

Research Article

Action-Video-Game Experience Alters the Spatial Resolution of Vision

C.S. Green and D. Bavelier

Department of Brain and Cognitive Sciences, University of Rochester

ABSTRACT—*Playing action video games enhances several different aspects of visual processing; however, the mechanisms underlying this improvement remain unclear. Here we show that playing action video games can alter fundamental characteristics of the visual system, such as the spatial resolution of visual processing across the visual field. To determine the spatial resolution of visual processing, we measured the smallest distance a distractor could be from a target without compromising target identification. This approach exploits the fact that visual processing is hindered as distractors are brought close to the target, a phenomenon known as crowding. Compared with nonplayers, action-video-game players could tolerate smaller target-distractor distances. Thus, the spatial resolution of visual processing is enhanced in this population. Critically, similar effects were observed in non-video-game players who were trained on an action video game; this result verifies a causative relationship between video-game play and augmented spatial resolution.*

Video-game players appear to outperform non-game players on several different visual tasks (Castel, Pratt, & Drummond, 2005; Gopher, Weil, & Bareket, 1994; Green & Bavelier, 2003, 2006a, 2006b; Greenfield, DeWinstanley, Kilpatrick, & Kaye, 1994; Trick, Jaspers-Fayer, & Sethi, 2005). For example, avid action-video-game players (VGPs) were found to localize a peripheral target in a field of distracting objects more accurately than non-action-video-game players (NVGPs), as well as to process a visual stream of briefly presented objects more efficiently and to track more objects at once than NVGPs. NVGPs trained on an action video game exhibited similar improvements, establishing

that the very act of playing an action video game results in an increased ability to perform such complex visual tasks (Green & Bavelier, 2003, 2006b). Although the effect of game play on performance of complex visual tasks is striking, it remains unclear whether the improvements are mainly due to strategic changes or to changes in more fundamental aspects of visual processing. Using a crowding paradigm, we show here that video-game play alters the spatial resolution of vision—one of the fundamental characteristics of vision.

Crowding refers to the general phenomenon that it is substantially more difficult to identify a target object when other distracting objects are present in its immediate vicinity than when the target object is presented in isolation. This decrement in performance is a function of the number of distractors and their distance from the target, with performance decreasing as the number of distractors increases, as well as when targets and distractors are moved closer together (Leat, Li, & Epp, 1999; Miller, 1991; Orbach & Wilson, 1999). The region in space around a target where the presence of distracting objects leads to decreased sensitivity for the target is known as the *crowding region* or the *zone of spatial interaction* (Bouma, 1970; Flom, Weymouth, & Kahneman, 1963; Intriligator & Cavanagh, 2001; Jacobs, 1979; Toet & Levi, 1992). In everyday life, crowding performance limits the ability to identify letters or words embedded in text, for example.

Several lines of explanation for visual crowding have been advanced. Some researchers have suggested important roles for interactions between the facilitatory and inhibitory regions within neuronal receptive fields in early visual areas or interactions between neurons via long-range horizontal connections (Flom, Heath, & Takahashi, 1963; Polat & Sagi, 1994; Tripathy & Levi, 1994). Others have suggested that crowding, particularly foveal crowding, is a form of spatial-frequency masking or contrast masking (Chung, Levi, & Legge, 2001; Levi, Klein, & Hariharan, 2002) or is related to the physical properties of the stimulus (Hess, Dakin, & Kapoor, 2000). Alternatively, it has

Address correspondence to C.S. Green, RC 270268, Meliora Hall, University of Rochester, Rochester, NY 14627-0268, e-mail: csgreen@bcs.rochester.edu.

been proposed that the size of the crowding region offers a measure of the resolution of visual attention (Intriligator & Cavanagh, 2001; Tripathy & Cavanagh, 2002). But whichever interpretation of crowding may prevail, all parties agree that crowding reflects a fundamental limitation on the spatial resolution of the visual system.

In the experiments reported in this article, we tested the hypothesis that playing action video games leads to enhanced spatial resolution, by using a crowding paradigm modeled after that of Toet and Levi (1992). Experiment 1 establishes that avid VGPs exhibit smaller crowding regions than NVGPs, meaning that VGPs maintain high performance at target-distractor separations that hinder NVGPs' performance. In Experiment 2, we used a training paradigm to demonstrate a causative relationship between action-video-game experience and performance in a visual task.

