# Abstract

Visual search is facilitated when a target item is positioned within an invariant arrangement of task-irrelevant distractor elements (relative to non-repeated arrangements), because learnt target-distractor spatial associations guide visual search. While such configural search templates stored in long-term memory (LTM) cue focal attention towards the search-for target after only a few display repetitions, adaptation of existing configural LTM requires extensive training. The current work examined the important question whether individuals claimed to have better attention performance (i.e., action video game players; AVGP) show improved acquisition vs. adaptation of configural LTM (relative to no-gamers; NAVGP) in a visual-search task with repeated and non-repeated search configurations and consisting of an initial learning phase and, following target relocation, a subsequent adaptation phase. We found that contextual facilitation of search reaction times was more pronounced for AVGP relative to NAVGP in initial learning, probably reflecting enhanced learn-to-learn capabilities in the former individuals. However, this advantage did not carry over to the adaptation phase, in which gamers and non-gamers exhibited similar performance and suggesting that attention control required for overcoming visual distraction from previously learned (but no more relevant) target positions is relatively uninfluenced by action-game experience.

**Words:** 192

**Total words:**

**Keywords:** visual search, contextual cueing, contextual adaptation, AVGP, action video gaming experience

# Introduction

## *Contextual learning and adaptation*

Our visual environment contains a high degree of regularity, as items around us are often located at constant and thus expectable locations (icons on a monitor, cooking tools in a kitchen etc.). Consequently, the human visual system learns to make use of these regularities in the form of distractor-target associative memories and to guide selective, i.e., focal, attention during visual search (Wolfe, 2021). In the laboratory, statistical learning of context-target associations is tested by asking participants to search for a certain target item (e.g., letter “T”) among task-irrelevant distractors (e.g., letters “L”). Their task is to detect the target letter as quickly as possible and to report the orientation of the T target item (rotated 90° to the left or right with equal probability; see Figure 1 for an example). Unknown to participants, 50% of search configurations are repeated across the experiment (i.e., repeated contexts), while search displays are generated anew in the other half of trials (i.e., non-repeated contexts). Note that for both – repeated and non-repeated – contexts, targets appear equally often at fixed sets of positions to rule out location probability effects (e.g., Geng & Behrmann, 2005). Thus, any reaction time (RT) advantage in the repeated condition can ultimately only be attributed to the effects of distractor-target associative memories on search behavior. The common finding is that participants respond faster in repeated relative to non-repeated displays (contextual-cueing effect) due to more efficient allocation of attention towards the target location (e.g., Chun & Jiang, 1998). – In the present study we asked whether robustly reported contextual cueing (CC) reflecting participants ability to more rapidly identify searched-for targets in the sensory array (e.g., Zinchenko, Conci, Hauser et al., 2020) is affected by action video training claimed to up-modulate attention functions (e.g., Bavelier & Green, 2019). We also ask whether gaming exerts an effect on the ability to overcome visual distraction from learned, but no more relevant, information in the visual scene.

Concerning the latter, interestingly, once a memory representation of repeated distractor-target relations has been acquired, the adaptation of a new target location within an otherwise unchanged distractor context could be rather inflexible. In more detail, it was shown that such a change can severely reduce or even completely abolish contextual cueing, and it takes an extended period of practice, of ~80 repetitions, with the changed target location within an otherwise unchanged distractor layout for a contextual-cuing effect to be newly established (Zellin et al., 2014). Thus, although initial context learning occurs rapidly, incorporating a relocated target into an existing context representation seems to require significant cognitive efforts and considerable number of repetitions (Makovski & Jiang, 2010; Manginelli & Pollmann, 2009; Zellin, Conci, von Mühlenen, & Müller, 2013).

