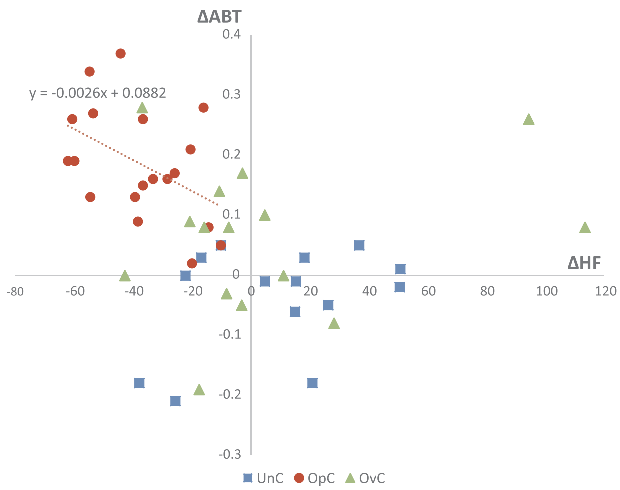

Fig. 5. Changes in ABT versus changes in HF for UnC, OvC, and OpC groups.

OpC group showed significant decreases in HF ($M = -37.08$, $SD = 16.49$), $t(19) = -10.06$, $p < 001$, but no significant changes in LF ($M = 1.72$, $SD = 75.81$), $t(18) = 0.09$, $p = .9$) or in the ratio ΔLF/HF ($M = -1.14$, $SD = 5.19$), $t(18) = 0.95$, $p = .35$. The pattern of HF decreasing and LF increasing (or remaining unchanged) indicates a reduction in parasympathetic activity and increase in sympathetic activity with a shift in balance toward relative sympathetic enhancement (Toledo et al., 2003). The UnC group did not show significant changes in either HF ($M = 8.85$, $SD = 28.11$), $t(13) = 1.18$, $p = .26$ or LF ($M = 22.18$, $SD = 88.83$), $t(13) = 0.93$, $p = .37$), or in the ratio ΔLF/HF ($M = 2.41$, $SD = 8.01$), $t(13) = 0.13$, $p = .28$, indicating unchanged parasympathetic and sympathetic activities (Toledo et al., 2003).

While both the OvC and OpC groups showed increased sympathetic activation, only the OpC group showed a withdrawal from parasympathetic control (as indicated by HF decreases), suggesting that the HF decreases are related to the improvement on the ABT task. In order to test this, we first regressed the changes in ABT performance (ΔABT) from pre-test to post-test1 on the changes in HF (ΔHF) for the participants from all three groups. Overall, ΔHF significantly predicted ΔABT, $R = 0.33$, $R^2 = 0.11$, $F(1, 48) = 5.58$, $p = .02$. Second, we regressed ΔABT from pre-test to post-test1 on ΔHF separately for each of the three groups (see Fig. 5). For both the UnC and OvC groups, there were non-significant relationships between ΔHF and ΔABT for ($R = 0.37$, $R^2 = 0.03$, $p = .20$ for the UnC and $R = 1.86$, $R^2 = 0.034$, $p = .51$) for the OvC). In contrast, for the OpC group, ΔHF significantly predicted ΔABT, explaining a significant proportion of variance in ΔABT, $R = 0.460$, $R^2 = 0.211$, $F(1, 18) = 4.83$, $p = .04$.

In summary, our results in Experiment 2 showed that only the OpC group exhibited a significant improvement on the ABT task from the pre-test to post-test 1, lending support to our hypothesis that the observed enhancements were not due specifically to the activity of video-gaming, but due to enhanced cognitive states requiring special conditions such as active participation (Experiment 1) and optimal skill-challenge match (Experiment 2). Furthermore, our finding that the OpC group was the only group that had significant HF decreases suggests that the decrease in parasympathetic activity is critical for reaching enhanced states. Moreover, the regression analyses showed the magnitude of attentional enhancements to be directly related to HF decreases, suggesting that the enhanced cognitive state is not uniform across individuals. Another interesting finding from Experiment 2 is that although the OvC group showed sympathetic activation, no improvement was observed in their performance on the ABT task. Thus, according to our results although sympathetic activation is a necessary condition for enhanced cognitive states, it is not sufficient by itself to induce the state.

4. Experiment 3

The goal of Experiment 3 was to further investigate which cognitive processes are enhanced during the enhanced cognitive states. Specifically, we hypothesized that various attentional networks – conflict, orienting, and alerting (Fan et al., 2002) – and visual memory and spatial transformation abilities may be enhanced as a result of playing FPS.

4.1. Method

4.1.1. Participants

Twenty-three experienced video-game players (all males) with 1–10 years of experience in action video-gaming ($M_{years} = 8.64$, $SD = 3.96$; $M_{age} = 21.3$, $SD = 1.31$) were recruited from the online portal of the Research Participation (RP) Programme in the Department of Psychology at the National University of Singapore for credit reimbursement. All the participants were naive to the purpose of the study.

The participants played a minimum of 3 h per week during the six months preceding the experiment (mean = 11.52, SD = 7.74).

4.1.2. Materials and apparatus

As in Experiments 1 and 2, the action video game chosen for the current experiment was *UT 2004* by Atari using 'Single Player' mode with manual difficulty adjustments.

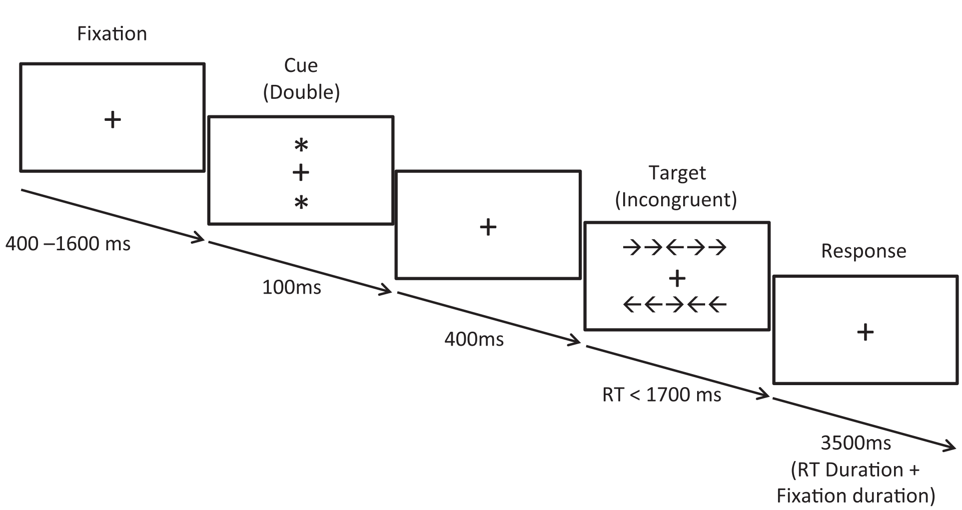

Fig. 6. Illustration of an Attention Network Test (ANT) trial.

