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Changes in search rate but not in the dynamics of exogenous attention in action videogame players

Bjorn Hubert-Wallander · C. Shawn Green · Michael Sugarman · Daphne Bavelier

Abstract Many previous studies have shown that the speed of processing in attentionally demanding tasks seems enhanced following habitual action videogame play. However, using one of the diagnostic tasks for efficiency of attentional processing, a visual search task, Castel and collaborators (Castel, Pratt, & Drummond, Acta Psychologica 119:217–230, 2005) reported no difference in visual search rates, instead proposing that action gaming may change response execution time rather than the efficiency of visual selective attention per se. Here we used two hard visual search tasks, one measuring reaction time and the other accuracy, to test whether visual search rate may be changed by action videogame play. We found greater search rates in the gamer group than in the nongamer controls, consistent with increased efficiency in visual selective attention. We then asked how general the change in attentional throughput noted so far in gamers might be by testing whether exogenous attentional cues would lead to a disproportional enhancement in throughput in gamers as compared to nongamers. Interestingly, exogenous cues were found to enhance throughput equivalently between gamers and nongamers, suggesting that not all mechanisms known to enhance throughput are similarly enhanced in action videogamers.

Keywords Attention · Visual search · Cognitive and attentional control

B. Hubert-Wallander · M. Sugarman · D. Bavelier (✉)
Department of Brain and Cognitive Sciences,
University of Rochester,
Meliora Hall 0268,
Rochester, NY 14627-0268, USA
e-mail: daphne@cvs.rochester.edu

B. Hubert-Wallander
Department of Psychology, University of Washington,
Seattle, WA 98195, USA

C. S. Green
Department of Psychology, Center for Cognitive Sciences,
University of Minnesota,
Minneapolis, MN 55455, USA

Introduction

Over the past decade, action videogame play has been shown to enhance many distinct aspects of visual performance (Hubert-Wallander, Green & Bavelier, 2011). "Action" videogames are defined as fast-paced videogames that require excellent sensory–motor coordination, force a fast pace of processing on the player, and place a premium on divided attention. In practice, these most commonly consist of first-person shooter games (e.g., the *Halo*, *Call of Duty*, and *Battlefield* series of games) or third-person shooter games (e.g., the *Gears of War* and *Grand Theft Auto* series). As an example of the sorts of improvements action games have been shown to induce, the findings of larger useful fields of view (Feng, Spence & Pratt, 2007; Green & Bavelier, 2003, 2006a; Spence, Yu, Feng & Marshman, 2009; West, Stevens, Pun & Pratt, 2008) and larger Goldmann perimetry fields (Buckley, Codina, Bhardwaj & Pascalis, 2010) in action gamers suggest an enhancement in spatial characteristics of visual attention, particularly in the ability to spread attentional resources to the far periphery. Reductions in the crowding threshold at central and peripheral eccentricities confirm enhanced processing in the visual periphery, but indicate processing advantages in central vision as well (Green & Bavelier, 2007). Furthermore, reductions in the duration and magnitude of the attentional blink (Dye & Bavelier, 2010; Green & Bavelier,

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2003), reduced backward masking (Li, Polat, Scalzo & Bavelier, 2010), and more veridical representation of the times of occurrence of events (Donohue, Woldorff & Mitroff, 2010) indicate enhancements in the temporal characteristics of visual processing and visual attention. A number of studies have also shown superior performance on multiple-object tracking and enumeration tasks (Green & Bavelier, 2003, 2006b; Trick, Jaspers-Fayer & Sethi, 2005), supporting enhancements in object-based characteristics of attention, in particular the ability to divide attention across several moving objects at once, even as the scene changes drastically over the course of tracking. Enhanced change detection (Clark, Fleck & Mitroff, 2011) and faster recovery from attentional capture (Chisholm, Hickey, Theeuwes & Kingstone, 2010) also point to more efficient attentional processes in action videogame players. More generally, enhanced divided attention and more efficient selective attention in action gamers may result from better suppression of irrelevant, potentially distracting information (Mishra, Zinni, Bavelier & Hillyard, 2011). Taken together, the preponderance of the literature seems indicative of an enhancement in throughput in action gamers—or, in other words, the efficiency with which sensory signals are converted into information relevant to the decision at hand.

Others, however, have offered alternative accounts to explain some of the action gaming data. For instance, because many of the enhancements noted in gamers are manifested via faster reaction times (RTs), it has been suggested that rather than reflecting differences in information processing, these faster search times are instead the byproduct of better stimulus–response mapping or other postdecisional processes in action gamers. Such an argument was made, for example, by Castel, Pratt and Drummond (2005) on failing to find faster search rates in gamers using a hard visual search task. The authors measured subject RTs to find a randomly placed target letter among a varying number (3, 9, 17, or 25) of distractor letters. As is found throughout the action videogame player (VGP) versus nongamer (NVGP) literature, the VGP group demonstrated faster search times in every condition. More critically for the hypothesis at hand, however, analysis of the data also revealed a significant group x set size interaction effect. This interaction appeared to be driven by a lower RT cost of additional distractor items in VGPs than in NVGPs or, in other words, more efficient search in VGPs. The authors, however, suggested that RTs at the smallest set size represented a floor effect and that this artifact, rather than a true change in visual search throughput, was what drove the initial interaction. After the removal of the data points from the smallest set size, the interaction of interest was no longer significant, leading the authors to conclude that visual search rates remained unchanged by action videogame play. This led the authors to state, “Thus, unlike the hypothesis that differences would emerge between VGPs and NVGPs in tasks that involve the endogenous control of attention (i.e., visual search), it seems that VGPs display an overall RT advantage due to stronger associations between the detection of a stimulus and the production of an appropriate response” (Castel et al., 2005, p.228).

The proposal that the action gamer advantage in RT tasks can be explained entirely by changes in postdecisional processes, however, is inconsistent with a recent meta-analysis of the action videogaming literature. Dye, Green and Bavelier (2009b) compared the RTs of action gamers and nongamers in more than 80 different experimental conditions. The best fit to the data was captured by a multiplicative relationship (VGPs being 12% faster than NVGPs across all tasks), which suggests a change in throughput rather than a change in motor execution time, which would have been suggested by an additive shift across all tasks. Similar results were observed when comparing NVGPs before and after training on action games, indicating the causal nature of game play in this effect. More recently, using tasks that required subjects to filter signal from noise in both the visual and auditory domains, Green, Pouget and Bavelier (2010) demonstrated how action game play causally leads to reductions in RTs without changing accuracy. Using drift-diffusion modeling and statistical modeling, this work established that the RT advantages noted in NVGPs trained on action games could not be accounted for solely by a change in motor execution times. Rather, they found that changes in the rates of accumulation of information were necessary to account for these data, confirming again the causal role of action game play in enhanced throughput.

In this context, the finding of similar search rates in gamers and nongamers in Castel et al., (2005) seems anomalous. An understanding of exactly which aspects of processing are altered in VGPs will be essential to uncovering the underlying mechanism for the changes. After all, once understood, such a mechanism might be harnessed in order to improve visual capabilities in populations for whom such improvement would be most needed, such as those with severe visual impairments (e.g., amblyopic patients and stroke victims; see Achtman, Green & Bavelier, 2008; Bavelier, Levi, Li, Dan & Hensch, 2010) and those whose profession requires supernormal visual attention (e.g., commercial and military pilots, air traffic controllers). Here, we compared action videogame players to nongamers on hard search tasks in order to clarify the scope of differences in the efficiency of their visual selective attention.