The guidance of attention based on contextual LT memories can also explain why contextual cueing is typically resistant to updating (e.g., Geyer et al., 2021). Worth telling is that in the above-mentioned ERP study by Zinchenko, Conci, Töllner et al. (2020; see also Pollmann & Manginelli, 2009 for converging evidence albeit using oculomotor measures) it was also found that when the target in a learnt repeated array was subsequently relocated to the opposite hemifield, contextual cueing was effectively abolished – with the N1pc (indexing attentional-priority signaling) now being reversed in polarity, indicative of a persistent ‘distraction’ signal misguiding attention to the original target location. Thus, once learnt, repeated layouts trigger attentional-priority signals from memory that, after target relocation, interfere with contextual re-learning. In the visual search literature, there is now a consensus that the brain can limit distraction by salient, unexpected stimuli (e.g., Chelazzi et al., 2019). One mechanism is active distractor inhibition (e.g., Liesefeld & Müller, 2019; Sawaki & Luck, 2010; Gaspar & McDonald, 2014; see also Chisholm and Kingstone, 2015, and further reviewed below), that is, the capability to detect and actively suppress further processing of the irrelevant item.

### *Video games and attentional performance*

Prior studies suggest that people who play action video games (i.e., action video games players, AVGPs) possess greater selective-attention capabilities than non-action video games players (NAVGPs; for review, see, e.g., Green & Bavelier, 2019). Action video games are a specific genre of computer games that frequently requires active hand-eye coordination and prediction of forthcoming events, as well as often emphasizes speeded responses and shorter reaction times (RT; Green & Bavelier, 2012). Some of the sub-genres of AVGs include fighting games, shooter games, and platform games. For instance, Bejjanki et al. (2014) presented a Gabor patch with varying contrast at one of two peripheral locations of the screen which were preceded and followed by a noise patch. AVGPs did not only outperform non-gamers in discriminating the orientation of the Gabor patch at low contrast, but they also learned the perceptual templates of the task faster than NAVGPs. The authors suggested that the knowledge gained via action video game training does not only elicit direct and immediate benefits (Bejjanki et al., 2014), but also leads to quicker learning of task-relevant features that in turn enable a better general understanding of the task at hand. Applied to the main question of the present investigation, i.e., of statistical learning of environmental structure in search tasks, it is possible that AVGPs relative to NAVGPs would be stronger susceptible to repeated sensory information and, therefore, would be better able to allocate spatial attention towards the T-type target presented in a repeated array of L-type non-target, i.e., distractor, elements.

The existing studies also lend support for the idea that experience with action video games enhances other forms of selective attention, such as ignoring task-irrelevant, distracting information, besides an improved ability to focus on task-relevant information. Chisholm and

Kingstone (2015) found that AVGPs compared to NAVGPs were better able to ignore the attention-grabbing singleton distractor and instead deployed a higher proportion of initial saccades towards the target item in distractor-present trials. Such advantages have also been confirmed in electroencephalographic (EEG) studies, where AVGPs relative to NAVGPs showed reduced amplitudes of steady-state visual evoked potentials (SSVEPs) to unattended peripheral distractors (i.e., neural correlates of the advanced suppression of irrelevant items; Mishra et al., 2011). Finally, in an fMRI study, Bavelier and colleagues (2012) showed that AVGP relative to NAVGP elicited reduced activation in the visual motion-sensitive area (MT/MST) in response to peripheral distractors, which was indicative of improved filtering of irrelevant information in the AVGP group. Most importantly, the authors reported that NAVGP showed enhanced activation patterns in the frontoparietal attention network (Corbetta & Shulman, 2002; Stokes et al., 2012) when the task was more challenging, while the AVGPs group did not. This implies that action video game experience can benefit the performance in discrimination tasks that can be of high perceptual load and thus demanding on attentional resources (Lavie, 1995; Pessoa et al., 2005). One straightforward prediction that follows from this is that gamers are quite well able to engage selective-attention processes when search is difficult; that is, performance differences between AVGPs and NAVGPs may be more marked under these [difficult] task conditions (see also Föcker et al., 2018).

In summary, prior results suggest that AVGPs outperform NAVGPs in relatively difficult sensory tasks, due to better focusing of spatial attention to task-relevant information, while also showing improved attentional capabilities for suppressing irrelevant information. However, it is difficult to compare the results across the extant studies which used different task designs and display manipulations. Therefore, in the present investigation we used a factorial design including manipulations of spatial attention based on learned environmental structure in an initial training phase and the requirement for attentional suppression of initially learnt, but (following a change) no longer relevant target positions in a subsequent adaptation phase. This was done to test the impact of action video game experience on the acquisition and relearning of context memories, as well as to validate previous findings by means of a new statistical learning paradigm. Specifically, we ask whether individuals with higher gaming experience show improved contextual guidance of attention in the initial context learning phase and/or better ability to overcome interference from exiting distractor-target memories in the context adaptation phase.