EXPERIMENT 1

If spatial resolution is enhanced in VGPs, the size of the crowding region should be smaller in VGPs than in NVGPs. We measured the size of the crowding region by testing the ability of participants to discriminate between a right-side-up and an upside-down T shape as a function of the distance between this target object and two flanking distractor T shapes presented above and below the target (Fig. 1; Toet & Levi, 1992). The size of the crowding region was assessed at three different eccentricities (0° , 10° , and 25°) chosen to allow the measurement of potential changes both well within (0° and 10°) and just at the limit of (25°) the field of view of normal game playing (most of our gamers reported playing on screens that subtended an average of $\pm 15^\circ$ from the center of the screen). If changes in the size of the crowding region do arise as a result of action-video-game experience, but the learning is specific to the trained region of space, one would predict greater enhancements for 0° and 10° than for 25° . Conversely, if similar changes were observed across eccentricities, this would be evidence for generalization of the learning beyond the more highly trained regions of space.

Method

Subjects

Twenty right-handed males (all undergraduates at the University of Rochester) with normal or corrected-to-normal vision were placed into one of two groups, VGP or NVGP, on the basis of the outcome of an interview about their video-game playing habits (only males were tested in Experiment 1 because of the relative scarcity of female VGPs). For each of several different types of video games (action, sports, fantasy, role-playing, other), participants were asked to name all the games they had played in the past 12 months. For each video game participants reported playing, they were asked how often they played that game in the

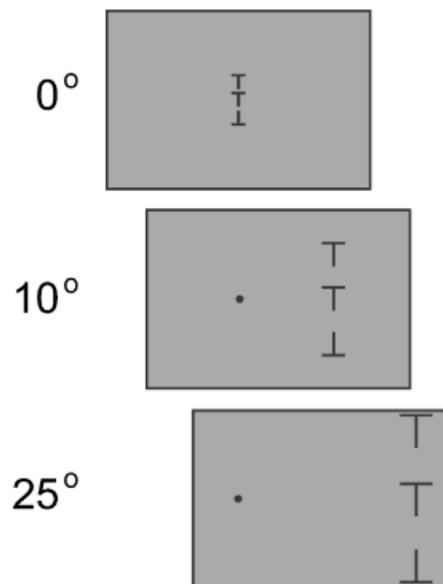


Fig. 1. Illustration of the test stimuli. The stimuli consisted of three T shapes randomly oriented either right side up or upside down. The subject's task was to indicate the orientation of the center T. In separate blocks, three eccentricities were tested— 0° , 10° , and 25° . The size of the Ts was set to be 1.5 times each individual subject's T-alone threshold at each eccentricity.

previous 12 months (daily, weekly, monthly or less), how long they played it during a typical session, and, if applicable, how many hours they played it per week (0, 0–1, 1–2, 3–5, 5–10, 10+).

To be considered a VGP, a subject needed to report a minimum of 5 hr a week of action-video-game usage for the previous 6 months ($N = 10$, mean age = 19.7 years). The criterion to be considered an NVGP was a report of 0 hr per week of action-video-game play for at least the previous 6 months ($N = 10$, mean age = 20.3 years; note: subjects in this group could play other kinds of video games). Subjects provided written informed consent to participate and were paid \$8 per hour.

Apparatus

The apparatus consisted of a Macintosh G3 computer running a program to present stimuli and collect the data using the Matlab computer language (The Math Works Inc., Natick, MA) and the Psychophysics Toolbox routines (Brainard, 1997; Pelli, 1997). The stimuli were displayed on a 24-in. Sony GDM-FW900 driven at a resolution of 1920×1440 pixels at 75 Hz by an MP850 video card (Village Tronic Computer, Sarstedt, Germany).

Stimuli

The stimuli and procedure were modeled after those of Toet and Levi (1992; Fig. 1). The stimuli consisted of three vertically aligned T shapes formed by black pixels (3 cd/m^2). The shapes had a stroke width of 2 pixels and were presented either right

side up or upside down against a uniform white background (70 cd/m²). For each eccentricity tested, the size of the Ts was set to 1.5 times each individual subject's T-alone discrimination threshold. The T-alone discrimination threshold was derived by averaging the threshold obtained in two blocks in which the T was presented in isolation.