In Experiment 1, we used two search methods in a within-subjects design to obtain independent measures of visual search rates in VGPs and NVGPs. In the first, search rate was calculated from RTs to static displays, as is standard in the field. In the second, search rate was calculated via response accuracy to quickly presented displays. By allowing subjects as much time as they wished to give their responses, the latter method allowed for the estimation of search rates in the absence of possible contamination from motor execution factors. Our proposal of greater throughput in gamers predicts that we should observe faster search rates in gamers in both of these procedures. In addition, we predicted that search rate estimates calculated from the RT procedure would be correlated with search rate estimates via the accuracy procedure, since these two measures should estimate a common factor—throughput. Both predictions were borne out by the data. In Experiment 2, we turned to exogenous cuing, an attentional manipulation known to change throughput (Carrasco, Giordano & McElree, 2004, 2006; Carrasco & McElree, 2001; Hikosaka, Miyauchi & Shimojo, 1993; Schneider & Bavelier, 2003; Shore, Spence & Klein, 2001; Stelmach & Herdman, 1991). Here, we asked whether exogenous cuing might disproportionally enhance throughput in VGPs, in line with their greater throughput in other studies. Interestingly, we found that exogenous cues had similar effects in VGPs and NVGPs, demonstrating that not all attentional manipulations equally modify throughput in action gamers. These results are discussed in the larger context of the burgeoning literature on the skills afforded by action game play.

Experiment 1: Visual search

The goal of Experiment 1 was to compare visual search rates in VGPs and NVGPs using the same type of hard visual search used in Castel et al. (2005). To evaluate our prediction that faster search rates should be found in VGPs, in Experiment 1 we estimated search rates in the same subjects using two different measures. In Experiment 1A, a standard hard search paradigm was employed, wherein sets of search items were displayed until the subject's response. Rates of visual search were then calculated by regressing RT against set size. In Experiment 1B, the task was modified to make RTs irrelevant, and thus accuracy was the primary dependent measure. While in Experiment 1A the search arrays were visible until subject response, in Experiment 1B the search arrays were presented for short, discrete amounts of time. The search rate in this case was calculated by examining how accuracy grew with presentation time. By relying on accuracy rather than RTs, this method afforded a measure of the rate of information accrual, or throughput, without any confounds from motor or postdecisional processes. A change in throughput in action gamers, as we hypothesized, would predict greater search rates in both methods, as well as correlated and converging estimates across methods, since they putatively measure the same process. Alternatively, a change in motor execution time or postdecisional processes would involve no change in search rates, and thus would predict only a shift in baseline RTs in Experiment 1A and no differences between groups in Experiment 1B.

Method

Subjects The subjects were recruited from the University of Rochester community through electronic and physical advertisements explicitly seeking both habitual action videogame players and individuals who do not regularly play fast-paced videogames. All subjects completed a videogame history questionnaire previous to the experimental tasks, in which they freely reported which videogames they had played during the past year and for how many hours per session and sessions per month that they had done so. A number of subjects had completed that survey in the month before this study; the others were asked to complete it upon arrival at the study location. Responses to the questionnaire were used to place subjects into the videogame player (VGP) and non-videogame-player (NVGP) groups. Individuals who did not qualify for either group participated in the study, but their data were not analyzed ($n = 3$). The criterion to be considered a VGP was a minimum of 5 h per week, on average, of action videogame play over the previous year. The criterion to be considered a NVGP was one or fewer hours per week on average of action videogame play over the previous year. It is important to note that only experience with *action* videogames counted toward this requirement. As mentioned earlier, action videogames feature fast motion and emergent gameplay, as well as high demands on visuomotor coordination, all while requiring vigilant monitoring of the periphery for unexpected events and simultaneous tracking of multiple objects. As one might imagine, these games heavily stress divided attention. An abridged list of the action games reported as played by the VGP group includes *Halo*, *Counterstrike*, *Gears of War*, and *Call of Duty*. A group of 10 males with a mean age of 19.0 years fell into the VGP group, while 11 males with a mean age of 19.5 years fell into the NVGP group. As expected, subjects in the VGP group reported significantly more action videogame play during the past year than did those in the NVGP group (VGP = 9.00 ± 5.31 h/week, NVGP = 0.05 ± 0.15 h/week; $t(19) = 5.60$, $p < .001$). Of the NVGPs, 10 reported no action videogame play at all over the past year. The remaining NVGP subject quantified his experience as once per month. Only males were recruited and tested because of the relative scarcity of females with sufficient action videogame experience. All subjects had normal or corrected-to-normal vision. Written informed consent was obtained from each subject, and all were compensated for their participation.

Apparatus Stimuli were presented on a 22-in. Mitsubishi DiamondPro monitor receiving input from a Power Mac G4. The experiment was programmed using functions included in the PsychToolbox module for MATLAB (Brainard, 1997; Pelli, 1997), running under Apple's OS 9. Each subject viewed the display from approximately 57 cm in a normally lit room. A chinrest was used to stabilize head position.

Procedure All subjects participated in two search paradigms during one testing session, with the order of experimental paradigms randomized. The methods in Experiment 1A adhered very closely to that described in Castel et al. (2005), with the notable exceptions of set sizes (Castel et al. presented 4–26 items in each search array; here, we presented 8–20 items), pacing (Castel et al. enforced a strict trial-to-trial time schedule; here, the trials were self-paced), and distractor selection (Castel et al. allowed for multiple instances of the same distractor letter in a given array; here, each distractor was unique).

See Fig. 1 for an example of the search stimuli. The subjects' task on each trial was to identify which of two potential target letters was present among a field of distractor letters. At the start of each trial, the subject was presented with a small fixation point that remained on the screen throughout the trial. The subject began each trial by pressing the spacebar; the search array appeared 500 ms afterward. Subjects were told to fixate on the point at the start of each trial, but that they were free to move their eyes once the search array had appeared.

The search array on each trial was made up of exactly one target letter ("b" or "d") and either 7, 11, 15, or 19 distractor letters, providing four total set sizes of 8, 12, 16, and 20 letters. The set of possible distractors was made up of the 23 lowercase letters in the alphabet minus the letters "b," d," and "x," and the distractors on each trial were selected randomly from this set without duplication. All the letters appearing on a given trial were arranged randomly on an invisible 10º × 10º grid centered on the fixation point. Each letter was jittered randomly by 0.0º–0.1º within its 1º × 1º cell, and no letter appeared within 1º of another. All of the letters in the search array were white and appeared on a solid black background, with each letter subtending approximately 0.6º vertically and 0.4º horizontally.

Once it had appeared, the search array remained on the screen until the subject made his response using the left or right arrow key on a standard English keyboard. At this point the array disappeared, leaving only the fixation point. The experimenter instructed the subject to respond as quickly as possible on each trial while still being accurate. Auditory feedback was given after each trial. Each subject completed 400 trials total, 100 at each set size. Trials from all four set sizes were interleaved randomly into one large block of trials. Since a keypress initiated each trial, subjects were able to take breaks during the experiment by simply delaying the start of the next trial. Subjects took approximately 20 min to complete the task. Before testing began, subjects were given 32 practice trials (8 per set size) to ensure comprehension.

