SUPPLEMENTARY INFORMATION for

Title: Enhancing the Contrast Sensitivity Function through Action Video Game Training

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Supplementary Note 1: EXPERIMENTAL PROCEDURES

Subjects:

All subjects were recruited among students and staff of the University of Rochester and their relatives. Subjects all lacked previous experience in psychophysics experiments. They were recruited through flyers posted on a public university notice board or through university mail. All subjects provided informed written consent before the experiments and were paid $8/hour for their participation.

Contrast sensitivity function: 10 male VGPs (age range 19-27 years old, mean age 23.34, mean visual acuities for left, right and both eyes: 20/18.65, 20/18.34 and 20/18.03 as measured by the Logarithmic visual acuity chart "2000"(ETDRS)) and 10 male NVGPs (age range 19-25 years old, mean age 22.23; mean visual acuities: 20/19.69, 20/18.29 and 20/18.18).

Critical Duration for Contrast Sensitivity: 7 male VGPs (age range 19-29 years old, mean age 22; mean visual acuities for left, right and both eyes: 20/17.86, 20/18.43 and 20/16.71) and 9 male NVGPs (age range 19-29 years old, mean age 23.8, mean visual acuities: 20/18.72, 20/19.77 and 20/17.11).

Four VGPs participated in both the Contrast Sensitivity and the Critical Duration experiments.

Training Studies: For the Contrast Sensitivity study, 13 NVGPs were divided randomly into 6 action group participants (3 males and 3 females, 20-30 years old, mean age 26.51 years old) and 7 control group participants (2 males, 5 females, 22-28 years old, mean age 23.72 years old). For the Critical Duration study, 22 NVGPs were divided randomly into 13 action group participants (8 males and 5 females, 20-30 years old, mean age 24.9 years old) and 9 control group participants (5 males, 4 females, 21-29 years old, mean age 25.1 years old). All subjects had normal or corrected-to-normal vision and performed at 20/20 or better with the Logarithmic visual acuity chart "2000."

Videogame Questionnaire: Video game playing skills were assessed through a video game playing questionnaire aimed at establishing the frequency of action video game usage in the 12 months prior to testing. For each video game the participants reported playing, they were asked how often they played that game in the previous 12 months, and for how long they played it during a typical session. This approach was motivated by that used in surveys to elicit information that can be hard for interviewees to accurately recall. For example the method is similar to that used in the UK's General Household Survey to acquire information on alcohol consumption [1]. Subjects who reported playing at least 5 hours of action video games per week during the past six months were classified as VGP, and those who reported playing less than 1 hour of action or sport video games per week in their past year were classified as NVGP; note that some NVGPs did play other kinds of games.

Apparatus:

For all experiments, stimuli were displayed on a Mitsubishi Diamond Pro SB CRT monitor with 1280*1024 resolution and 100 Hz refresh rate, using Windows XP system. The subjects were tested in a dark room, where the only light came from the display screen. The mean display luminance was 17 cd/m^2, and viewing distance was 1.5 m. Subjects were tested binocularly.

Stimuli and procedure for contrast sensitivity:

The stimuli and procedure were similar to those used by Polat and Sagi [2]. In all experiments, the stimuli consisted of one central Gabor signal with λ (wavelength) = σ (standard deviation of the Gaussian envelop). The luminance distribution of a Gabor signal is described by $L(x,y|x_0,y_0) = \cos(2\pi/\lambda(x- x_0)) * \exp(-((x- x_0)^2+ (y- y_0)^2)/\sigma^2)$, where x,y are the horizontal and vertical coordinates respectively, λ is the wavelength, and σ is the space constant of the Gaussian envelope. Gamma was calibrated to fit the best linearity between 10 different luminances on the monitor (full field) and readings from a photometer (Minolta Chromameter, CS-100).

A temporal two-alternative forced-choice paradigm was used. Before each trial, a small white circle fixation point was presented at the center of the screen where the target Gabor signal was to be flashed. Trials were self-paced and started by pressing the space bar. A 300 ms blank screen followed. Then each trial consisted of two 30 ms stimulus presentations, marked by four peripheral (6 deg from center) high contrast crosses and separated by a 800 ms blank. Only one of the intervals, at random, contained the central Gabor target. Subjects indicated which interval had the target by pressing keys labeled

"1st" or "2nd". An auditory beep signaled incorrect responses. Target contrast increased by 0.1 log unit after one error and decreased by 0.1 log unit following three consecutive correct responses. Each block terminated after 10 reversals or after 80 trials, whichever was reached first. Contrast threshold, which converges to 79% correct under such conditions [3], was defined as the mean of the final eight reversals. Each spatial frequency (1.5, 3, 6, 9, 12 cyc/deg) was tested twice in a separate block, and the order of blocks was random.