Two recent studies of Schmidt and colleagues (2019, 2020) examined whether gaming experience leads to more efficient contextual learning in search tasks. Consistent with the findings reviewed above, these studies found that visual search was generally faster in gamers, but their overall RT contextual-cueing effect was comparable to that of non-gamers. However, there was no way to determine whether Schmidt et al.'s visual-search task was as difficult as Bejjanki et al's (2014) visual-discrimination task. Assuming that there is a trade-off between search speed (reflecting the difficulty of the task) and contextual cueing, such that there is a greater likelihood that context-based guidance of attention comes to the fore particularly with longer searches (e.g., Peterson & Kramer, 2001; Wolfe & Horowitz, 2017; Geyer et al., 2010; Schankin & Schubö, 2009, 2010), then Schmidt et al.'s null findings be taken to suggest that their search task was too easy to let gaming-related improvements of contextual-cueing become measurable (see also Green & Bavelier, 2003; Safei et al., 2022 for similar conclusions albeit using a different paradigms). Therefore, in the current study we used a relatively difficult T-type vs. L-type letter search task (by varying the offset in the line junction of the T and L stimuli; cf. Chun & Phelps, 1999) in a full factorial contextual-cueing training-phase/ test-phase design (and changes of the target position at the transition of the two phases; cf. Zinchenko, Conci, Töllner et al., 2020). Participants in one group had heavy gaming experience (5 to 10 hours of video game playing per week in the last year), while the other group consisted of non-video game players. We hypothesized that with difficult search, gaming experience would lead to enhanced contextual cueing during the initial learning phase, reflecting the more efficient learning of task parameters (including the constant distractor array) in AVGP observers (Bejjanki et al., 2014). During the relocation phase, the ability for contextual adaptation was hypothesized to be improved as well, but this time reflecting AVGPs enhanced attentional ability to overcome visual distraction by the originally learnt position in order to adapt their context memory to the new target location (Zinchenko, Conci, Töllner et al., 2020).

To summarize, in the present study, we aim to break down the attentional processes that are involved in initial context learning and later contextual adaptation, that is, after having established distractor-target memories, attention needs to be disengaged from the previously learned target positions. Furthermore, we aim to investigate these contextual learning processes in individuals who have shown enhanced attentional control functions, such as action video game players. We hypothesized that action video game players might outperform non-video game players in the following scenarios: 1) in the learning of repeated distractor-target arrays, reflected by shorter RTs and more efficient allocation of focal attention towards the target item, and 2) the adaptation of contextual LT memories, expressed by a relatively quick recovery of the contextual-cueing effect after target position changes and marking the ability to overcome attentional misguidance from previously learned target positions in repeated sensory arrays.

## Method

### *Participants*

Forty participants took part in this study (20 females; mean age: 22.5 years, *SD* = 4.07, range: 19-35); all right-handed; all with normal or corrected-to-normal visual acuity, all students). The sample size was determined based on the effect-size measures from previous studies that examined CC in gamers (e.g., Schmidt et al., 2020). Accordingly, our sample size is appropriate to detect an f(U) effect size of 1.0 with 85% power (partial eta2 = 0.4, groups = 2, number of measurements = 4), given an alpha level of .05 and a nonsphericity correction of 1. Participants were classified as action video game players and non-action video game players based on the numbers of hours they played first and third person shooter games during the past year (VGM questionnaire, see Bediou et al., 2018). Participants who indicated to play 5-10 hours or more than 10 hours of action video game play were classified as action gamers, and participants who indicated to play never or maximum 0-1 hour per week of action video games were classified as non-action video game players.

A total of 20 participants (females = 10; mean age = 21.85, age range = 19 – 31 years, *SD* = 3.00) were assigned to the action video game group and 20 other participants (females = 10; mean age = 23.15, age range = 19 – 35, *SD* = 4.83) were identified as non-action video game players. The groups did not differ in age or gender distribution. All participants were students from the LMU Munich, Germany and the University of Lincoln, UK. The Ethics Committees of the Department of Psychology, the University of Lincoln approved the study. All experimental procedures adhered to the Declaration of Helsinki (2013). All participants provided written informed consent and received 20 € or SONA points (i.e., credit points required for graduation) for taking part in the study.