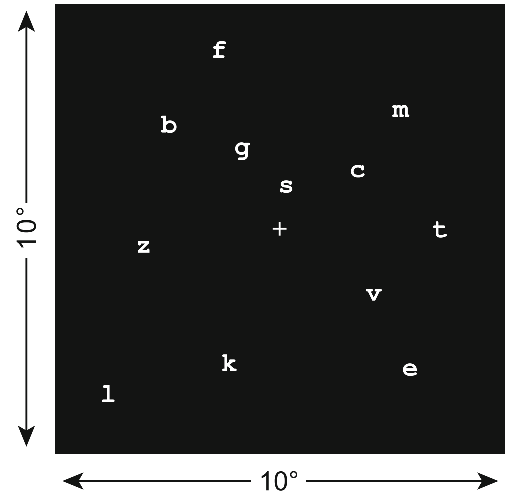

Fig. 1 An example of the search stimuli presented to subjects. The subjects' task on each trial was to decide whether a letter "b" or "d" was present among a set of unique distractor letters. Exactly one target letter was present on each trial. The search array remained on the screen until the subject made a response via a keypress

The subjects' task in each trial of Experiment 1B was the same as in 1A. However, in Experiment 1B the search array was present for only a fixed amount of time on each trial. The same four set sizes were used as in Experiment 1A (8, 12, 16, and 20), but here each set size was presented for five unique exposure durations, selected through initial pilot work to avoid floor or ceiling effects (set size 8: 27, 53, 93, 173, or 333 ms; set size 12: 40, 67, 133, 253, or 493 ms; set size 16: 53, 93, 173, 333, or 653 ms; set size 20: 53, 107, 213, 413, or 813 ms). Since accuracy was likely to rise sharply at low durations and then to asymptote at higher ones, it was necessary to use different exposure durations at each set size to capture the rising portion of the performance curve in each condition. The display durations were determined via an initial pilot study that looked for the two display durations that would give near-chance performance and near-95% performance for each set size. We then used steps, even in log values, to fill in the space between those two values.

Just as in Experiment 1A, each trial began after the subject pressed the spacebar. After a 500-ms delay, the search array appeared for the prescribed exposure duration, after which it was removed from the screen. In order to prevent the undue use of afterimages to complete the task, each letter in a given array was masked by the uppercase letter "X" immediately following its offset until subject response. The physical appearance of the stimuli, the makeup of the search arrays, and the manner of response were otherwise identical to those aspects of Experiment 1A.

In contrast to the instructions in Experiment 1A, here the experimenter instructed the subject to emphasize only accuracy in their responses and to guess if they needed to. Trials from all set sizes and exposure durations were randomly interleaved into one block of 1,000 trials, resulting in 250 trials per set size and 50 trials per set size–exposure duration combination. Again, auditory feedback was given after each trial, and subjects could rest between trials at will by waiting to press the spacebar after the previous trial. Subjects took approximately 45 min to complete the task. Before testing began, subjects were given 40 trials of practice distributed evenly among the two condition dimensions to ensure comprehension of the task.

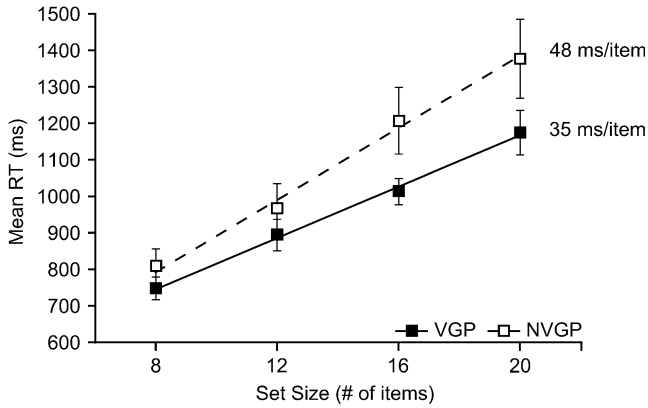

Fig. 2 Mean reaction time data from Experiment 1A, along with best-fit lines for each group. RTs increased linearly with the addition of distractor letters to the display across groups, but the VGP group appeared to suffer a smaller RT cost for each additional distractor than did the NVGP group. This manifests here as a shallower slope in the VGP best-fit line as compared to the NVGP line. Error bars represent standard errors. One NVGP subject is not included (see the Experiment 1B analysis)

Results

Data treatment In order to compare search processes in the two groups across the two experimental paradigms, we obtained a measure of visual search speed, or throughput, for each subject in each experiment as follows.

In Experiment 1A, RTs were filtered on a per-subject basis in order to reduce the impact of outliers. First, RTs from incorrectly answered trials were removed from the analysis. The proportions of trials removed due to incorrect answers were similar in the two groups, a fact that also demonstrates that no speed–accuracy trade-off was in play [no main effect of group on accuracy performance: VGP = 97.5 ± 2.4%, NVGP = 97.9 ± 1.1%; $F(1, 19) = 0.353$, $p = .56$, partial eta-squared (η_p^2) = .02; no interaction between group and set size: $F(3, 57) = 0.098$, $p = .96$, $\eta_p^2 = .005$]. Then, RTs that were more than three standard deviations from the condition mean were removed, where the condition mean was defined as the mean of the RTs for all correct trials within a given set size within a given subject (1.73% of all trials in the NVGP group and 1.38% of all trials in the VGP group).

A measure of search efficiency for a given subject was obtained by fitting the RT x set size data with a linear function. The slope of this function represented the amount of additional time that the subject required to find the target item as distractor items were added to the display. A lower milliseconds-per-item value indicated more efficient search. Each subject's data were well-fit in this way, and positive slopes were found in all subjects; see Fig. 2.

In Experiment 1B, each subject's data contained 20 accuracy values (four set sizes by five exposure durations; see Fig. 3). To estimate search rates, we used the exponential saturation function, a common model in the literature for critical duration experiments (Fiser, Bex & Makous, 2003; Li, Polat, Makous & Bavelier, 2009). The function we used was given by

$$P_i = \lambda - \delta_i * \exp\{\beta * \text{presentation time} * \log[(\text{set size}_i - 1)/\text{set size}_i]\},$$

with P_i being the proportion correct above chance for each set size. In this model, the asymptotic value is fixed at 100% correct, and thus the value of λ is set to .5. The intercept δ is allowed to vary across set sizes but is constrained to fall between chance and ceiling performance. Finally, a search rate β is estimated, common across all set sizes. There are thus five free parameters: β and four δs for each subject fit. Note that the primary parameter of interest in our case is the one search rate, β, which can be thought of as the number of items searched per unit of time (seconds, in our case).

The model fit well for both groups, but 1 subject in the NVGP group had to be removed from the data, as his rate parameter fell far above the mean for his group (nearly four standard deviations above the NVGP group mean and, surprisingly, three standard deviations above the VGP group mean as well). All analyses below were performed without this outlier. Even after removal of this NVGP outlier, the fits were significantly better for VGPs than for NVGPs (r^2: VGP = .78, NVGP = .70; $t(18) = 2.6$, $p = .02$; see Fig. 2). We suggest that this is due to more consistent performance in VGPs than NVGPs, a common finding when comparing these two populations. Subjects' rate parameters were converted from items/s to ms/item to allow for direct comparisons with the search slopes obtained in Experiment 1A.