Stimuli and procedure for critical duration:

Stimuli and procedure were identical to the contrast sensitivity experiment, except for the following changes. Contrast sensitivity was measured at six durations (10, 20, 30, 60, 120, and 180 ms) at a fixed spatial frequency of 6 cyc/deg. Each duration was tested twice in a separate block, and the order of blocks was random.

Supplementary Note 2: VIDEO GAME TRAINING

Training Procedure:

For both groups, training consisted of playing a video game for 50 total hours. The subjects were allowed to play a maximum of 2 hours per day and a maximum of 10 hours per week. No minimum amount of game play per week was enforced, but subjects were required to finish the 50 hours training in no more than 9 weeks. The subjects completed the 50 hours in an average of 44 days. The training games for both the action and the control conditions covered the entire extent of the screen (a visual angle of approximately 15° height x 18° width).

Participants in the control group played the game The Sims™ 2 (2004, Electronic Arts Inc.). The Sims™ 2 is a simulation-style game, wherein the player takes complete control of the life of a character, which involves everything from everyday activities (eating, bathing, etc.) to going to work, managing relationships with other characters, getting married, having and raising children, and eventually growing old and dying. As characters are added to the household, the player takes control of those characters as well. Our trainees took control of an average of 10 different characters during the 50 hours of training.

Participants in the action group played games similar to those played by our VGPs. During the first half of training, the action group played the game Unreal® Tournament 2004 (Epic Games) in Death Match mode, where the goal is for the player to kill as many of the computer controlled characters as possible, while minimizing the number of times the player dies. During piloting of the training regimen, we noticed that the difficulty level changes non-linearly in that game such that, after about 25 hours, trainees reach a level that is too hard for anyone with that level of experience to play. Unfortunately, the next level down was clearly too easy for these trainees. In an attempt to minimize the difference with control game trainees who keep experiencing new and rewarding situations, during the second half of training, the action group played the game Call of Duty® 2 (ActiVision). This game puts the player into fictionalized World War II combat situations, with the primary goal again being to kill as many computer controlled characters as possible while minimizing the player's own deaths. Subjects were re-tested on all levels of Unreal Tournament 2004 at the end of training in order to assess improvement in skill. It should be noted that even by asking the action group to play two games, the control group trainees played five times as many characters, had more variable goals and were exposed to more diversity in their environment than the action group trainees. We chose to keep the action game trainees at a disadvantage for these factors to ensure that amount of stimulating situations encountered could not explain any improvements in the action group beyond what is seen in the control group. Assignment of the subjects to the two groups was random.

Each group was requested to log their performance regularly (control game: accumulated wealth; experimental game: ratio of kills to death). In addition, the experimental group was told to reach a ratio of two kills for one death before switching to a harder level. This ensures that players progress through the game smoothly, avoiding long periods of frustration because the game is too hard or boredom because it is too easy. This was not an issue in the control game, which progresses automatically through more and more advanced situations.

Game Training Results:

In order to quantitatively assess game improvement and engagement in training, several measures were used. For the control game, the best measure was money accumulated (which increases with positive actions such as being promoted or adding a member to the household and decreases with negative actions such as burning down one's house or having a character die due to neglect). All subjects showed an accelerating increase in accumulated wealth over the course of training, indicating improvement in game performance with training. The time course of the accumulation was well fit by a quadratic function: (i) For the contrast sensitivity study, wealth = $(64 * \text{training hour})^2 + (1593 * \text{training hour}) + 11753$, $r^2 = 97.59$; (ii) For the critical duration study, wealth = $(57 * \text{training hour})^2 + (1980 * \text{training hour}) + 10340$, $r^2 = 94.44$

For the action game, kills and deaths in each block were used to calculate a skill metric S = ([Kills – Deaths]/[Kills + Deaths]). The S score was measured at all six levels of difficulty pre-training, after 25 gaming hours (after Unreal Tournament training) and post-training (after all 50 hours of game training). As with the control game, we compared pre- and post-training S scores. These increased dramatically for all subjects at all levels of difficulty indicating improved performance as training proceeded. For the contrast sensitivity study, at the easiest level of difficulty the score S_{level1} went from 0.48[4] to 0.97(post), at the hardest difficulty level the score S_{level6} went from -0.77(pre) to -0.20(post). For the critical duration study, S_{level1} = 0.58(pre) and 0.95(post), S_{level6} = -0.67(pre) and -0.16(post). These results demonstrate that both groups were engaged in their training and showed improvement on their respective training task.