Viewing Conditions

The three eccentricities tested, 0°, 10°, and 25°, called for three different viewing distances (300 cm, 90 cm, and 50 cm, respectively). For the two peripheral conditions, the stimuli were always centered on the horizontal meridian to the right of fixation, and we used an eyetracker to enforce fixation. The eyetracking analysis was conducted off-line; thus, trials in which an eye movement occurred could not be removed from the final analyses. However, the number of eye movements made was quite low (< 4% of trials) and did not differ between groups ($F < 1$) or among eccentricities ($F < 1$). Each eccentricity was presented in a separate block, and the order of the blocks was counterbalanced across subjects. No effect of run order was found, and we do not discuss this variable further.

Procedure

Each trial began with a short auditory tone followed by a 150-ms interstimulus interval. For the 0° stimulus, the fixation dot was extinguished during this interval to diminish any possible forward masking. For the two peripheral conditions, the fixation dot remained visible throughout the trial. The stimuli were then presented for 100 ms. The task was to indicate the orientation (up/down) of the center T by pressing the corresponding key on the keyboard. Subjects were free to respond at any time following stimulus presentation and were told that accuracy rather than speed of response was critical. Following response, auditory feedback was given (low tone for an incorrect response and high tone for a correct response).

The critical manipulation was the center-to-center spacing between the two flanking Ts and the target T (initial spacing was 30, 400, and 600 min of arc for the 0°, 10°, and 25° conditions, respectively), which was controlled by a three-up, one-down staircase (step size of 5%). We did not end the staircase procedure after a certain number of reversals; rather, to ensure that subjects were given equal experience (as three different eccentricities were tested and compared), we had all subjects complete 200 trials per condition. The final crowding-threshold value was calculated by averaging the center-to-center target-distractor spacing across the final 10 trials.

Results and Discussion

The crowding threshold varied from approximately 10 min of arc for the 0° condition, to 120 min of arc at 10°, to more than 300 min of arc for the 25° condition. The finding that the crowding region increased dramatically with eccentricity mirrors previous

reports in the field (Leat et al., 1999; Toet & Levi, 1992). To be able to compare the effect of video-game experience across eccentricities, we first converted the distance thresholds to log₁₀ values, thus allowing a relative equalization of the means and variances across conditions (Leat et al., 1999).

The effects of VGP status (VGP, NVGP) and eccentricity (0°, 10°, 25°) were analyzed in a 2 × 3 analysis of variance (ANOVA) run on log distance thresholds. A main effect of eccentricity was observed, $F(2, 36) = 331.7, p_{\text{rep}} > .99, \eta_p^2 = .95$, with the size of the crowding region increasing with increasing eccentricity, as expected. A main effect of VGP status was also observed, $F(1, 18) = 22.4, p_{\text{rep}} > .99, \eta_p^2 = .55$, with VGPs demonstrating smaller crowding regions than NVGPs (Fig. 2a). Eccentricity did not interact with VGP status ($F < 1$), which suggests that the effect of VGP status was consistent across the eccentricities tested.

Although our primary goal was to ascertain the size of the crowding zones in VGPs and NVGPs, another interesting pattern of results was observed in the T-alone condition. A 2 (VGP status: VGP, NVGP) × 3 (eccentricity: 0°, 10°, 25°) ANOVA on log₁₀ transformed values of these thresholds revealed, as expected, a main effect of eccentricity, $F(2, 36) = 412.6, p_{\text{rep}} > .99, \eta_p^2 = .96$, with the size of the T at threshold increasing with increasing eccentricity. Unexpectedly, though, a main effect of VGP status was also observed, $F(1, 18) = 15.9, p_{\text{rep}} > .99, \eta_p^2 = .47$, with VGPs being able to discriminate smaller Ts than NVGPs. VGP status did not interact with eccentricity, $F(2, 36) = 1.2, p_{\text{rep}} < .65$, which suggests the effect was consistent across the eccentricities tested.

Together, these results demonstrate that VGPs have both smaller regions of spatial interaction and better visual acuity thresholds than NVGPs. It is worth noting that the performance improvement seen in gamers was consistent across all eccentricities tested. A difference between groups at 0° is somewhat surprising as it is generally assumed that foveal vision is near optimal, and therefore more difficult to enhance through training than peripheral vision (Neville & Bavelier, 2002). Nonetheless, the present study establishes a central performance enhancement of a magnitude comparable to that observed in the periphery. In addition, the presence of a group difference at 25° of eccentricity suggests that some transfer of learning had occurred, as this eccentricity was not within the well-trained region of space. If this improvement were found to be truly due to experience with action video games, this effect would be unexpected because the perceptual learning literature has demonstrated exquisite spatial specificity for learning in many training tasks (Fahle, 2004, 2005; Karni & Sagi, 1991).