### *Apparatus and stimuli*

The experimental routine was programmed in Matlab with Psychtoolbox extensions (Brainard, 1997; Pelli, 1997) and was run on a PC under the Windows 7 operating system. Participants were seated in a dimly lit room in front of a 23-inch LCD monitor (ASUS, Taiwan; refresh rate 60 Hz; display resolution: 1920 × 1080 pixels) at a viewing distance of approximately 80 cm (unrestrained). The search displays consisted of 12 dark-gray items (luminance: 1.0 cd/m2; 1 T-shaped target and 11 L-shaped distractors) presented against a black background (0.11 cd/m2). All stimuli extended 0.35° of visual angle in width and height. The items were arranged on four (invisible) concentric circles around the display center (with a radius of 1.74°, 3.48°, and 5.22° for Circles 1 through 3, respectively). The target was always positioned on the third circle (see Figure 1).

There were overall 24 possible target locations, eight of which were used for repeated displays with constant distractor layouts in the learning phase. Another eight target locations were used for non-repeated displays with random distractor arrangements. Another set of eight target locations was used for repeated displays in the relocation phase. In the latter, the target item was always swapped with one of the distractors in the opposite hemifield (see Figure 1). For each set of target locations per condition (repeated displays in learning; non-repeated displays in learning; repeated displays in relocation), there were two targets presented in each of the four display quadrants. Among the eight targets, two appeared on circle 1 and three other targets were presented on circles 2 and 3 each. Importantly, participants were not informed about the fact that some of the search arrays were presented repeatedly, and they were not told about the target location swap in the middle of the experiment. The “T” target was rotated randomly by 90° to either the left or the right. The 11 remaining items were L-shaped distractors rotated randomly at orthogonal orientations (0°, 90°, 180°, or 270°). Similar to previous studies (e.g., Jiang and Chun, 2001; Zang et al., 2015), the ‘L’ distractors had a small offset (0.18°) at the line junctions to make them more similar to the target ‘T’ and thus increasing search task difficulty. Figure 1 presents example display layouts. Note that repeated search arrays were generated randomly for each participant at the beginning of the search task. The same constraints relating to the positioning of the target (in rings 1-3 and two in each quadrant) were also applied to non-repeated displays, thus mitigating effects of target probability cueing (e.g., Geng & Behrmann, 2005), except that these display arrangements were, by definition, never repeated. It is thus unlikely that specific, low-level display features (uniquely) relating to the spatial composition of repeated displays had a systematic influence on contextual learning and adaptation in our experimental conditions.

### *Trial sequence*

A trial started with the presentation of a fixation cross (size: 0.10° luminance: 1.0 cd/m2) for 500 ms, followed by a blank interval of 200 ms before the onset of the search display. Observers were instructed to respond as quickly and accurately as possible to the orientation of the “T” (left vs. right). Each search display stayed on the screen until the observer’s manual choice response was registered. Observers responded to the left/right orientation of the “T” target by pressing the left/right arrow button on a computer keyboard with their corresponding index finger. Following an erroneous response, a word “Wrong” appeared on the screen for 1,000 ms. Each trial was followed by a blank intertrial interval of 1,000 ms.

### *Design and procedure*

The repeated condition was composed of eight randomly arranged target–distractor configurations, generated at the beginning of the experiment. These arrangements were repeatedly presented on randomly selected trials throughout the search task, with the restriction that each repeated display was shown only once per block. Displays in the non-repeated condition were generated at the beginning of a given trial. Repeated arrangements were presented in half of the trials, and non-repeated arrangements in the other half. Trial order was randomized in each block. To equate target location repetition effects between the two types of displays, the target appeared equally often at each of 16 possible locations throughout the experiment: eight locations were used for repeated displays and the remaining eight for non-repeated displays. The orientation of the target in each repeated display was selected at random on each trial, whereas the non-targets were held constant across repetitions (cf. Chun & Jiang, 1998). Figure 1 depicts example search displays for the repeated and non-repeated conditions. Each (learning, relocation) phase was divided into 25 blocks each x 16 trials in each block, yielding a total of 400 trials per phase and 800 trials in total. Individual target positions were swapped with that of a distractor in the opposite hemifield at the transition from the learning to the relocation phase in repeated displays. Participants had the opportunity to take a short break between blocks or continue directly with the next block. To acquire reliable estimates of contextual cueing, we collapsed five consecutive blocks into one epoch for analysis.