4.1.2.1. Attention Network Task (ANT). The participants were administered the ANT (see Fig. 6), a computerized test “assessing the efficiencies of three brain networks underlying attention: alerting, orienting, and conflict of attention” (Posner & Rothbart, 2009, p. 109).

While the alerting network underlies the ability to “increase and maintain response readiness in preparation for an impending stimulus” (Raz & Buhle, 2006, p. 372), the orienting network underlies the ability to “prioritize sensory input by selecting a modality or location” (Raz & Buhle, 2006, p. 372). The conflict network underlies “supervisory, selective, conflict resolution” (Raz & Buhle, 2006, p. 374).

Participants were seated approximately 35 cm from a 14-inch color display. A row of five horizontal arrows was presented on the screen, and participants indicated the direction (left or right) that the center arrow (the target) pointed to by pressing a corresponding key as quickly as possible. The flanker arrows (i.e., arrows surrounding the target) pointed either in the same direction as the target (the congruent condition), or in the opposite direction (the incongruent condition). The stimulus row was presented either above a fixation point (top) or below (bottom). Furthermore, the stimulus row could be preceded by a cue (the cued condition) or not (the no-cue condition). The cue was presented either at the central fixation location (the center-cue condition) at the top or bottom location where the stimulus row was due to appear (the spatial-cue condition), or at both top and bottom locations (the double-cue condition). Each trial was initiated by a fixation cross for 400–1600 ms, followed by the cue condition for 100 ms, and then the stimulus (row of arrows), which remained visible on the screen until response but for no longer than 1700 ms. The version used in the present study consisted of 3 blocks of 96 trials (~10 min per block) preceded by one practice block with 24 trials. All trial types were presented in random order.

The efficiency scores for the alerting network were calculated as the time taken to respond to the no-cue condition minus the time taken to respond to the double cue condition. This is because attention tends to remain diffused across potential target locations when no cue is provided, and the double cue alerts the participant of the appearance of the target (temporal cue) while keeping attention diffused between the two locations (Fan et al., 2002). For the orienting network, scores were calculated as the time taken to respond to the center-cue condition minus the time taken to respond to the spatial-cue condition. While both center- and spatial-cues promote the orientation of attention to one location, only the spatial-cue condition provides predictive information about the orientation of the upcoming target (Fan et al., 2002). Finally, the efficiency of the conflict network was calculated as the time taken to respond to the incongruent cue minus the time taken to respond to the congruent cue condition (Fan et al., 2002). The internal reliabilities of the ANT are 0.93 for the conflict network, 0.65 for orienting, and 0.80 for alerting (Ishigami & Klein, 2010).

4.1.2.2. Visual Memory Test (VMT). The VMT (MM Virtual Design, 2004) consisted of two parts. In the first part, participants were administered six trials during which a single image appeared for 5 s and was subsequently replaced by an array of six images. The array consisted of the original image along with five distractors, and participants were asked to identify the original image (see Fig. 7). The second part of the VMT consisted of 18 trials during which participants first viewed an array of seven images for 8 s followed by another array of seven images, six of which appeared in the previous array and one novel image. Participants were asked to determine which image in the second array did not appear in the first.

4.1.2.3. Mental Rotation Test (MRT). On each trial of the MRT (Shepard & Metzler, 1971), participants viewed a pair of three-dimensional objects, which were rotated relative to each other around the x, y, or z-axis. Across trials, the amount of rotation ranged from 40° to 180°, in 20° increments. Participants were asked whether the two objects were identical or mirror images. The test consisted of 36 trials, 18 in which the objects were the same, and 18 in which they were mirror images.

4.1.3. Procedure

All the participants were tested individually, in a session lasting about 2.5 h. They completed the ANT, MRT, and VMT as a pre-test (the order of the tests was randomized), followed by 30 min of video gaming. After that, the participants were assigned randomly to one of the two following conditions (Fig. 8):

(1) Condition 1 ($N = 13$): Participants were asked to complete the MRT and VMT in a randomized order, as posttest 1 (immediately after 30 min of action video-gaming), and ANT as posttest 2 (after 30 min of rest, following completion of post-test 1).
(2) Condition 2 ($N = 10$): Participants were asked to complete the ANT as posttest 1, and MRT and VMT in randomized order as posttest 2.

The above two conditions were created to minimize the repeated administration of the ANT and visual tasks to the participants. Previous studies demonstrate significant practice effect for the ANT conflict network measure (Costa, Hernández, & Sebastián-Gallés, 2008; Ishigami & Klein, 2010) and a similar practice effect for visual-spatial tasks (Lohman & Nichols, 1990). In addition, administration of the ANT alone takes a full 30 min, which might be longer than the duration of enhanced cognition, thus making it impossible to administer all the three tests (ANT, VMT, and MRT) as part of the posttest 1 condition.

4.2. Results

The above experimental design assumes similar performance by participants in both Conditions 1 and 2 on the pretest, and indeed, there were no significant differences between pre-test scores across the two conditions, on any measure (conflict network [$F < 1$]; orienting network, $F(1, 22) = 1.73$, $p > .2$; alerting network [$F < 1$]; VMT [$F < 1$]; MRT [$F < 1$]).