Before any conclusions about the effects of action-video-game experience can be reached, self-selection needs to be ruled out as a contributing factor. It is possible that by selecting avid game players, we chose a population that would have superior visual skills even without the difference in training. It may be, for example, that individuals with better visual skills are more

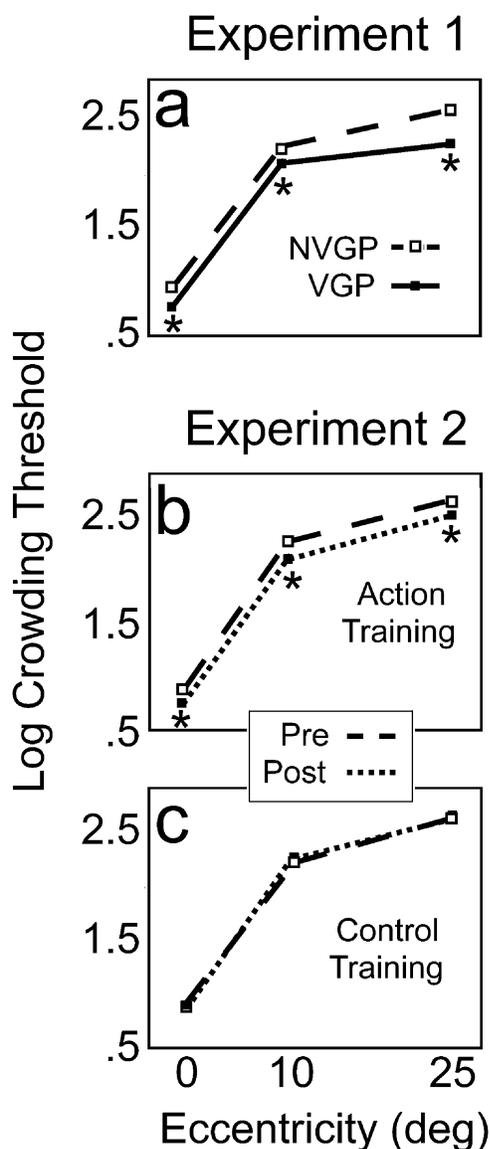


Fig. 2. Crowding thresholds in Experiments 1 and 2. In Experiment 1 (a), thresholds of action-video-game players (VGPs) and non-action-video-game players (NVGPs) were compared. In Experiment 2, NVGPs were trained on an action video game (b) or a control game (c), and their crowding thresholds were measured before (“Pre”) and after (“Post”) training. Standard errors of the means for all data points were less than the size of the squares denoting the values. Significant differences between thresholds at the same eccentricity are indicated by asterisks, $*p_{rep} > .92$.

likely to excel at game playing and therefore more likely to become avid players.

EXPERIMENT 2

Experiment 2 employed a training paradigm to investigate whether a causative relationship exists between action-video-game experience and enhanced spatial resolution. Thirty-two nongamers were divided into two training groups. One group was then trained on an action game that was similar to the games

played by the VGPs in Experiment 1, whereas the other was trained on a game that was less visually intense, but that did require substantial visuomotor coordination. In addition to controlling for any effects of improved visuomotor coordination (better hand-eye coordination could conceivably reduce the resources necessary for response execution, leaving more resources free for target identification), the control group acted as a control for test-retest improvements (improvements due to practice on the tests themselves) and for any Hawthorne-like effects (improvements due to the fact that the experimenters had “paid attention” to the subjects during the training—Benson, 2001). Crowding thresholds were measured before and after training (30 hr of training over a span of 4–6 weeks). If action-video-game experience is sufficient to cause a decrease in the size of the crowding region, a greater reduction in threshold would be expected in the group trained on the action game than in the control group.

Method

Subjects

Thirty-two NVGPs were equally and randomly divided between the experimental and control groups. The criteria for being considered an NVGP were the same as in Experiment 1. All subjects underwent training as described in this section. In all, 8 females and 8 males (mean age = 21.3; all right-handed) made up the final experimental group; the final control group consisted of 9 females and 7 males (mean age = 21.0, 15 right-handed).