Supplementary Note 3: CONTRAST SENSITIVITY RESULTS

The absolute size of the effect we document for a 6 cy/deg stimulus is an average improvement of 58% in contrast sensitivity (0.2 on a log scale) in regular action gamers, and a 43% improvement (0.16 on a log scale) in the action-trained as compared to the control-trained participants (**Table 1**).

Spatial Frequency (cyc/deg)	1.5	3	6	9	12
VGP/NVGP comparison	0.099 (25%)	0.081 (20%)	0.209 (62%)	0.217 (65%)	0.177 (50%)
pre/post comparison in experimental group	0.058 (14%)	0.072 (18%)	0.155 (43%)	0.112 (29%)	0.074 (19%)
pre/post comparison in control group	-0.037 (-8%)	0.009 (2%)	0.044 (11%)	0.034 (8%)	0.063 (16%)

Table 1. Mean difference in contrast detection thresholds at 6 cyc/deg. The first row reports the mean difference (in log units and percent improvement) between VGP and NVGP contrast sensitivity as a function of the spatial frequency tested. The next two rows report mean improvements in contrast sensitivity between pre- and post-training (in log units and percent improvement) for the experimentally-trained group and the control-trained group. The effect of action video game playing on contrast sensitivity is stronger at intermediate frequencies (6 and 9 cyc/degree) than at lower or higher spatial frequencies.

These improvements, established at the population level, are extremely robust. To illustrate this point, we extracted contrast sensitivity detection thresholds of non-action gamers (NVGP) and action gamers (VGP) from five different studies that have been run in our laboratory (**Fig. 1**) Two of these studies were reported in our manuscript; the three others are new. For each of these, we recovered the CSF at 6 cyc/deg (this condition was identical in all five experiments).

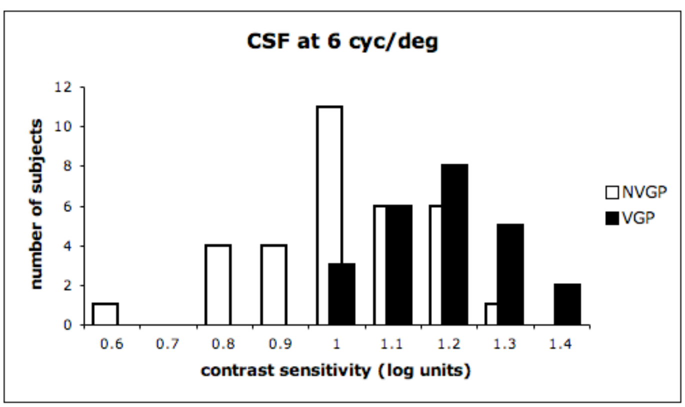

Figure 1. Contrast sensitivity detection thresholds at 6 cyc/deg across 5 studies. Data from 33 different NVGPs and 24 different VGPs were recovered from 5 different studies. The separation between the two samples is clear, as is their normal distribution. The effect size for the population effect is medium to large – partial $\eta^2 = 0.27$ ($F(1,55) = 19.96$, $p < 0.0001$). Hence the difference between the two samples is not an artifact due to a few exceptional participants; rather it reflects a true underlying difference between the two populations.

Interestingly, contrast sensitivity at 6 cyc/deg is associated with skills of practical significance, such as reading. Accordingly, 6cyc/deg is the peak frequency of the channel that processes letters that are at the optimal size for reading[5,6], and contrast sensitivity at 6 cyc/deg was shown to be a robust predictor of reading skills in a sample of normal adults[7].

Supplementary Note 4: CRITICAL DURATION RESULTS

The critical duration value shortened in 77% of the subjects in the action trained group as compared to 22% in the control trained group.