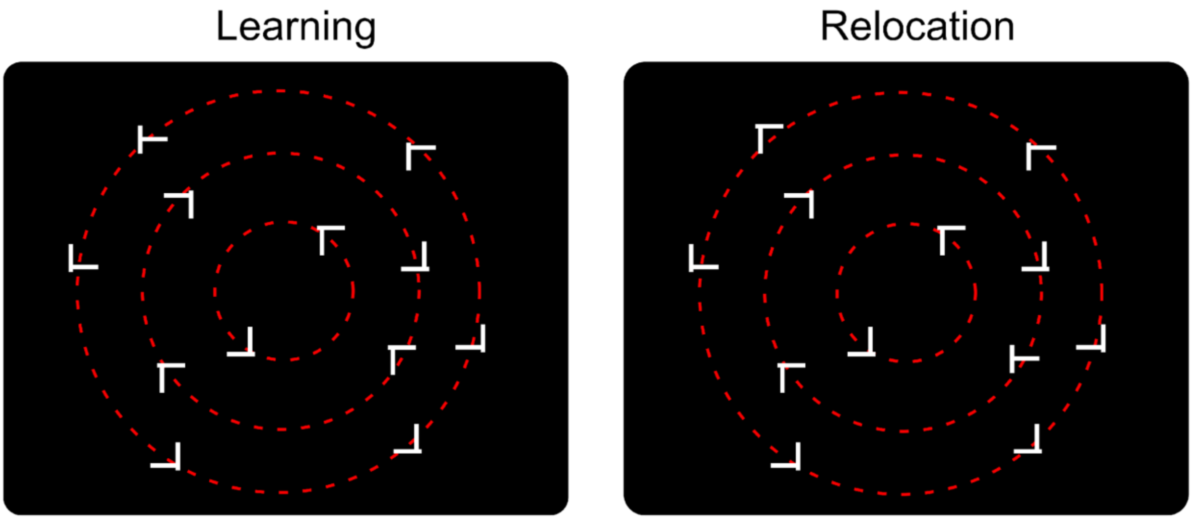

**Figure 1.** Example search display presenting a repeated target-distractor configuration. In the display, the target position swaps with a distractor from the opposite hemifield across the learning and relocation phases, while all other items remain unchanged—so as to examine how the target location change affects the RT advantage for repeated versus non-repeated displays (the contextual-cueing effect) when visual search is performed by groups with different gaming experience. Note that the red, dashed circles, depicting the three concentric rings on which the search items were arranged, were not shown in the actual search displays.

### *Recognition test*

At the end of the experiment, observers performed a yes/no recognition test, intended to examine whether they had any explicit memory of the repeated configurations. To this end, eight repeated displays from the search task and eight newly composed displays were shown, and observers were asked to indicate whether they had seen a given display previously. The eight repeated and eight non-repeated displays were presented in random order. Displays were presented with a target at the initial (learning-phase) location because explicit recognition of a given repeated context (if demonstrable at all) would be expected to manifest more clearly for the initial, more reliably learnt target-distractor relations. The recognition responses were non-speeded, and no error feedback was provided.

## Results

### *Behavioral data*

Individual mean error rates and RTs were calculated for each combination of factors (Gaming group x Epoch × Context × Phase). For the RT analysis, trials with errors were excluded from the analysis. Additionally, RTs of more than 2.5 standard deviations from the mean (in both directions) were excluded from analysis, leading to the removal of less than 2% of all trials. Mean values for each group were then submitted to a mixed design analysis of variance (ANOVA) with the factors phase (learning, relocation), context (repeated, non-repeated), and epoch (1–5; one experimental epoch combining data across five consecutive trial blocks), while the factor Group (AVGP, NAVGP) was treated as a between-group factor. Greenhouse-Geisser-corrected values are reported when Mauchley's test of sphericity was significant ($p < .05$). When interactions were significant, least-significant-difference post hoc tests were conducted for further comparisons. All analyses were performed in R (version 4.0.3; R Core Team, 2020).