Testing: Apparatus, Stimuli, and Procedure

The apparatus, stimuli, and procedure were identical to those in Experiment 1 with three exceptions. First, because subjects underwent several unrelated experiments, the total testing duration was minimized, and thus only one T-alone block was completed prior to the experimental block. Second, to decrease running time, we set the step size of the change in T size at 20% until three reversals were observed and then decreased the step size to 5%, allowing stable thresholds to be reached in 120 trials. Finally, because no effect of run order was found in Experiment 1, the three eccentricities were run in a fixed order: 0°, 10°, and 25°. Eye movements were again measured for the two peripheral conditions and, as in Experiment 1, were quite rare (approximately 3% of trials); they did not differ as a function of test (pretest, posttest), trained game (action game, control game), or eccentricity, nor were there interactions between any of these variables.

Training: Apparatus, Stimuli, and Procedure

For both groups, training consisted of playing the predetermined video game for a total of 30 hr (maximum of 2 hr per day, minimum of 5 hr per week, maximum of 8 hr per week). The 16 members of the experimental group played the game Unreal Tournament 2004 (henceforth referred to as the action video

game). This game was chosen because it is similar to the games played by the VGPs in Experiment 1; it has a relatively simple interface, uses first-person point of view, and requires effective monitoring of the entire visual field (extent from fixation: about 13° high \times 16° wide). Each 1-hr session of play was divided into three 20-min blocks. The difficulty of each block was adjusted on the basis of the kill/death ratio. If in a block the player scored more than twice as many kills as deaths, the difficulty of the next block was increased one level. Also, players were periodically retested on levels of lower difficulty to assess improvement quantitatively.

The 16 members of the control group played the game Tetris, which was displayed to cover the entire extent of the screen (extent from fixation: 18° high \times 13° wide). Thus, the field of view of the Tetris game was slightly larger than that of the action game. Tetris was selected to control for the effect of improved visuomotor coordination while minimizing the processing of multiple objects at once. Accordingly, the version of Tetris on which subjects were trained had the preview-block option turned off. Improvement was measured quantitatively by comparing performance on Day 1 and Day 30.

The groups played their respective games on 20-in. monitors. The action-game group played on Dell FlatPanel displays, whereas the control group played on CRT monitors.

Results and Discussion

Game Play

Improvement in game play was assessed using several measures. For the action game, the two measures were kills and deaths. For each of five levels of game difficulty (Level 5 being the highest level that all players attained), the measures taken on subjects' first playing of the level (which, because of the way in which difficulty was increased, was not necessarily on the 1st day of training) were compared with the measures taken on their final playing of the level on Days 29 and 30. Number of kills increased substantially and number of deaths decreased substantially at each difficulty level (Level 1: 226% increase in kills, 64% decrease in deaths; Level 2: 147%, 38%; Level 3: 160%, 27%; Level 4: 80%, 33%; Level 5: 52%, 32%).

For the control game, the mean and median scores from Day 1 and Day 30 were compared. As did the action-game players, the control players showed substantial improvements after training, the mean score improving by 323% and the median score by 359%.

These results demonstrate that both groups were engaged in their training and showed improvement on the training task.

Crowding Thresholds

As in Experiment 1, the crowding thresholds were converted to \log_{10} values before analysis. A $2 \times 2 \times 3$ ANOVA with trained game (action, control), test (pretest, posttest), and eccentricity (0° , 10° , 25°) as factors yielded a strong main effect of eccen-

tricity, $F(2, 60) = 2,506.5, p_{\text{rep}} > .99, \eta_p^2 = .98$, with crowding thresholds increasing with increasing eccentricity. A main effect of test was also observed, $F(1, 30) = 4.8, p_{\text{rep}} = .93, \eta_p^2 = .14$, with crowding thresholds being lower at posttest than pretest. The significant interaction between trained game and test, $F(1, 30) = 11.6, p_{\text{rep}} = .99, \eta_p^2 = .28$, confirmed the results from Experiment 1: The action group showed larger decreases in crowding threshold from pretest to posttest than the control group did (Figs. 2b and 2c, respectively). This effect did not interact with eccentricity ($F < 1$), which suggests that the effect of training was similar across the eccentricities tested.

Unlike in Experiment 1, in which VGPs showed lower thresholds than NVGPs, no effect of trained game or test was detected in the T-alone data in Experiment 2. Only a main effect of eccentricity was observed, $F(2, 60) = 918.8, p_{\text{rep}} > .99$; as is typical, thresholds increased with increasing eccentricity.