4.2.1. Attention networks

We analyzed performance on the ANT using response time (RT) scores for correct trials only. Outlier response times (RTs; i.e., more than 1000 ms or less than 200 ms) were deleted ~1.7% of responses). All participants had an overall accuracy of more than 91% ($M = 98.13$, $SD = 1.94$) on each test session. For each of the attention networks (alerting, orienting, and conflict) we conducted a mixed 2 × 2 ANOVA with Time (pre-test and post-test) as a within-subject variable and Condition 1 vs 2 as a between-subject variable. For the Alerting network, we found a significant main effect of Time [$F(1, 22) = 6.29$, $p = .02$, $\eta_p^2 = 0.22$]. However, we found no significant main effects of Condition [$F < 1$] nor Time × Condition interaction [$F < 1$]. For the Orienting and Conflict networks, no significant main effects or interactions were found ($p > .17$ for all comparisons).

4.2.2. Visual-spatial tasks

Previous studies have indicated the existence of a speed-accuracy trade-off on visual-spatial tasks, especially after practice or repeated exposure to the tests (e.g., Lohman & Nichols, 1990). In order to avoid any confounds arising from a speed-accuracy trade-off, a measure of *visual-spatial processing efficiency* was computed for the mental rotation and visual memory tasks, similarly to what was done in previous studies (Kozhevnikov et al., 2009). Visual-spatial processing efficiency was calculated by dividing each participant’s proportion of correct responses by the natural log of his or her average RT. Thus, the efficiency measure we report below refers to the number of correct responses made by the participant in one unit of time (log seconds). The analysis of visual-spatial processing efficiency is presented below.

4.2.2.1. VMT. Outlier response times (RTs ± 2.5 SD from a participant’s mean) were deleted (VMT pretest: 1.57% of responses;

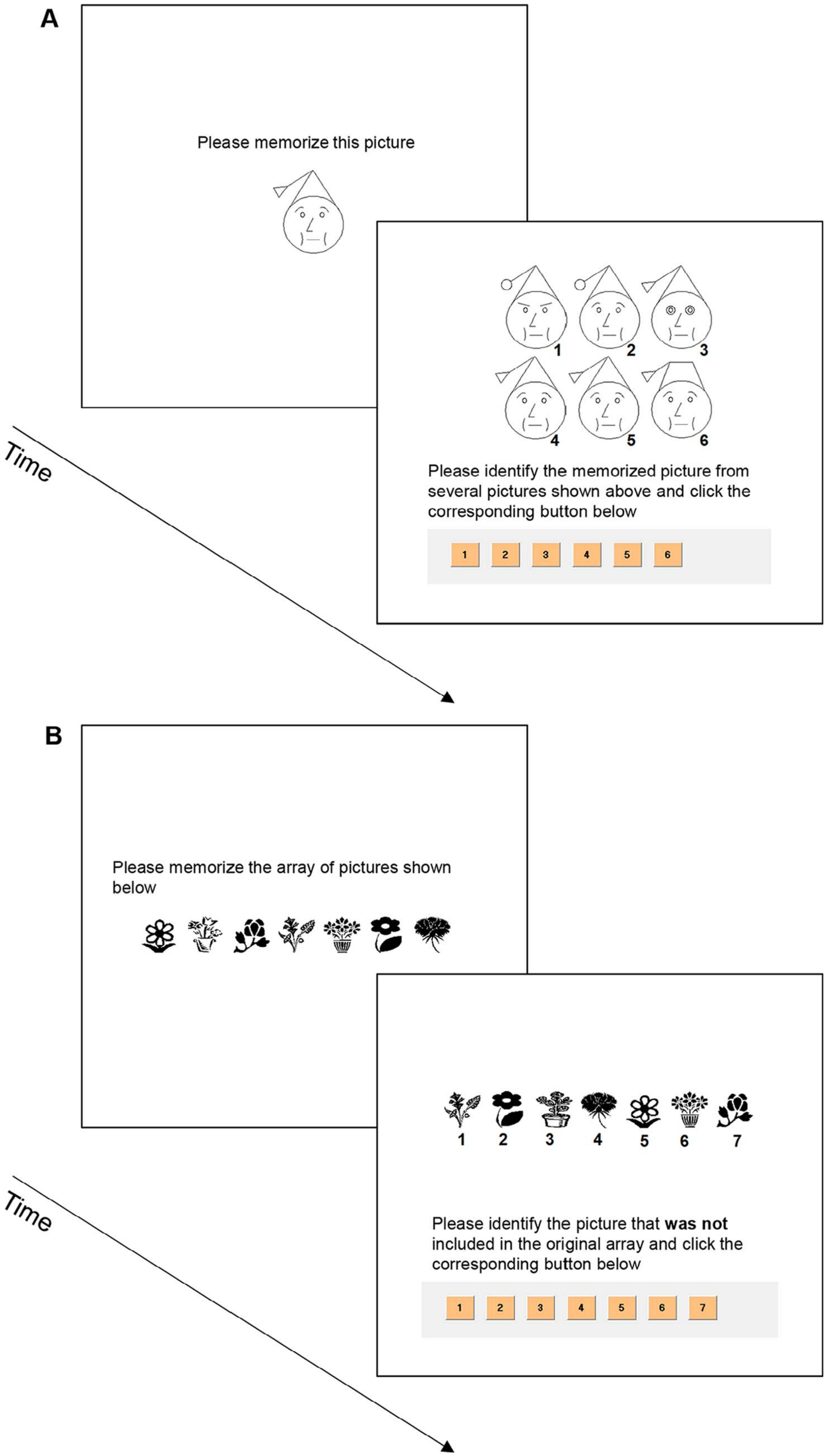

Fig. 7. Examples of items from the Visual Memory Test (VMT).

VMT posttest: 1.50% of responses). Fig. 9 presents the results for VMT processing efficiency.