Analysis of error rates revealed a significant main effect of phase: mean error rates were higher in the relocation phase (*M* = 9.1%; *SD* = 11.39) relative to the initial learning phase (*M* = 7.1%; *SE* = 9.93), $F(1, 38) = 8.31$, $p = .006$, $\eta_p^2 = 0.18$. No other main effect and/or interactions were significant (all *p*'s > 0.1; see Figure 2).

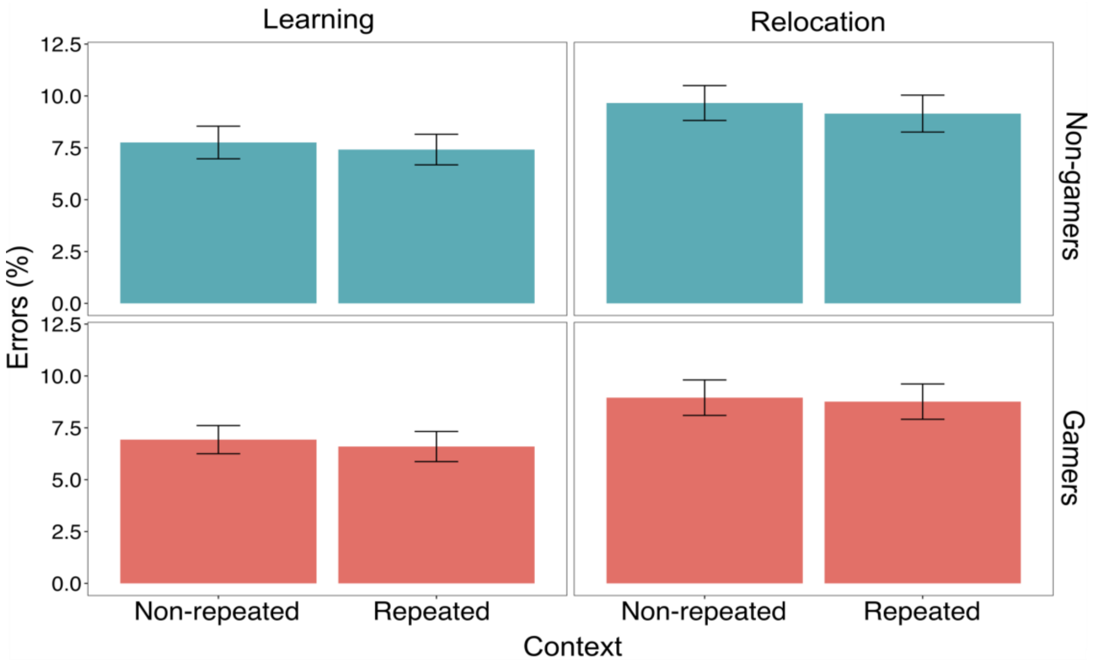

**Figure 2.** Mean error rates (in %, with associated 95% confidence intervals) for repeated and non-repeated contexts as a function of groups (Gamers, Non-gamers) in the learning and relocation phases.

Figure 3 depicts the mean RTs for repeated and non-repeated displays for each epoch in the learning and relocation phases. We found a main effect of Context: repeated displays ($M = 2474$ ms; $SD = 1231$) results in overall speeded responses relative to non-repeated displays ($M = 2572$ ms, SE = 1239; CC = 98 ms), $F(1, 38) = 15.18$, $p < .001$, $\eta_p^2 = 0.29$. The main effect of the phase was significant too, as participants responded overall faster in the relocation Phase ($M = 2430$ ms; $SE = 1179$) relative to the learning phase ($M = 2615$ ms; SE = 1284), $F(1, 38) = 13.66$, $p = .001$, $\eta_p^2 = 0.26$. We found a significant main effect of Epoch, with faster responses in Epoch 5 ($M = 2392$ ms; $SE = 1131$) relative to Epoch 1 ($M = 2714$ ms; $SE = 1362$), $F(4, 152) = 8.91$, $p < .001$, $\eta_p^2 = 0.19$. The interaction of Context x Epoch showed a marginal trend, $F(4, 152) = 2.42$, $p = .051$, $\eta_p^2 = 0.06$. Follow-up analyses revealed that the main effect of context was significantly stronger in Epoch 5 (mean CC = 180 ms), F(1, 39) = 22.94, $p < .001$, $\eta_p^2 = 0.37$), relative to Epoch 1 (mean CC = 85 ms), $F(1, 39) = 5$, $p = .031$, $\eta_p^2 = 0.11$). There was also an expected interaction of Context and Phase, $F(1, 38) = 16.19$, $p < .001$, $\eta_p^2 = 0.3$. Follow-up analyses revealed that the main effect of Context was absent in the relocation phase (repeated = 2427, non-repeated = 2433 ms, CC = -6 ms, $F(1, 38) = 0.02$, $p = .879$, $\eta_p^2 = 0$), relative to initial learning phase (repeated = 2716, $SD = 1268$, non-repeated = 2515 ms, $SD = 1294$; CC = 201 ms, $F(1, 38) = 37.86$, $p < .001$, $\eta_p^2 = 0.5$). These findings indicate that the attentional misguidance at the relocation phase resulted in a numerical relocation cost. Finally, the Context x Gaming group interaction revealed a numerical trend, as the Context effect was overall weaker in Non-gamers (CC = 50 ms) relative to Gamers (CC = 146 ms), $F(1, 38) = 3.71$, $p = .062$, $\eta_p^2 = 0.09$.