The results of Experiment 2 establish that subjects trained on an action video game exhibit significantly greater decreases in crowding threshold than subjects trained on a control game. Unlike in Experiment 1, visual acuity (T-alone threshold) was not detectably modified by training on an action video game. Although it is unclear at this point whether more than 30 hr of training could produce a reliable change in visual acuity, Experiment 2 unambiguously demonstrates that visual crowding can be altered through action-video-game training.

DISCUSSION AND CONCLUSIONS

Action-video-game experience was shown to lead to an increase in the spatial resolution of vision as measured by crowding. VGPs could tolerate smaller center-to-center spacing between target and distractors than could NVGPs. This improvement was noted not only at peripheral locations, but also in central vision, indicating that even the high central resolution can be enhanced with proper training. In addition, improvements in the periphery were seen not only at locations well within the range of playing, but also at more eccentric locations; this result indicates transfer of training beyond the highly trained regions of space. NVGPs specifically trained on an action video game for 30 hr showed similar improvement in the size of the visual crowding region; this finding establishes a causative relationship between video-game experience and reduction in the size of the crowding region. Thus, video-game play may alter basic properties of the visual system.

This study extends previous findings on the impact of video-game and visual skills by showing that video-game play can alter visual performance even in a task in which the location and time of arrival of the stimulus are fixed and known ahead of time to the subject. In contrast, previous work in gamers focused on complex visual tasks that by design relied on uncertainty, such as visual search tasks in which the target location is uncertain and has to be found. Although the finding that video-game play changes performance on such complex visual tasks is interest-

ing, a number of other manipulations are known to affect performance on such tasks as well. For example, much previous research documents that visual spatial resolution is enhanced when exogenous cues are used to reduce spatial and temporal uncertainty (Carrasco, Williams, & Yeshurun, 2002; Yeshurun & Carrasco, 1999) and that performance is impaired when a difficult secondary task is added (Zenger, Braun, & Koch, 2000). In the present study, VGPs demonstrated reductions in crowding thresholds even though where and when the stimulus would appear was fixed, and subjects could therefore focus at their optimal level. The finding of improved performance under such conditions cannot easily be attributed to strategic factors. Rather, one of the mechanisms by which action-video-game play may enhance visual processing is by increasing the spatial resolution of visual processing across the visual field.

The present study highlights the potential of action-video-game training for rehabilitation of visual deficits. Indeed, a common feature in visually impaired patients is increased vulnerability to crowding, as is seen in amblyopia or normal aging (Ball, Beard, Roenker, Miller, & Griggs, 1988; Ball & Owsley, 1992; Hariharan, Levi, & Klein, 2005; Levi, Hariharan, & Klein, 2002; Levi & Klein, 1985; Polat, Sagi, & Norcia, 1997). Of course, much work remains to characterize the level (or levels) of processing at which video-game playing may act; however, by establishing that a video-game training regimen can reduce the detrimental effects of crowding, this research opens new avenues for the development of rehabilitation software.

Acknowledgments—We thank W. Makous for much helpful advice and J. Cohen for help with subjects. This work was supported by National Institutes of Health Grants EYO16880 and DC04418 to D.B.