A 2 (Time: pretest vs. posttest) × 2 (Condition: 1 vs. 2) mixed-model ANOVA yielded a significant main effect of Time, $F(1, 21) = 16.95$, $p < .001$, $\eta_p^2 = 0.45$, as well as a significant effect of Condition, $F(1, 21) = 5.62$, $p < .05$, $\eta_p^2 = 0.21$. The Time × Condition interaction was also significant, $F(1, 21) = 12.53$, $p < .01$, $\eta_p^2 = 0.37$. Follow-up ANOVAs revealed a significant increase

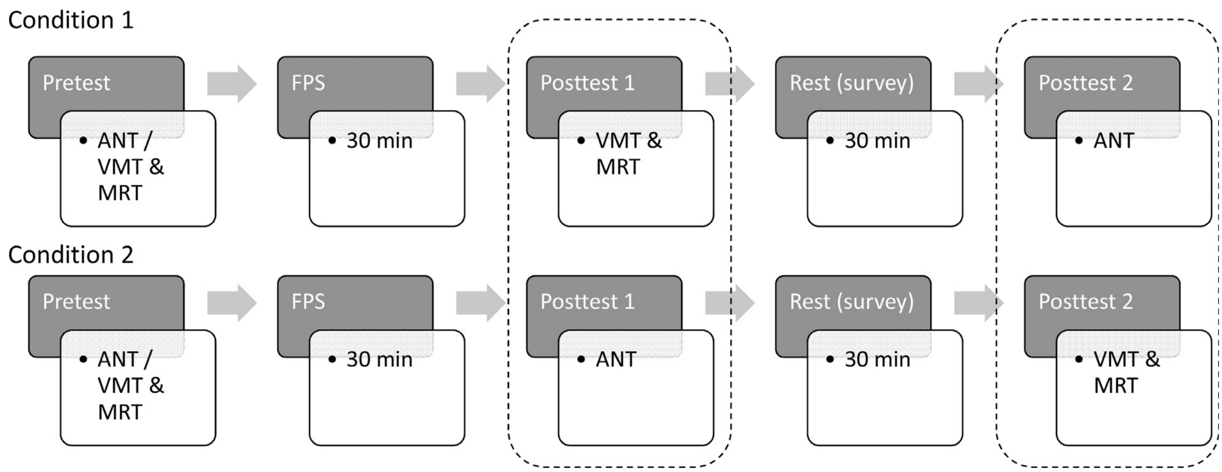

Fig. 8. The time sequences of the different Conditions for Experiment 2.

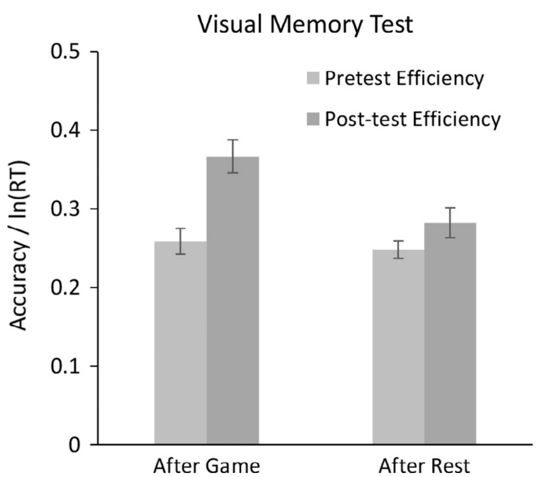

Fig. 9. Processing of efficiency on the visual memory pre- and post-tests as a function of Condition. Error bars show ± 1 *SEM*.

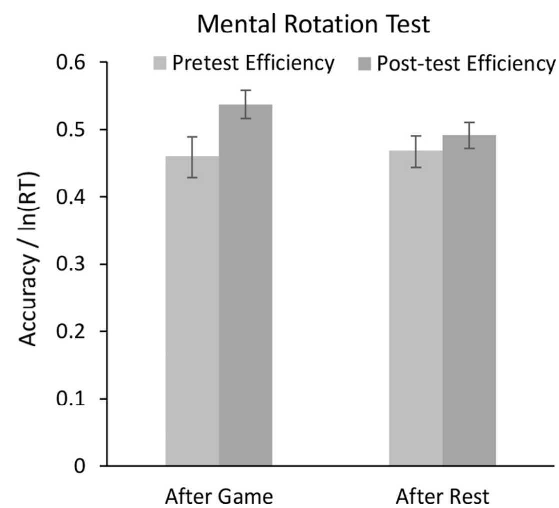

Fig. 10. Processing of efficiency on the mental rotation pre- and post-tests as a function of Condition. Error bars show ± 1 *SEM*.

in VMT processing efficiency from the pretest to the posttest for Condition 1 (after the video-game), Mpre = 0.27, SD = 0.06. Mpost = 0.37, SD = 0.08, $F(1, 12) = 29.15$, $p < .001$, $\eta_p^2 = 0.71$, but no significant change for Condition 2 (after ANT), Mpre = 0.26, SD = 0.04, Mpost = 0.27, SD = 0.06 [$F < 1$]. This suggests that improvement in VMT processing efficiency after video gaming may be of short duration.

4.2.2.2. MRT. Outlier response times (RTs ± 2.5 SD from a participant's mean) were deleted (MRT pretest: 1.09% of responses; MRT posttest: 1.79% of responses). The MRT data for one participant whose performance was below chance (50% accuracy) were removed.

Fig. 10 presents the results for MRT processing efficiency.

A 2 (Time: pretest vs. posttest) × 2 (Condition: 1 vs. 2) mixed-model ANOVA yielded a significant main effect of Time [$F(1, 20) = 11.84$, $p < .01$, $\eta_p^2 = 0.37$], but no main effect of Condition [$F < 1$]. Moreover, the Time × Condition interaction was marginally significant, $F(1, 20) = 3.44$, $p = .078$, $\eta_p^2 = 0.15$. Follow-up ANOVAs revealed a significant increase in MRT processing efficiency from the pretest to posttest 1 for Condition 1 (after video-game), Mpre = 0.46, SD = 0.10, Mpost = 0.54, SD = 0.12, $F(1, 11) = 13.04$, $p < .01$, $\eta_p^2 = 0.54$, but did not reveal a significant change for Condition 2 (after rest), Mpre = 0.47, SD = 0.07, Mpost = 0.49, SD = 0.08, $F(1, 9) = 1.49$, $p = .25$, $\eta_p^2 = 0.14$. This suggests that, as with VMT performance, improvement in MRT performance following video gaming is of short duration, as would be expected if resulting from a temporary state of enhanced cognition.