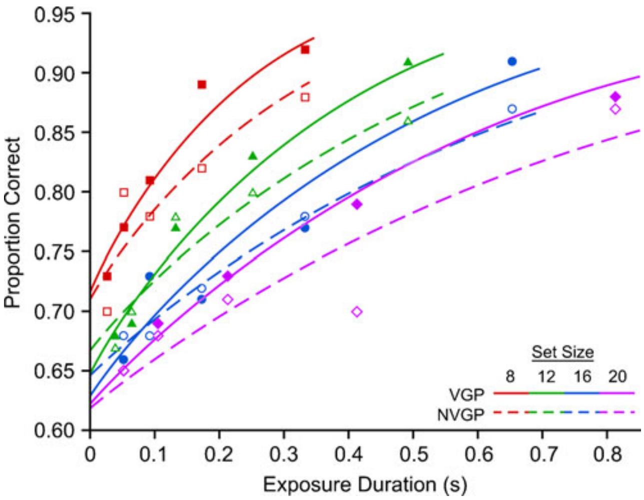

Fig. 3 Mean accuracy data for each group in Experiment 1B. Accuracy increased with search array exposure duration and was well-fit by an exponential saturation function in both groups, yielding one search rate (growth) parameter and four intercepts (one per set size) in each subject. Statistical comparison of the search rate parameters between the two groups revealed higher search throughput in the VGP group (see the Results section)

Analyses of search rate The derived search rates for Experiment 1 are given in Table 1. We note that both groups' search rates fall within the range expected in this type of search task (Wolfe, 1998), and this was the case when estimates were derived not only from the RT paradigm but also from the accuracy paradigm. We first performed a repeated measures ANOVA on the search speeds (in ms/item) with experiment as the within-subjects variable and group (VGP, NVGP) as the between-subjects variable.

A main effect of group was observed [$F(1, 18) = 7.198$, $p = .015$, $\eta_p^2 = .286$], driven by faster search rates in the VGP group than in the NVGP group. No main effect of experiment was found [$F(1, 18) = 0.303$, $p = .59$, $\eta_p^2 = .017$], nor was there a significant experiment x group interaction [$F(1, 18) < 0.001$, $p = .99$, $\eta_p^2 < .001$], in line with our proposal that these differing experimental paradigms provide converging estimates of search rate.

Separate analyses were then carried out for Experiments 1A and 1B to confirm faster search rates within each paradigm. For Experiment 1A, the mean RTs for both the VGP and the NVGP group are shown as a function of set size in Fig. 2. A repeated measures ANOVA on mean RTs, with set size as the within-subjects variable and group as the between-subjects variable, indicated a main effect of set size [$F(3, 54) = 103.690$, $p < .001$, $\eta_p^2 = .852$], due to longer RTs as set size increased, and no main effect of group [$F(1, 18) = 2.467$, $p = .134$, $\eta_p^2 = .121$]. As expected from the higher-throughput hypothesis, the ANOVA also revealed a significant set size x group interaction [$F(3, 54) = 3.207$, $p = .03$, $\eta_p^2 = .151$].

In Experiment 1B, all four set size conditions contributed to the estimate of one search rate parameter β per subject. We therefore carried out an independent-samples *t*-test on this parameter. The search rate was higher in the VGP group than in the NVGP group [VGP = 31.3 ± 6.7 items/s, NVGP = 22.9 ± 7.2 items/s; $t(18) = -2.680$, $p = .015$], again indicating higher throughput in VGPs as compared to NVGPs. For completeness, we also conducted a repeated measures ANOVA on the model intercepts. This analysis revealed a main effect of set size, with intercepts moving closer to chance with increasing set size [$F(3, 54) = 21.8$, $p < .001$]. No main effect of group and no interaction between group and set size (both *p*s > .7) confirmed that the intercepts were comparable across groups.

Table 1 Mean estimated search rates in milliseconds/item for the two groups in the two paradigms of Experiment 1

	Experiment 1A	Experiment 1B
VGP	35.1 ± 9.5 ms/item	33.3 ± 7.2 ms/item
NVGP	48.9 ± 20.9 ms/item	47.0 ± 12.7 ms/item

See the Results section for derivation details of search rates in each paradigm. Values after the ± signs are the standard deviations of the means

Search speed correlation Our proposal that Experiments 1A and 1B measured a common process, throughput, predicted that individual estimates of search rate from Experiment 1A should be significantly correlated with those of Experiment 1B. Statistical analysis revealed that the two measurements were indeed significantly correlated ($R = .52$, $p = .018$; Fig. 4) in the 20 subjects whose data underwent full analysis in both tasks. Although it is not diagnostic of a common cause, this outcome increases the probability of a model utilizing a common cause, throughput, over those that posit no such single cause.

Discussion

The results from Experiment 1 demonstrate that those who habitually play action videogames demonstrate faster search rates as compared to those who do not. Estimates of search rates obtained from both RT- and accuracy-based paradigms were significantly higher in the VGPs than in the NVGPs, a difference that is in line with the proposal of a faster rate of information integration in action gamers (Dye et al., 2009b; Green et al., 2010; see below for a discussion of these findings).

The measures of search speed obtained in the accuracy-based paradigm fell well within the normal range of those obtained from RT-based paradigms (25–60 ms/item; see Wolfe, 1998), and a correlational analysis demonstrated a significant positive correlation between the search speeds

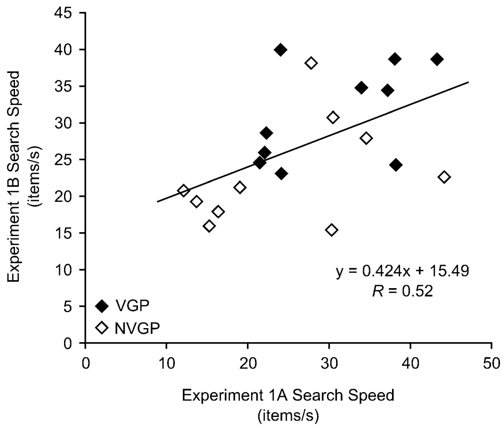

Fig. 4 Scatterplot of search speed estimates (in items/s) obtained in Experiments 1A and 1B. Each point represents 1 subject. The two estimates of search speed were significantly correlated within subjects, $R = .52$, $p = .018$, suggesting that the search tasks used in Experiments 1A and 1B measure similar underlying processes

obtained in the two parts of Experiment 1, reinforcing the view that search rates estimated from accuracy do show an enhancement similar to the one for search rates measured in the traditional RT-based analysis. The observation of faster visual search rates in VGPs as measured by an accuracy-based method rules out speed–accuracy trade-offs as an explanation for the finding in Experiment 1A. In addition, it supports the view that the VGP advantage truly stems from a difference in the rate of information integration or throughput, and cannot be solely accounted for by faster motor execution or more efficient postdecisional processes in that population. Indeed, the latter hypothesis predicts group differences in experiments measuring RTs, but no such differences in accuracy-based paradigms. The finding that VGPs show more efficient attentional processing in an accuracy-based paradigm is not an isolated finding. Indeed, action-game-related improvements to visual attention have been documented using many such tasks, such as the useful field of view, multiple-object tracking, and attentional blink tasks (see Hubert-Wallander et al., 2011, for a review). Further evidence comes from modeling approaches that have shown that changes in postdecisional processes cannot uniquely explain any significant amount of variance in the VGP/NVGP performance on several perceptual and attentional tasks (Green et al., 2010). Additionally, a recent meta-analysis of VGP/NVGP performance on RT tasks by Dye et al. (2009b) showed a multiplicative change in RTs in VGPs across many tasks, rather than the additive one that would be predicted by faster motor execution alone. Together, this evidence strongly suggests that the action-game-related improvements to visual attention seen here and elsewhere cannot be explained by action gamers simply being better at pressing keys in response to visual stimulation.