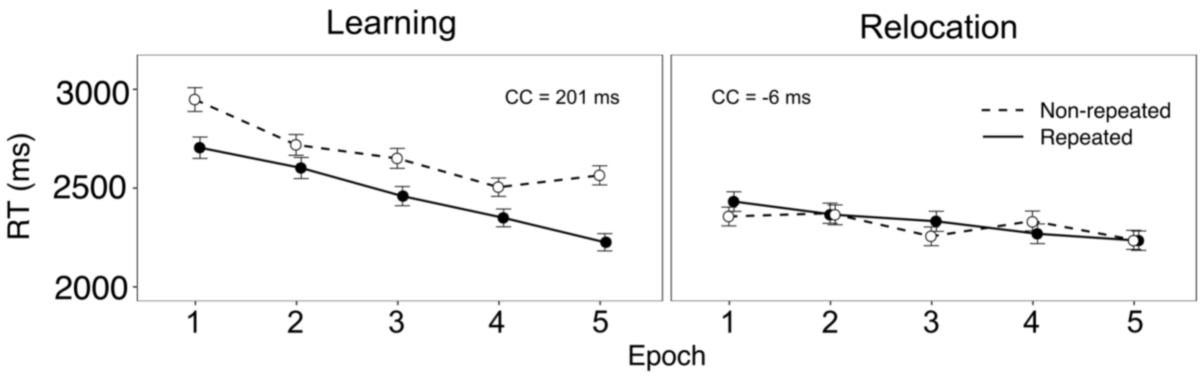

**Figure 3.** Mean reaction times (RTs, in milliseconds; with associated 95% confidence intervals) for repeated and non-repeated contexts (solid and dashed lines, respectively) as a function of epoch in the learning and relocation phases.

When contrasting contextual-cueing effects between AVGP and NAVGP separately in the learning and relocation phases (see Figure 4), we found a significant interaction of the Context x Gaming group in the learning phase ($F(1, 38) = 4.63$, $p = .038$, $\eta_p^2 = 0.11$), which was due to the main effect of Context being stronger in the group of Gamers (non-repeated = 2548, $SD = 1264$, repeated = 2276, $SD = 1194$, CC = 272 ms, $F(1, 19) = 36.88$, $p < .001$, $\eta_p^2 = 0.66$) relative to Non-gamers (non-repeated = 2884 ms, $SD = 1309$, repeated = 2753 ms, $SD = 1301$, CC = 131 ms, $F(1, 19) = 7.52$, $p = .013$, $\eta_p^2 = 0.28$). But there was no difference between the two groups in the relocation phase (CC gamers = 20 ms, CC non-gamers = -32 ms), $F(1, 38) = 0.45$, $p = .506$, $\eta_p^2 = 0.01$.