In summary, the results of Experiment 3 indicate that the participants experienced an enhanced cognitive state in which their visual memory and spatial transformation capacities significantly improved, but the enhancements were only temporary since they were no longer observed after 30 min of rest. Interestingly, we did not find any improvements on the conflicting and orienting networks, but we found changes in performance on the alerting network aspect of the ANT, which were *not* influenced by the timing of the ANT administration (either immediately after gaming, or after 30 min of rest), in contrast to VMT and MRT. Thus, the changes in performance on the alerting network are likely to be attributed to other reasons (e.g., the effect of a rest period or test-retest effect), rather than to the enhanced cognitive state.

5. General discussion

In contrast to previous studies that assessed durable cognitive and attentional improvements in performance on cognitive tasks associated with long-term video-game training, the findings of the current research demonstrated that actively engaging in video-gaming that was calibrated to one's own skill level for a mere 30 min is associated with dramatic performance enhancements on particular types of attentional and visual tasks. Although one of the limitations of this research is a relatively small sample size (due to the ground-laying nature of this research), the effects were consistent across all the experiments. The results of the three experiments suggest the existence of temporary cognitive states in which temporal and spatial aspects of attention are dramatically enhanced for limited durations. These states are similar to flow experiences described in the phenomenological literature in the following aspects: First, consistent with the phenomenological literature that active engagement is indeed critical for the induction of enhanced state, the results of Experiment 1 showed a significant improvement on the attentional blink task, a measure of temporal aspects of attention, for those participants who actually played the video game (but not the ones who just observed). The findings of Experiment 1 not only showed that there is a qualitative similarity between the experiences reported by our game players and the terms used to characterize the flow state, but it also showed that two dimensions of the FSS scale — "loss of self-consciousness" and "concentration on task" — correlated with our gamers' degree of improvement on the attentional blink task. Second, the results of Experiment 2 showed that the observed *attentional enhancements are not due to video-gaming per se,* as only participants whose skills optimally matched the video-game level significantly improved their performance on the attentional blink task. Third, the OpC group experienced the greatest decrease in HF in comparison with other groups, suggesting that heightened arousal is also a necessary condition for a flow state to occur. It is, however, not a sufficient condition, since there were participants in the other two groups (UnC and OvC) who were exhibiting heightened arousal without any attentional enhancements. Thus, although heightened arousal was a contributing factor, achieving an enhanced cognitive state also depends on active engagement *and* optimal challenge.

Which specific cognitive processes are enhanced during these states? We observed a significant improvement on the attentional blink task immediately after video gaming, where participants are required to focus their attention on a limited visual-spatial field. Similarly, we observed a significant improvement on visual memory and spatial transformation tasks, which also depend on focused attention (Awh & Jonides, 2001; Corbetta, Kincade, & Shulman, 2002; Makovski & Jiang, 2007; Wheeler & Treisman, 2002). However, we did not find clear evidence of improvement on the ANT attentional networks, and further studies are necessary in order to completely delineate which cognitive functions are boosted during these states. It is worth noting, however, that although the conflict network has been considered important for "supervisory, selective, conflict resolution" (Raz & Buhle, 2006, p. 374), it does not require narrowing the focus of spatial attention. As for the orienting network, it reflects an ability to shift attention to different spatial locations (Petersen & Posner, 2012), thus it taps distributed rather than focused spatial attention. Finally, the alerting network taps an aspect of attention related to sustaining optimal vigilance or tonic alertness over long periods. A well-established approach to assessing tonic alertness is to use a long and usually rather boring or repetitive task requiring sustained vigilance (Petersen & Posner, 2012), quite different from the arousing and challenging nature of action video gaming. Taken together, our results suggest that the aspect of cognition that improves significantly during this enhanced state is focused visual-spatial attention. As our participants themselves described, they entered a state of "tunnel focus", in which they were able to "zoom in on the target much more than usual" with "absolutely no distractions". This highly focused attention may explain why gamers, during or immediately after playing an action video-game, feel "desensitized" or "numb" to other external emotional or social stimuli (Anderson & Bushman, 2001; Anderson et al., 2010; Barlett, Harris, & Baldassaro, 2007; Bushman, 2004; Bushman & Anderson, 2009; Carnagey, Anderson, & Bushman, 2007), possibly perceiving them as distractors. It is interesting that all previous research suggesting the existence of enhanced cognitive states, whether after listening to a Mozart sonata or following different types of focused meditation, reported improvement on attentional blink and visual-spatial tasks only.

It is also worth reiterating that the cognitive capacities that showed improvements were not the ones that have been shown to improve as a result of long-term video-game training. The distribution of spatial attention (related to the orienting attentional network) improves significantly (and durably) as a result of long-term video-game playing (Green & Bavelier, 2003; Greenfield, DeWinstanley, Kilpatrick, & Kaye, 1994), but we did not observe any improvement on the orienting network in Experiment 3. Thus, the observed enhancement cannot be simply due to specific video gaming conditions (e.g., optimal skill-demand compatibility during video-gaming) alone. Future research should examine the full scope of attentional capacities by administering a variety of different attention tasks, such as tasks assessing general executive and distributed attention.

We were surprised to find, in both Experiments 1 and 2, that there was no significant decline in game-players' performance on the attentional blink task after 30 min of rest (although we did observe a trend in this direction in Experiment 2). At the same time, we observed a significant decline of performance in Experiment 3 when about 35–40 min had passed after completion of video gaming (about 5–10 min of posttest 1 and 30 min of rest period). It is possible that the enhanced cognitive states experienced by the players in these experiments lasted more than 30 min following the gaming. Furthermore, it could be that the temporal characteristics of attention, as measured by the ABT task, decline more slowly than the spatial characteristics, as measured by visual-spatial tasks requiring focused attention. Another possibility, however, is that *learning* during the enhanced state was especially efficient, enabling players to develop potent strategies for performing the ABT, which they later used when performing post-test2. Since participants in Experiment 3 were presented with different tasks during post-test1 (given during the enhanced state) and post-test2 (given after the rest), learning was not a factor. Future research should investigate the duration of the enhanced state, the factors affecting it (e.g., the level of challenge experienced during the inducing activity, baseline attentional capacities, and experience with the activity) as well as the possibility to achieve efficient learning in these states.