Supplementary Note 5: DURATION OF THE EFFECT

Out of all the participants included in the two training studies described in this work, 16 action-trained subjects and 11 control-trained subjects were brought back to the laboratory in December of 2008. These subjects had been trained either five months ago, in the summer of 2008, or more than 1 year ago (Action-trained: 5 from 2008, 11 from 2007-2006; Control-trained: 4 from 2008, 7 from 2007-2006). Participants were asked about their video game habits between the time they had participated in our experiment and the present test. None of the participants reported having changed their video game playing habits; in particular, none of the participants had become regular players of either action games or the control game. All participants were tested again exactly as in the study in which they had participated (contrast sensitivity or critical duration). The experimental block that measures contrast sensitivity at 6cyc/deg with a 30 ms presentation time is identical across these studies. We therefore report the improvement from pre-test as a function of training group for that 6 cyc/deg condition at post-test1 (carried 5 days after the end of training) and post-test2 (carried at least 5 months and up to two and a half years after the end of training) (**Fig. 2**).

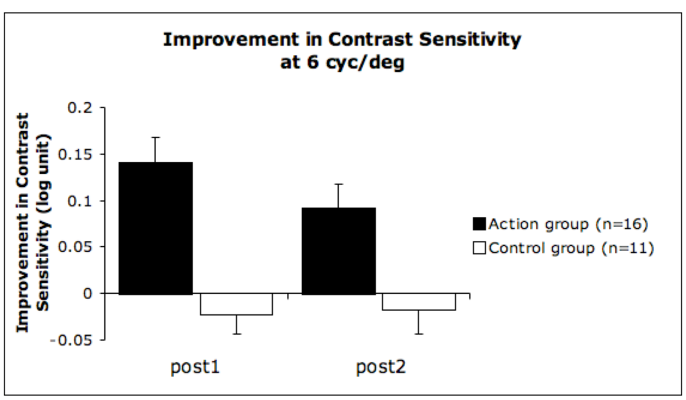

Figure 2. Improvement in contrast sensitivity at 6 cyc/deg a few days (post1) and several months (post2) after training. The improvement is plotted as an increase in sensitivity from pre-test. Post1 shows the improvement noted 5 days after the end of training. Post2 shows the improvement noted in the same subjects tested months later (5 months to 2.5 years depending on when the initial training occurred).

A 38% change in CS was noted after 5 days post training (post1). An analysis performed between pre and post1 CS thresholds revealed an interaction between group and time of testing ($F(1, 25) = 17.9$, $p = 0.0001$, partial $\eta^2 = 0.4$) in line with the results reported in the main paper. This change was reduced to 23% when the same participants were tested between 5 months to two years or so after training (post2). Importantly, the effect of training was still significant at these longer durations. Change in performance between pre and post2 was analyzed by using a 2x2 ANOVA with time of test (pre/post2) and group (action/control) as factors. The only significant effect was the interaction between time of test and group ($F(1, 25) = 7.8$, $p = 0.01$, partial $\eta^2 = 0.24$), indicating that a sizeable benefit in CS remains for months to years.

Supplementary Note 6: MECHANISMS AND ATTENTION

The mechanisms underlying the change in contrast sensitivity we report remain to be elucidated. The cortical plasticity induced by action game playing may occur at several different levels of visual processing and through a variety of neural mechanisms. The existing literature suggests that the most likely include sharpening, gain enhancement, and/or changes in feedback connectivity to better tune the visual system to task demands[8-10]. Teasing those apart goes beyond the scope of this short paper. One mechanism we can rule out, however, is attention, at least according to the standard definition in the field. Visual attention is called upon when a target needs to be selected in time or space from distractors or when there is some unknown about time or place of arrival of the stimulus. In accordance with psychophysical studies that focus on perception, the two paradigms used in our work displayed only a target in isolation and no uncertainty was present on either the place or time of arrival of the target (fixed target location, fixed SOA). The possibility that action gamers show greater benefit due to greater reduction in spatial uncertainty also seems unlikely. Indeed, this mechanism predicts a larger effect as spatial frequency increases and thus stimulus size decreases. This is not what was found. The enhancement in sensitivity is, if anything, greater at 6 cycle/degree than at 12 cycle/degree for both the VGP/NVGP comparison and the training study, contrary to what is predicted by a spatial uncertainty argument.

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