It should be noted, of course, that the present study cannot conclusively establish the causal role of action videogame play in the benefits in search rate noted here, due to the lack of a training study. For example, it is possible that the members of the VGP group possessed innately greater visual search skills, which is what drew them to action videogame play, rather than the other way around. However, much previous work on this topic has implicated the causal role of videogame play on attentional throughput via controlled training studies in which groups of nongamers were pretested, randomized into action game and control game groups, given experience playing the games, and then posttested (Cohen, Green & Bavelier, 2007; Dye et al., 2009b; Feng et al., 2007; Green & Bavelier, 2003, 2006a, 2006b, 2007; Green et al., 2010; Spence et al., 2009). The aim of this work was not to establish that greater throughput can be trained through action game play, as this has been established before, but rather to clarify the status of search rate in the context of a hard visual search task, especially given the previous null report by Castel et al. (2005). Experiment 1 revisited this issue and has allowed us to conclude that the rate of search in hard visual searches is not an exception to the generalized pattern of enhanced throughput noted throughout the literature, but instead matches it (see Fig. 5, which plots the data from the present experiment alongside those from a recent meta-analysis of the VGP literature from Dye et al., 2009b).

Experiment 2: Exogenously driven attention

We have just reviewed a body of evidence pointing to faster throughput in VGPs than in NVGPs in a variety of attentional tasks. It remains unclear, however, whether all varieties of attention may lead to enhanced throughput in VGPs. Here, we turn to one way of enhancing throughput—the use of exogenous cues. Indeed, since the seminal cuing studies of attention by Posner and collaborators (Posner, 1980; Posner & Cohen, 1984; Yantis & Jonides, 1984, 1990), faster processing speed has been identified as one of the mechanisms by which exogenous cuing affects performance (Carrasco et al., 2004, 2006; Carrasco & McElree, 2001; Hikosaka et al., 1993; Shore et al., 2001; Stelmach & Herdman, 1991). In Experiment 2, we asked whether exogenous cuing may disproportionally enhance throughput in VGPs as compared to NVGPs, as might be suggested by their greater throughput noted in other tasks.

There are mixed reports on this issue in the literature. Of the three studies comparing exogenous cuing in VGPs and NVGPs, one reported enhancements in VGPs using an unconventional way to probe exogenous cuing (West et al., 2008), while the remaining two noted no changes, using the

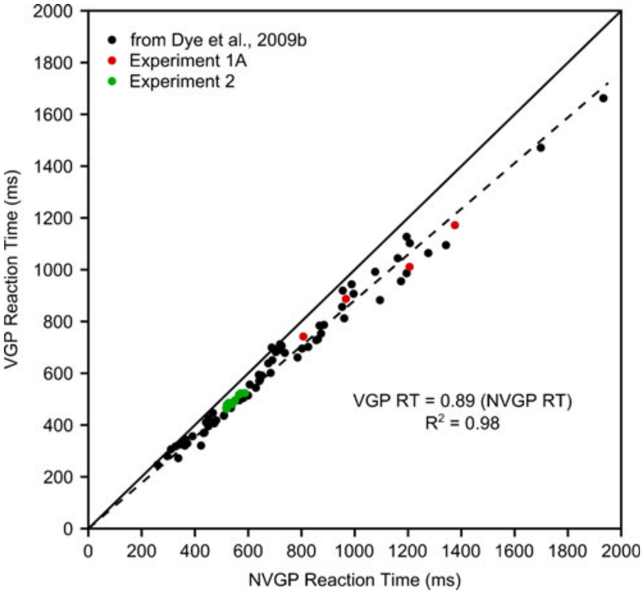

Fig. 5 Brinley plot showing VGP reaction times (RTs, on the *y*-axis) and NVGP RTs (on the *x*-axis) on 11 different visual tasks. The black dots and the dashed fit line represent data from 9 distinct tasks, as reviewed in a recent meta-analysis (Dye et al., 2009b). The colored dots represent data from the present manuscript and are overlaid on the data and fit line from Dye et al. for comparison. The present data appear to fit the established trend well, consistent with the hypothesis that action videogame play increases the throughput of visual processing

more traditional Posner cuing paradigm (Castel et al., 2005; Dye, Green & Bavelier, 2009a). Unfortunately, the latter two studies did not fully probe the time course of exogenous cuing in VGPs and NVGPs. Thus, it remains unclear whether reflexive attentional processes may modify throughput differentially in action gamers and nongamers.

To assess the impact of action videogame use on exogenous cuing, we used a modified Posner cuing task in Experiment 2 (Posner, 1980; Posner & Cohen, 1984). In this paradigm, RTs for targets are lowered if the target's location is cued shortly before its appearance (a valid cue), and raised if some other location is cued before its appearance (an invalid cue). The magnitude of the RT difference between validly and invalidly cued targets is thought to correlate with the amount of attentional resources drawn to that location by the cue (Jonides & Mack, 1984; Luck, Hillyard, Mouloua & Hawkins, 1996; Posner, 1980; Posner, Nissen & Ogden, 1978; Yantis & Jonides, 1984). Thus, if action videogame play leads to a greater throughput following exogenous cues, we might expect to see a larger RT difference between validly and invalidly cued targets in VGPs as compared to NVGPs. By systematically probing this effect at different cue–target lags, we can also ask whether exogenous cues might summon attention and thus affect throughput more quickly in VGPs, which would manifest in that group showing an earlier benefit for validly cued targets, but not necessarily a larger one. However, if action videogame play does not alter the mechanisms of exogenous cuing, we should expect to see similar patterns of RTs in VGPs and NVGPs across valid and invalid cues at all time points.

Method

Subjects Groups of 19 VGPs and 15 NVGPs were obtained from the University of Rochester community according to the same recruitment process described for Experiment 1 above. Because Experiment 2 was conducted more recently than Experiment 1, subjects completed an updated version of the videogame questionnaire used previously. In light of evidence that action-game-related effects can persist 2 years or more after cessation of play (Li et al., 2009), this questionnaire was designed to be more sensitive to past videogame play. The subjects reported their play in various game genres both during the past year and previous to the past year by selecting from six possible responses for each (never played, as well as 0–1, 1–3, 3–5, 5–10, and greater than 10 h played per week). The subjects were instructed to select their average hours/week when reporting play for the past year and to select their average hours/week during periods when they played regularly when reporting play previous to the past year, since averaging over such a long time period would not likely be informative. The criteria for inclusion in the NVGP group were a report of 0 or 0–1 h/week of action game play during the past year along with 0, 0–1, or 1–3 h/week previous to the past year. Subjects who selected 5–10 or >10 h/week of action game play for the past year, or subjects who selected 3–5 h/week for the past year along with 5–10 or >10 h/week previous to the past year were included in the VGP group. A total of 11 subjects who did not fit either the VGP or the NVGP criteria participated in the experiment, but their data are not presented here. Since subjects selected from unequally sized ranges to describe their game play, the average amount of action game play in each group was computed via a weighted average, using the midpoints of the ranges as weights (10 was used for 10 + h/week). As expected, the VGP group played more action videogames in the past year than did the NVGP group [VGP = 5.55 ± 2.20 h/week, NVGP = 0.11 ± 0.21 h/week; $t(31) = 9.174$, $p < .001$]. The mean ages were 19.5 years for the VGP group and 21.2 years for the NVGP group. All subjects were male and had normal or corrected-to-normal vision. Two of the subjects in this pool (1 VGP and 1 NVGP) had participated in Experiment 1 previously.