Another important finding is that arousal is a critical prerequisite for reaching enhanced cognitive states. In particular, not only sympathetic activation, but also a withdrawal of parasympathetic control, appears to be a critical physiological marker of enhanced cognitive states, and the magnitude of decreases in parasympathetic activity was directly related to the magnitude of attentional enhancements in the OpC group. Although the very term " flow" suggests a state of effortlessness, and the phenomenological literature connects the flow state with "euphoric feelings" (Csikszentmihalyi, 1990), it also describes flow in the context of coping with stress (Csikszentmihalyi, 1992). Wilson (1972) claims that life-threatening experiences such as fighting in a battlefield or engaging in an extremely dangerous task (e.g. defusing a bomb) inherently require intense focus, and LeFevre (1988) argues that flow cannot be induced by stress-free and low-challenge activities (like passively watching TV). Therefore, neither too relaxed nor too stressful activities, but a perfect balance between two extremes of boredom and anxiety is required.

In conclusion, our study is the first to experimentally demonstrate that video-game playing for a mere 30 min can elicit an enhanced cognitive state that resembles prior descriptions of flow or peak experiences, and is characterized by a significant temporary boost in focused attention. For this boost to occur, several conditions must be met, such as heightened arousal, active participation and optimal skill-challenge match. These enhanced cognitive states appear to be universal, in the sense that the observed enhancements seem to be similar across different activities (video-gaming, listening to music, or doing certain types of meditation), not limited specifically to video-gaming. For example, previous research has shown that enhanced cognitive states are accessible to experienced Tibetan meditators. Despite the obvious differences between these two practices, the effect sizes of performance enhancements in visual memory and spatial transformation for focused meditation ($\eta_p^2 = 0.65$ for VMT and $\eta_p^2 = 0.58$ for MRT; Kozhevnikov et al., 2009) and action video-gaming ($\eta_p^2 = 0.71$

for VMT and $\eta_p^2 = 0.54$ for MRT) were very similar.

The current findings have not only theoretical but also practical implications. First, this study proposes a tool (video-gaming) to cognitive psychologists and neuroscientists to investigate enhanced states experimentally. Second, this study could make such experiences more accessible to the general population. Although it is transient, a temporary boost in focused attention can nevertheless be utilized in order to enhance performance during critical periods. In addition, the enhanced cognitive states might be directly related to creativity, and understanding how to attain such states may help us to boost creative performance (Csikszentmihalyi, 1996). Furthermore, even though these states are of limited duration, the learning experience obtained during this state could be long lasting. Psychologists should further investigate these states and the ways to induce them, since this will open up the possibility of consciously accessing the latent resources of our brain and boosting our cognitive capacities upon demand.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2018.01.006.

References

Akselrod, S., Gordon, D., Ubel, F. A., Shannon, D. C., Barger, A. C., & Cohen, R. J. (1981). Power spectrum analysis of heart rate fluctuation: A quantitative probe of beat to beat cardiovascular control. *Science, 213*, 220–222.

Amihai, I., & Kozhevnikov, M. (2015). The influence of Buddhist meditation traditions on the autonomic system and attention. *Biomed Research International* (Special Issue on Physiological Effects of Mind and Body Practices (EMB)).

Amihai, I., & Kozhevnikov, M. (2014). Arousal vs. relaxation: A comparison of the neurophysiological and cognitive correlates of Vajrayana and Theravada meditative practices. *PLoS ONE, 9*(7), e102990. http://dx.doi.org/10.1371/journal.pone.0102290.

Anderson, C. A., & Bushman, B. J. (2001). Effects of violent video games on aggressive behavior, aggressive cognition, aggressive affect, physiological arousal, and prosocial behavior: A meta-analytic review of the scientific literature. *Psychological Science, 12*(5), 353–359.

Anderson, C. A., Shibuya, A., Ihori, N., Swing, E. L., Bushman, B. J., Sakamoto, A., ... Saleem, M. (2010). Violent video game effects on aggression, empathy, and prosocial behavior in eastern and western countries: A meta-analytic review. *Psychological Bulletin, 136*(2), 151–173. http://dx.doi.org/10.1037/A0018251.

Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences, 5*(3), 119–126.

Barlett, C. P., Harris, R. J., & Baldassaro, R. (2007). Longer you play, the more hostile you feel: Examination of first person shooter video games and aggression during video game play. *Aggressive Behavior, 33*(6), 486–497. http://dx.doi.org/10.1002/Ab.20227.

Berntson, G. G., Bigger, J. T., Jr., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., ... Van Der Molen, M. W. (1997). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology, 34*, 623–648.

Bigger, J. T., Fleiss, J. L., Rolnitzky, L. M., & Steinman, R. C. (1992). Stability over time of heart period variability in patients with previous myocardial infraction and ventricular arrhythmias. *American Journal of Cardiology, 69*, 718–723.

Billman, G. E. (2013). The LF/HF ratio does no accurately measure cardiac sympatho-vagal balance. *Frontiers in Physiology, 4*, 1–5.

Bushman, B. (2004). Effects of violent video games on aggressive behavior, helping behavior, aggressive thoughts, angry feelings, and physiological arousal. *Entertainment Computing – ICEC, 2004*(3166), 22.

Bushman, B. J., & Anderson, C. A. (2009). Comfortably numb: Desensitizing effects of violent media on helping others. *Psychological Science, 20*(3), 273–277. http://dx.doi.org/10.1111/j.1467-9280.2009.02287.x.

Camm, A. J., Malik, M., Bigger, J. T., Breithardt, G., Cerutti, S., Cohen, R. J., ... Singer, D. (1996). Heart rate variability – Standards of measurement, physiological interpretation, and clinical use. *Circulation, 93*, 1043–1065.

Carnagey, N. L., Anderson, C. A., & Bushman, B. J. (2007). The effect of video game violence on physiological desensitization to real-life violence. *Journal of Experimental Social Psychology, 43*(3), 489–496.

Castel, A., Pratt, J., & Drummond, E. (2005). The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychologica, 119*(2), 217–230. http://dx.doi.org/10.1016/j.actpsy.2005.02.004.

Chabris, C. (1999). Prelude or requiem for the Mozart effect'? *Nature, 400*, 826–827.

Corbetta, M., Kincade, J. M., & Shulman, G. L. (2002). Neural systems for visual orienting and their relationships to spatial working memory. *Journal of Cognitive Neuroscience, 14*(3), 508–523.