REFERENCES

- Ball, K., Beard, B., Roenker, D., Miller, R., & Griggs, D. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America, A*, 5, 2210–2219.
- Ball, K., & Owsley, C. (1992). The useful field of view test: A new technique for evaluating age-related declines in visual function. *Journal of the American Optometric Association*, 63, 71–79.
- Benson, P.G. (2001). Hawthorne effect. In W.E. Craighead & C.B. Nemeroff (Eds.), *The Corsini encyclopedia of psychology and behavioral science* (3rd ed., Vol. 2, pp. 667–668). New York: John Wiley and Sons.
- Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, 226, 177–178.
- Brainard, D.G. (1997). The Psychophysics Toolbox. *Spatial Vision*, 10, 433–436.
- Carrasco, M., Williams, P.E., & Yeshurun, Y. (2002). Covert attention increases spatial resolution with or without masks: Support for signal enhancement. *Journal of Vision*, 2, 467–479.
- Castel, A.D., 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, 217–230.
- Chung, S.T., Levi, D.M., & Legge, G.E. (2001). Crowding: A classical spatial-frequency masking effect? *Vision Research*, 41, 1833–1850.
- Fahle, M. (2004). Perceptual learning: A case for early selection. *Journal of Vision*, 4, 879–890.
- Fahle, M. (2005). Perceptual learning: Specificity versus generalization. *Current Opinion in Neurobiology*, 15, 154–160.
- Flom, M.C., Heath, G.G., & Takahashi, E. (1963). Contour interaction and visual resolution: Contralateral effects. *Science*, 142, 979–980.
- Flom, M.C., Weymouth, F.W., & Kahneman, D. (1963). Visual resolution and contour interaction. *Journal of the Optical Society of America*, 53, 1026–1032.
- Gopher, D., Weil, M., & Bareket, T. (1994). Transfer of skill from a computer game trainer to flight. *Human Factors*, 36, 387–405.
- Green, C.S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, 423, 534–537.
- Green, C.S., & Bavelier, D. (2006a). The cognitive neuroscience of video games. In L. Humphreys & P. Messaris (Eds.), *Digital media: Transformations in human communication* (pp. 211–223). New York: Peter Lang.
- Green, C.S., & Bavelier, D. (2006b). Enumeration versus multiple object tracking: The case of action video game players. *Cognition*, 101, 217–245.
- 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, 105–123.
- Hariharan, S., Levi, D.M., & Klein, S.A. (2005). “Crowding” in normal and amblyopic vision assessed with Gaussian and Gabor C’s. *Vision Research*, 45, 617–633.
- Hess, R.F., Dakin, S.C., & Kapoor, N. (2000). The foveal ‘crowding’ effect: Physics or physiology. *Vision Research*, 40, 365–370.
- Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology*, 43, 171–216.
- Jacobs, R.J. (1979). Visual resolution and contour interaction in the fovea and periphery. *Vision Research*, 19, 1187–1195.
- Kami, A., & Sagi, D. (1991). Where practice makes perfect in texture discrimination: Evidence for primary visual cortex plasticity. *Proceedings of the National Academy of Sciences, USA*, 88, 4966–4970.
- Leat, S.J., Li, W., & Epp, K. (1999). Crowding in central and eccentric vision: The effects of contour interaction and attention. *Investigative Ophthalmology & Visual Science*, 40, 504–512.
- Levi, D.M., Hariharan, S., & Klein, S.A. (2002). Suppressive and facilitatory spatial interactions in amblyopic vision. *Vision Research*, 42, 1379–1394.
- Levi, D.M., & Klein, S.A. (1985). Vernier acuity, crowding, and amblyopia. *Vision Research*, 40, 1775–1783.
- Levi, D.M., Klein, S.A., & Hariharan, S. (2002). Suppressive and facilitatory spatial interactions in foveal vision: Foveal crowding is simple contrast masking. *Journal of Vision*, 2, 140–166.
- Miller, J. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: A search for boundary conditions. *Perception & Psychophysics*, 49, 270–288.
- Neville, H., & Bavelier, D. (2002). Human brain plasticity: Evidence from sensory deprivation and altered language experience. *Progress in Brain Research*, 138, 177–188.

- Orbach, H.S., & Wilson, H.R. (1999). Factors limiting peripheral pattern discrimination. *Spatial Vision, 12*, 83–106.
- Pelli, D.G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442.
- Polat, U., & Sagi, D. (1994). The architecture of perceptual spatial interactions. *Vision Research, 34*, 73–78.
- Polat, U., Sagi, D., & Norcia, A.M. (1997). Abnormal long-range spatial interactions in amblyopia. *Vision Research, 37*, 737–774.
- Toet, A., & Levi, D.M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research, 32*, 1349–1357.
- Trick, L.M., Jaspers-Fayer, F., & Sethi, N. (2005). Multiple-object tracking in children: The “Catch the Spies” task. *Cognitive Development, 20*, 373–387.
- Tripathy, S.P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research, 42*, 2357–2369.
- Tripathy, S.P., & Levi, D.M. (1994). Long-range dichoptic interactions in the human visual cortex in the region corresponding to the blind spot. *Vision Research, 34*, 1127–1138.
- Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks. *Vision Research, 39*, 293–306.
- Zenger, B., Braun, J., & Koch, C. (2000). Attentional effects on contrast detection in the presence of surround masks. *Vision Research, 40*, 3717–3724.

(RECEIVED 12/12/05; REVISION ACCEPTED 4/13/06;
FINAL MATERIALS RECEIVED 4/26/06)