Apparatus Stimuli were presented on a 22-in. Mitsubishi DiamondPro 2070SB monitor running at a resolution of 1,400 x 1,050 and a frame rate of 100 Hz. The experiment was programmed using functions included in the PsychToolbox module (Brainard, 1997; Pelli, 1997) for MATLAB, running under Apple's OS X on a Power Mac G4. Each subject viewed the display from 70 cm away in a room where the only light source was the monitor itself. In this configuration, the screen subtended approximately 32.3º of visual angle horizontally and 24.6º vertically. A chinrest was used to stabilize head position throughout the experiment, and subjects made their responses on a standard English keyboard.

Procedure The method described here is based on the classical Posner cuing paradigm (Posner, 1980; Posner & Cohen, 1984), excepting that only exogenous cues were used and the number of possible target locations was four rather than the typical two. At the start of each trial, subjects were presented with the configuration seen in Fig. 6: a central fixation cross and four square target areas against a dark gray background. The width and height of the target areas were both 2.3º, and each was positioned 6.9º from the center of the fixation cross, which was 0.25º in diameter. Each target area was initially empty. Each trial was initiated by the subject via keypress, which triggered a random delay period between 400 and 500 ms. After the delay period, one of the four target areas was cued by a brief (40-ms) brightening and widening of that location's square border. Following the cue, the target appeared in one of the target areas after a designated stimulus onset asynchrony (SOA). The SOAs tested here were 0, 40, 80, 160, 240, 440, 640, and 840 ms, where a 0-ms SOA means that the cue and the target appeared at the same time.

On each trial, one of two possible targets was presented: Either an upright "T" shape or an inverted "T" shape appeared in one of the four square target areas (see Fig. 6). The subjects' task on each trial was to indicate via keypress which of the two possible targets they had seen (upright or inverted). In the valid cue condition, the target appeared in the same position as the cue. In the invalid cue condition, the target appeared in one of the three uncued positions. Importantly, the cue used here was valid on exactly 25% of trials, meaning that the cue was completely nonpredictive of the actual target location. The use of a nonpredictive cue ensured that subjects could not rely on top-down strategies to better guide their attentional allocation. Once it had appeared, the target remained on the screen for 150 ms, after which it was extinguished. Both targets appeared equally frequently, and only one target appeared during each trial. A total of 300 ms after the subject had responded, the fixation cross was enlarged and brightened for 150 ms in order to return attention to the center of the screen before the next trial.

Each subject completed seven blocks of 256 trials, evenly distributed among the four condition dimensions (eight SOAs, four cue locations, two validity conditions, and two target identities), for a total of 1,792 trials. Subjects were instructed to respond to each target as quickly as possible while maintaining an accuracy level of 90% or above. In order to facilitate responding, accuracy and RT feedback for the current block appeared on screen automatically every 60 trials. Subjects were also instructed to maintain eye fixation on the central cross throughout each trial, but eye position was not explicitly tracked. Auditory feedback was used to indicate an incorrect response; no sound was given for correct responses. Because each trial was initiated by keypress, subjects could take breaks between trials as they desired. After receiving instructions from the experimenter, the subjects were given 20 practice trials to ensure comprehension of the task before beginning

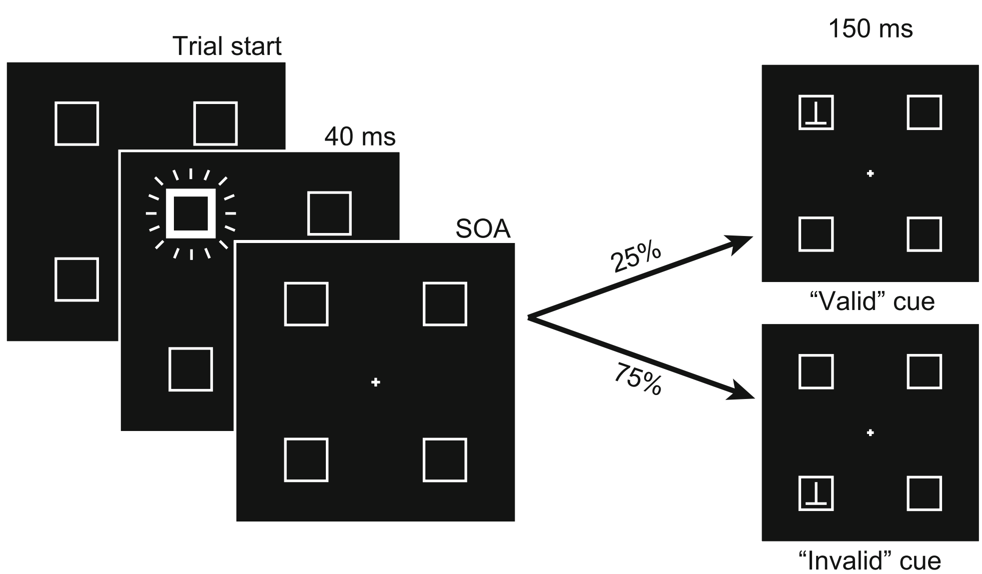

Fig. 6 The modified Posner cuing task used in Experiment 2. Shortly after the start of each trial, a salient event cued one of the four target areas. After a variable SOA, a target appeared briefly in either the cued location (a validly cued target) or an uncued location (an invalidly cued target). The cue was not predictive of the target's eventual location. The subject's task was to discriminate between two possible targets via keypress as quickly and accurately as possible

the main portion of the experiment. The subjects took approximately 70 min to complete the task.

Results

First, a repeated measures ANOVA revealed no significant main effect of group on task accuracy [VGP = 91.7 ± 4.7%, NVGP = 93.8 ± 4.1%; $F(1, 32) = 1.366$, $p > .20$, $\eta_p^2 = .041$]. Importantly, group also did not interact with any other variable or combination of variables (all *ps* > .15; also see the Appendix). These results suggest that the patterns of accuracies across the range of cue–target SOAs and the valid and invalid cues were similar between the two groups and that subsequent RT analyses would not miss a "true" difference between the VGPs and NVGPs in exogenous orienting due to speed–accuracy trade-offs.

Summarized mean RT results from both groups are shown in Fig. 7; full RT and accuracy results can be seen in the Appendix. First, RTs from incorrectly answered trials were discarded. Then, using the same method described in Experiment 1A above, RTs were filtered in order to reduce the impact of outliers, resulting in a further 1.7% of total NVGP trials and 1.6% of total VGP trials being removed from subsequent analysis. Mean RTs calculated on the remaining data were entered into a repeated measures ANOVA with SOA and cue validity as the within-subjects variables and group as the between-subjects variable. As is traditional in an exogenous cuing paradigm, a large main effect of cue validity was observed [$F(1, 32) = 21.457$, $p < .001$, $\eta_p^2 = .401$], with subjects responding more quickly for validly cued targets than for invalidly cued targets. A main effect of SOA was also found [$F(7, 224) = 42.026$, $p < .001$, $\eta_p^2 = .568$], driven by the higher RTs at very early SOAs and lower RTs at later SOAs. Taken together, these two effects confirm that our exogenous cue captured attention successfully and that the paradigm behaved as expected. It should be noted that the lack of an inhibition-of-return effect was not unexpected, as inhibition-of-return is typically less robust when using a discrimination task, as we did, rather than a detection task (Chica, Lupiáñez & Bartolomeo, 2006; Lupiáñez, Milliken, Solano, Weaver & Tipper, 2001).