Costa, A., Hernández, M., & Sebastián-Gallés, N. (2008). Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition, 106*(1), 59–86. http://dx.doi.org/10.1016/j.cognition.2006.12.013.

Cowley, B., Charles, D., Black, M., & Hickey, R. (2008). Toward an understanding of flow in video games. *Computers in Entertainment, 6*(2), 1–27. http://dx.doi.org/10.1145/1371216.1371223.

Csikszentmihalyi, M. (1975). Play and intrinsic rewards. *Journal of Humanistic Psychology, 15*(3), 41–63. http://dx.doi.org/10.1177/002216787501500306.

Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience* (1st ed.). New York: Harper & Row.

Csikszentmihalyi, M. (1992). A response to the Kimiecik and Ajckson papers. *Journal of Applied Sport Psychology, 4*, 181–183.

Csikszentmihalyi, M. (1996). *Creativity: Flow and the psychology of discovery and invention* (1st ed.). New York: Harper Collins Publishers.

Csikszentmihalyi, M. (1997). *Finding flow: The psychology of engagement with everyday life* (1st ed.). New York: Basic Books.

De Manzano, O., Theorell, T., Harmat, L., & Ulen, F. (2010). The psychophysiology of flow during piano playing. *Emotion, 10*, 301–311.

Dux, P., & Kelly, A. (2012). Different attentional blink tasks reflect distinct information processing limitations: An individual differences approach. *Journal of Vision, 12*(9), 1329. http://dx.doi.org/10.1167/12.9.1329.

Dye, M. W. G., Green, C. S., & Bavelier, D. (2009). The development of attention skills in action video game players. *Neuropsychologia, 47*(8–9), 1780–1789. http://dx.doi.org/10.1016/j.neuropsychologia.2009.02.002.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience, 14*(3), 340–347. http://dx.doi.org/10.1162/089892902317361886.

Getzels, J. W., & Csikszentmihalyi, M. (1976). *The creative vision: A longitudinal study of problem finding in art.* New York: Wiley.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature, 423*(6939), 534–537. http://dx.doi.org/10.1038/Nature01647.

Green, C. S., & Bavelier, D. (2006a). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology-Human Perception and Performance, 32*(6), 1465–1478. http://dx.doi.org/10.1037/0096-1523.32.6.1465.

Green, C. S., & Bavelier, D. (2006b). Enumeration versus multiple object tracking: The case of action video game players. *Cognition, 101*(1), 217–245. http://dx.doi.org/10.1016/j.cognition.2005.10.004.

Green, C. S., & Bavelier, D. (2007). Action-video-game experience alters the spatial resolution of vision. *Psychological Science, 18*(1), 88–94.

Greenfield, P. M., DeWinstanley, P., Kilpatrick, H., & Kaye, D. (1994). Action video games and informal education: Effects on strategies for dividing visual attention. *Journal of Applied Developmental Psychology, 15*(1), 105–123. http://dx.doi.org/10.1016/0193-3973(94)90008-6.

Hébert, S., Béland, R., Dionne-Fournelle, O., Crête, M., & Lupien, S. J. (2005). Physiological stress response to video-game playing: The contribution of built-in music. *Life Sciences, 76*(20), 2371–2380.

Ho, C., Mason, O., & Spence, C. (2007). An investigation into the temporal dimension of the Mozart effect: Evidence from the attentional blink task. *Acta Psychologica, 125*(1), 117–128.

Ishigami, Y., & Klein, R. M. (2010). Repeated measurement of the components of attention using two versions of the Attention Network Test (ANT): Stability, isolability, robustness, and reliability. *Journal of Neuroscience Methods, 190*(1), 117–128. http://dx.doi.org/10.1016/j.jneumeth.2010.04.019.

Jackson, S. A., & Marsh, H. W. (1996). Development and validation of a scale to measure optimal experience: The Flow State Scale. *Journal of Sport & Exercise Psychology, 18*(1), 17–35.

Keller, J., & Bless, H. (2008). Flow and regulatory compatibility: An experimental approach to the flow model of intrinsic motivation. *Personality and Social Psychology Bulletin, 34*(2), 196–209. http://dx.doi.org/10.1177/0146167207310026.

Kelly, A. J., & Dux, P. E. (2011). Different attentional blink tasks reflect distinct information processing limitations: An individual differences approach. *Journal of Experimental Psychology-Human Perception and Performance, 37*(6), 1867–1873. http://dx.doi.org/10.1037/A0025975.

Klasen, M., Weber, R., Kircher, T. T. J., Mathiak, K. A., & Mathiak, K. (2011). Neural contributions to flow experience during video game playing. *Social Cognitive and Affective Neuroscience*. http://dx.doi.org/10.1093/scan/nsr021.

Kozhevnikov, M., Louchakova, O., Josipovic, Z., & Motes, M. A. (2009). The enhancement of visuospatial processing efficiency through Buddhist Deity Meditation. *Psychological Science, 20*(5), 645–653.

LeFevre, J. (1988). Flow and the quality of experience during work and leisure. In M. C. Csikszentmihalyi, & I. Csikszentmihalyi (Eds.). *Optimal experience* (pp. 307–318). Cambridge, England: Cambridge University Press.

Li, R. J., Polat, U., Makous, W., & Bavelier, D. (2009). Enhancing the contrast sensitivity function through action video game training. *Nature Neuroscience, 12*(5), 549–551. http://dx.doi.org/10.1038/Nn.2296.

Lohman, D. F., & Nichols, P. D. (1990). Training spatial abilities: Effects of practice on rotation and synthesis tasks. *Learning and Individual Differences, 2*(1), 67–93. http://dx.doi.org/10.1016/1041-6080(90)90017-b.