As has been seen throughout the VGP vs. NVGP literature on visual tasks, the VGP group demonstrated overall lower RTs (VGP = 492 ± 59 ms, NVGP = 544 ± 71 ms) [$F(1, 32) = 5.203$, $p = .029$, $\eta_p^2 = .140$]. While this is perhaps indicative of greater attentional resources or overall faster processing speed in the VGP group, this by itself does not indicate a difference in exogenous orienting between the two groups. If exogenous cues were able to enhance throughput by a greater amount (or more quickly) in VGPs than in NVGPs, we would expect to see one or more significant interactions between group and the within-subjects variables. However, no other between-group differences were in evidence, as group did not interact significantly with cue validity [$F(1, 32) = 0.551$, $p = .46$, $\eta_p^2 = .017$] or SOA [$F(7, 224) = 0.639$, $p = .72$, $\eta_p^2 = .020$]. Finally, and most crucially, no significant three-way interaction was present in the data [$F(7, 224) = 1.601$, $p = .14$, $\eta_p^2 = .048$]. Evaluated together, these results indicate that the two groups responded similarly to the exogenous cue, with no apparent advantage for the VGPs.

It is possible that our method of filtering RTs eliminated valid data that would have contributed to a significant effect. To address this possibility, we performed the same omnibus ANOVA, this time relying on the use of median RTs to reduce the impact of outliers, instead of standard

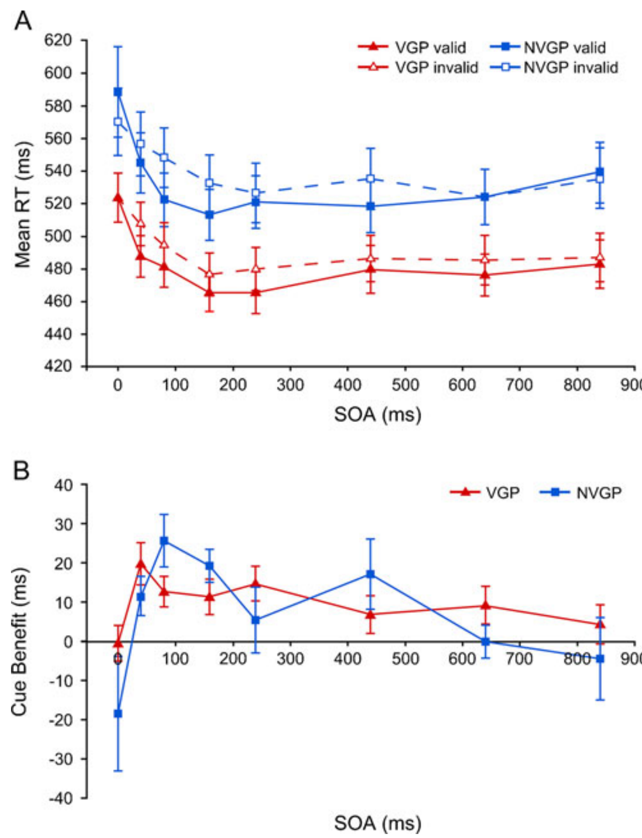

Fig. 7 Reaction time (RT) results from Experiment 2: **a** Mean RT data for each group as a function of stimulus onset asynchrony (SOA) and cue validity. As is traditional in exogenous cuing tasks, valid cues provided little effect initially, gave the greatest benefits around SOAs of 100 ms, and then had a tapering effect at the longer SOAs. Though the VGP group responded more quickly than the NVGP group across all conditions, both groups showed similar response patterns to the two cue types at short SOAs (<200 ms), suggesting that the dynamics of exogenous orienting were similar in the two groups. Error bars represent the standard errors of the means. **b** Mean cue benefit (invalid cue RT – valid cue RT) as a function of group and SOA. No statistically reliable differences were found in cue benefits across groups, even when focusing the analyses on early SOAs

deviation filtering. This analysis produced results that were qualitatively similar to the initial findings and did not change the significance of any effect.

The fact that a main effect of group on RTs was found in the present experiment (as well as in many previous published VGP vs. NVGP studies) indicates that action gamers and nongamers likely possess significant baseline differences in RTs. Since our analysis hinges on interpreting RT costs and benefits in these two groups, it was necessary to show that these baseline differences were not masking differential effects in the two populations (see Dye et al., 2009a, for an in-depth discussion of this issue). To address this, we normalized the mean RT in each condition in each subject by the overall mean RT for that subject, and performed a repeated measures ANOVA on the resulting proportional RTs. The results indicated that differences in the baseline RTs between the two groups did not mask any group differences in exogenous orienting, as the only effect that changed significance was the main effect of group, which, as expected, was no longer present [$F(1, 32) = 0.151$, $p = .70$, $\eta_p^2 = .005$].

Finally, it is also possible that the lack of a cuing effect at later SOAs (see Fig. 7) inhibited our ability to detect cuing differences between the two groups at the earlier SOAs, which are more relevant for measuring initial exogenous orienting. To test this, we redid the mean RT analysis, the median RT analysis, and the proportional RT analysis using data from only the first five SOAs (0, 40, 80, 160, and 240 ms). Again, none of these analyses changed the statistical significance of any effects, indicating that the particulars of our analysis did not hinder our ability to detect true exogenous orienting differences between the two groups.

Discussion

The RT and accuracy data from the cuing task used here demonstrated no apparent difference between the two groups in exogenous orienting. While the VGP group did respond more quickly overall, they showed within-subjects response patterns similar to those for the NVGP group, with validly cued targets leading to faster RTs than invalidly cued targets after about 100 ms, followed by a tapering off of the cue effect at longer SOAs. Importantly, both groups manifested similar RT costs and benefits in response to cue validity. Not only were the magnitudes of the cue validity effect similar in both groups, but the time course of that effect was also similar between the groups. Several additional analyses showed that the particulars of our initial omnibus ANOVA did not cause it to miss true effects. Additionally, the typical effects of cue validity and SOA were observed in the data, establishing that the paradigm did engage exogenous attention in each group. Overall, these results suggest that the dynamics of exogenous orienting are similar between those who play action videogames and those who do not, with VGPs showing the same throughput advantage after an exogenous cue as NVGPs.

General discussion

Our results indicate that visual search rate is enhanced in VGPs, whereas exogenous cuing equally enhances throughput in VGPs and NVGPs. In Experiment 1 we measured search speed using two different methods—one was an RT-based measure (Exp. 1A), while the other was an accuracy-based measure (Exp. 1B). Between-group comparisons of search rate from the two paradigms showed enhanced search rates in the VGP group, and separate follow-up analyses of data from the two methods showed that this group difference was present in each. In Experiment 2, we evaluated the changes in throughput triggered by exogenous cues. We used a Posner cuing task to show that although the gamers demonstrated the same overall change in throughput as seen throughout the VGP literature (see Fig. 5), the visual systems of action gamers and nongamers responded similarly to a sudden, salient visual cue that captured attention, suggesting that not all aspects of throughput are equally modified in action videogame players.