Makovski, T., & Jiang, Y. (2007). Distributing versus focusing attention in visual short-

term memory. *Psychonomic Bulletin & Review, 14*(6), 1072–1078. http://dx.doi.org/10.3758/bf03193093.
Malliani, A., Pagani, M., Lombardi, F., & Cerutti, S. (1991). Cardiovascular neural regulation explored in the frequency domain. *Circulation, 84*, 1482–1492.
Martens, S., Munneke, J., Smid, H., & Johnson, A. (2006). Quick minds don't blink: Electrophysiological correlates of individual differences in attentional selection. *Journal of Cognitive Neuroscience, 18*(9), 1423–1438.
Maslow, A. H. (1962). *Toward a psychology of being.* Princeton, NJ: Van Nostrand-Reinhold.
Maslow, A. H. (1999). *Toward a psychology of being* (3rd ed.). New York: J. Wiley & Sons.
May, C. J., Burgard, M., Mena, M., Abbasi, I., Bernhardt, N., Clemens, S., ... Housh, K. (2011). Short-term training in loving-kindness meditation produces a state, but not a trait, alteration of attention. *Mindfulness, 2*(3), 143–153.
Mayer, R. (2014). *Computer games for learning: An evidence based approach.* MIT Press.
Molgaard, H., Hermansen, K., & Bjerregaard, P. (1994). Spectral components of short-term RR interval variability in healthy subjects and effects of risk factors. *European Heart Journal, 15*, 1174–1183.
Moller, A. C., Meier, B. P., & Wall, R. D. (2010). Developing an experimental induction of flow: Effortless action in the lab. In B. Bruya (Ed.). *Effortless attention: A new perspective in the cognitive science of attention and action* (pp. 191–204). London, U.K.: MIT Press.
Nakamura, J., & Csikszentmihalyi, M. (2002). The concept of flow. In C. Snyder, & S. Lopez (Eds.). *Handbook of positive psychology* (pp. 89–105). New York: University Press.
Pagani, M., Lombardi, F., Guzzetti, S., Rimoldi, O., Furlan, R., Pizzinelli, P., ... Malliani, A. (1986). Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympathovagal interaction in man and conscious dog. *Circulation Research, 59*, 178–193.
Peifer, C., Schachinger, H., Baumann, N., Schultz, A., & Antoni, C. H. (2010, February). The relation between the stress-hormone cortisol nd the flow phenomenon. *Paper presented at the symposium "The concept of flow toward a scientific integration". Braunschweig*.
Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience, 35*, 73–89.
Pomeranz, M., Macaulay, R. J. B., Caudill, M. A., Kutz, I., Adam, D., Gordon, D., ... Benson, M. (1985). Assessment of autonomic function in humans by heart rate spectral analysis. *American Journal of Physiology, 248*, H151–H153.
Posner, M. I., & Rothbart, M. K. (2009). Toward a physical basis of attention and self-regulation. *Physics of Life Reviews, 6*(2), 103–120. http://dx.doi.org/10.1016/j.plrev.2009.02.001.
Procci, K., Singer, A. R., Levy, K. R., & Bowers, C. (2012). Measuring the flow experience of gamers: An evaluation of the DFS-2. *Computers in Human Behavior, 28*(6), 2306–2312. http://dx.doi.org/10.1016/j.chb.2012.06.039.
Rauscher, F. H., Shaw, G. L., & Ky, K. N. (1993). Music and spatial task performance. *Nature, 365*(6447), 611.
Raymond, J. E., Shapiro, K. L., & Arnell, K. M. (1992). Temporary suppression of visual processing in an rsvp task – An attentional blink. *Journal of Experimental Psychology-Human Perception and Performance, 18*(3), 849–860.
Raz, A., & Buhle, J. (2006). Typologies of attentional networks. *Nature Reviews Neuroscience, 7*(5), 367–379.
Segal, K. R., & Dietz, W. H. (1991). Physiologic responses to playing a video game. *American Journal of Diseases of Children, 145*(9), 1034–1036.
Seger, J., & Potts, R. (2012). Personality correlates of psychological flow states in videogame play. *Current Psychology, 31*(2), 103–121.
Shapiro, K. L., Arnell, K. M., & Raymond, J. E. (1997). The attentional blink. *Trends in Cognitive Sciences, 1*(8), 291–296.
Shepard, R. N., & Metzler, J. (1971). Mental rotation of three dimensional objects. *Science, 171*, 701–703.
Sherry, J. L. (2004). Flow and media enjoyment. *Communication Theory, 14*(4), 328–347.
Skosnik, P. D., Chatterton, R. T., Jr, Swisher, T., & Park, S. (2000). Modulation of attentional inhibition by norepinephrine and cortisol after psychological stress. *International Journal of Psychophysiology, 36*(1), 59–68. http://dx.doi.org/10.1016/S0167-8760(99)00100-2.
Slagter, H., Lutz, A., Greischar, L., Francis, A., Nieuwenhuis, S., Davis, J., & Davidson, R. (2007). Mental training affects distribution of limited brain resources. *PLoS Biology, 5*(6), e138. http://dx.doi.org/10.1371/journal.pbio.0050138.
Spence, I., & Feng, J. (2010). Video games and spatial cognition. *Review of General Psychology, 14*(2), 92–104. http://dx.doi.org/10.1037/a0019491.
Stein, K. M., Borer, J. S., Hochreiter, C., Okin, P. M., Herrold, E. M., Devereux, R. B., & Kligfield, P. (1993). Prognostic value and physiological correlates of heart rate variability in chronic severe mitral regurgitation. *Circulation, 88*, 127–135.
Toledo, E., Gurevitz, O., Hod, H., Eldar, M., & Akselrod, S. (2003). Wavelet analysis of instantaneous heart rate: A study in autonomic control during thrombolysis. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology, 284*, R1079–R1091.
van de Borne, P., Nguyen, H., Biston, P., Linkowski, P., & Degaute, J. P. (1994). Effects of wake and sleep stages on the 24-h automatic control of blood pressure and heart rate in recumbent men. *American Journal of Physiology, 266*(2), H548–H554.
van Dijk, A. E., van Lien, R., van Eijsden, M., Gemke, R. J., Vrijkotte, T. G., & de Geus, E. J. (2013). Measuring cardiac autonomic nervous system (ANS) activity in children. *Journal of Visualized Experiments, 74*, e50073.
Weber, R., Tamborini, R., Westcott-Baker, A., & Kantor, B. (2009). Theorizing flow and media enjoyment as cognitive synchronization of attentional and reward networks. *Communication Theory, 19*(4), 397–422. http://dx.doi.org/10.1111/j.1468-2885.2009.01352.x.
Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General, 131*(1), 48.
Wilson, C. (1972). *New pathways in psychology, Maslow & the post-Freudian revolution.* New York: Taplinger Publishing Company.