Although the visual search outcome reported here differs from that of Castel et al. (2005), there are more similarities in the results of these two studies than differences. Indeed, Castel et al. did report a significant interaction between group and set size in their RT-based visual search task, just as was observed in Experiment 1A here. Additionally, their results are among those included in the meta-analysis conducted by Dye et al. (2009b; see Fig. 5) and fit well with results from the other RT studies reviewed there. Castel et al., however, argued that the similar RTs between the VGP and NVGP groups at the smallest set size (four items) reflected a floor effect and thus should be removed from their analysis. Once those RTs were removed from the analysis, the effect of interest became nonsignificant, leading the authors to conclude that action videogame play did not affect visual search speed. However, an alternate explanation for the similar RTs between the two groups at the smallest set size is that the VGP group actually did possess higher search speeds that were not allowed to manifest reliably over the relatively small number of items in the array. In other words, if the VGP group did have faster search throughput, we might *expect* to see only very small differences in RTs at small set sizes, especially set sizes that are known to be within the subitizing range of both VGPs and NVGPs (Green & Bavelier, 2006b). The fact that the RTs excluded by Castel et al. seem quite slow (~790 ms for VGPs, ~875 ms for NVGPs) to represent genuine floor effects would seem to support this hypothesis. With this issue in mind, set sizes in Experiment 1 were chosen so as to avoid versions of the task in which the search task may have been either too trivial or too challenging, giving the present study a better chance to uncover group differences if present.

Results from Experiment 1B's accuracy-based method support those from Experiment 1A and provide further evidence that those who habitually play fast-paced action videogames do in fact benefit from enhanced visual search rates. Estimates of search speeds obtained from accuracy performance fell within the range of previously observed hard visual search speeds and followed the same VGP-versus-NVGP pattern as in Experiment 1A. Furthermore, search speed measures from Experiment 1B's accuracy-based method significantly correlated with search speed measures from the classical and well-studied RT-based search task, providing further validation for this new way of measuring search rates. More importantly, the finding of higher search rates in VGPs as derived from an accuracy-based measure establishes that the improved performance in VGPs cannot be accounted for entirely by better stimulus–response mappings but truly involves differences in the rate of integration of information, as proposed by Green et al. (2010).

We acknowledge that the present methods cannot tell us exactly how visual search rate might be enhanced in the VGP group. Specifically, our data cannot differentiate between action-game-related enhancements to item processing, faster reallocation of attention to new items, better inhibition of previously searched items, or a variety of other possible mechanisms. Similarly, if search represents a more parallel process, our data cannot distinguish between a larger parallel capacity and faster item processing. Thus, our estimates of search speed should not be taken as the literal amount of time it takes to search each item, but more as a measure of *effective* search speed or, in other words, how evidence for either target is accrued over time as the target and distractors vary in types and locations from trial to trial. To some extent, discovery of exactly how action videogames might improve visual search will be contingent on further progress in investigation of how the "normal" brain handles such a task, which is still a hotly debated topic.

In our Experiment 2, we showed that uninformative exogenous cues speed visual processing similarly in action gamers and nongamers. A task similar to ours in Castel et al. (2005) found comparable results in a two-location detection variant of the Posner cuing task and reached the conclusion that action game experience does not affect inhibition of return, part of the attentional response to exogenous cues. Another group of researchers measured orienting using the Attentional Network Test (Dye et al., 2009a) and also found no difference between VGPs and NVGPs. However, because the specific cue–target SOAs used in these previous studies were relatively long for measuring orienting (only two SOAs under 400 ms in Castel et al. 2005, one 500-ms SOA in Dye et al. 2009a), the present study is able to show with considerably greater temporal resolution that the neural mechanisms governing early exogenous orienting may not be affected by action videogame play. While it is true that the temporal order judgment task used in West et al. (2008) could represent measurement of early exogenous orienting (and thus provide counterevidence against our proposal, since VGPs were found to differ from NVGPs), this study did not directly assess exogenous attention, but rather its effect on the perceived temporal order of items. Exogenously cued items were found to maintain their prior-entry status for a longer duration in VGPs than in NVGPs. Thus, uncued items had to be displaced further in time in VGPs to appear subjectively simultaneous. Because this task relies on subjective report of temporal order judgments, its interpretation as a direct effect of exogenous cuing is less straightforward. The maintenance of a longer prior-entry status in gamers might result from a difference in how top-down attention modulates exogenously triggered events rather than a pure exogenous event (as proposed by Chisholm et al., 2010). In addition, the use of a subjective judgment complicates group comparisons, since different choice biases in each population could account for sizeable difference in performance (see Schneider & Bavelier, 2003, for a discussion of this issue). Given the mixed state of the previous literature on this topic, the present study clarifies the differences in exogenous orienting between action videogame players and nongamers and lends further credence to the proposal that action game play does not affect how or to what degree exogenous cues do speed visual processing.

The absence of a group difference in early orienting may be surprising to some, given the high frequency of exogenous events during modern action games. However, although it is true that enemies in these games often appear unexpectedly in previously empty locations, it is unclear whether faster or greater allocation of exogenous attention to these salient events would actually be adaptive for game play. For example, it may be that most of these events represent distracting information, in which case potent, indiscriminate capture of attention could be detrimental to overall performance in the game. Furthermore, it should be noted that simply because certain visual or cognitive skills might be heavily tapped or rewarded during action videogame play, this does not guarantee enhancements of those skills in avid players. A plausible mechanism for plastic change must exist in order for action-game-related benefits to manifest. Such a mechanism may not exist for exogenous orienting, often thought of as an evolutionarily older, and thus more reflexive and less plastic, behavior (however, see Kristjánsson 2009; Kristjánsson, Mackeben & Nakayama 2001, for evidence that previous task experience can alter attentional responses to briefly flashed cues).

Both the existing literature and the present work point to selective and controlled aspects of attention as the main attentional beneficiaries of action game play, with little to no change in transient, automatic aspects of attention. This proposal is attractive, as it naturally accounts for the varieties of attentional enhancements noted in VGPs as well as the enhanced attentional throughput documented in a variety of attention-demanding tasks. However, it will be for future studies to further confirm this dissociation and reveal the underlying mechanisms at play.

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Appendix: Experiment 2 Data

Table 2

		Cue–Target SOA							
		0 ms	40 ms	80 ms	160 ms	240 ms	440 ms	640 ms	840 ms
Mean RT (ms)									
VGP	Invalid	523	507	494	477	480	486	485	487
	SE	15	14	14	13	13	14	15	15
	Valid	524	488	481	466	465	480	476	483
	SE	15	13	13	12	13	15	13	15
NVGP	Invalid	570	557	548	533	526	536	524	535
	SE	20	20	18	17	18	18	17	19
	Valid	589	545	522	513	521	518	524	539
	SE	28	19	17	16	16	16	17	23
Accuracy (%)									
VGP	Invalid	91.4	90.7	90.8	90.6	91.4	91.9	92.1	91.9
	SE	1.4	1.2	1.3	1.2	1.3	1.0	1.1	1.3
	Valid	92.7	92.9	93.3	94.1	93.1	93.1	91.2	91.4
	SE	1.4	1.3	1.3	1.2	1.5	1.4	1.5	1.7
NVGP	Invalid	93.6	94.2	93.3	93.3	93.0	93.9	94.0	93.6
	SE	1.1	0.9	1.5	1.0	1.4	1.1	1.3	1.1
	Valid	94.8	93.9	95.0	94.1	94.7	93.6	95.0	91.8
	SE	1.1	1.4	1.0	1.4	1.1	1.6	1.2	1.4

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