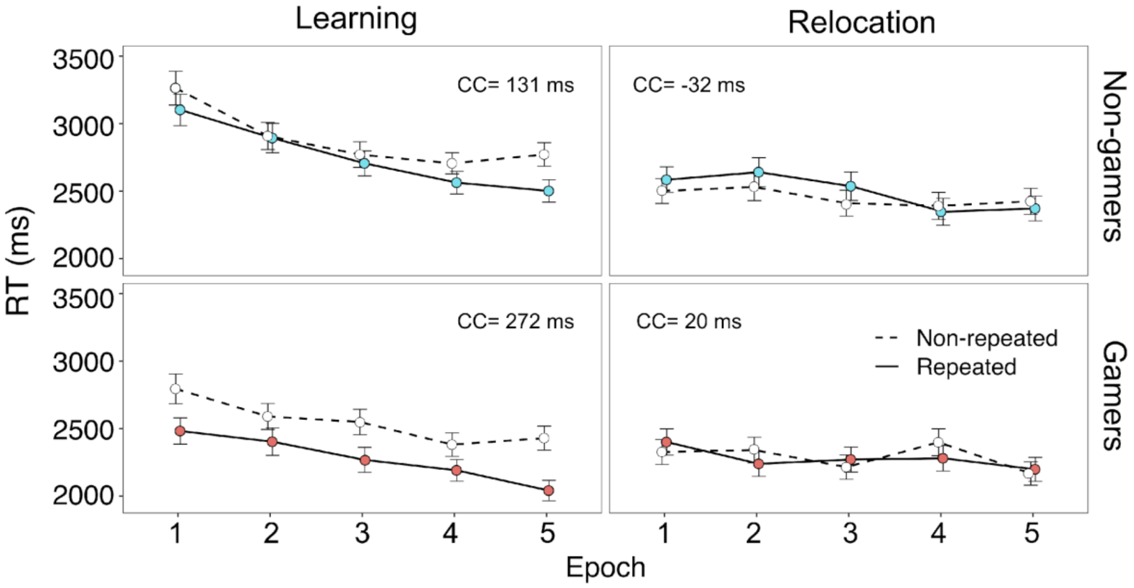

**Figure 4.** Mean reaction times (RTs, in milliseconds; with associated 95% confidence intervals) for repeated and non-repeated contexts (solid and dashed lines, respectively) as a function of epoch in the learning (left panel) and relocation (right panel) phases and separately for the AVGP and NAVGP.

In a separate analysis we explored whether the gaming x context interaction varied as a function of gender of participants. For this purpose, we have performed repeated measures ANOVA again, but now also included gender as a between-group factor. As a result, we found no significant interactions of Context, Gaming and Gender (all p's > 0.1). What we did observe, though, is an interaction of Gaming x Gender, F(1, 36) = 4.32, p = .045, $\eta_p^2$ = 0.11. Follow-up tests showed further that the main effect of Gender was not significant among NAVGP (males = 2810 ms, *SD* = 1524; females = 2621 ms, *SD* = 857), F(1, 18) = 0.12, p = .728, $\eta_p^2$ = 0.01, but it was significant among AVGP (males = 1695 ms, *SD* = 1005; females = 2966 ms, *SD* = 1040).

*Analysis of normalized RTs*

Two further analyses were conducted in order to test the relationship between contextual cueing and overall response speed. In the first analysis, we compared the two different groups of participants based on the observation that gamers responded overall faster than non-gamers (2331 ms, *SD* = 1204, vs. 2715 ms, *SD* = 1238, respectively; see also Figure 4). As mentioned in the Introduction, these general baseline differences in reaction times could have potentially impacted contextual cueing, such that faster RTs are associated with less cueing and thus underestimate the already higher cueing effects in AGVPs than NAGVPs (e.g., Peterson & Kramer, 2001, Chun & Phelps, 1999; Manns & Squire, 2001; see also Ratcliff, 1992; Darby et al., 2015; Schmidt et al., 2019). To control for differences in baseline speed, we calculated normalized contextual-cueing effects by dividing a given participants contextual-cueing effect, i.e., mean RT non-repeated display minus mean RT repeated displays, by his/ her mean RT in baseline, i.e., non-repeated, displays (Darby et al., 2014; Manginelli et al., 2013). Normalized contextual cueing scores were then submitted to a 2 (Phase: Learning, Relocation) x 5 (Epoch: 1 to 5) mixed design ANOVA with gaming groups as a between-group variable.

As a result, there was a significant main effect of gaming group: the normalized cueing effect was overall larger for gamers (0.069) relative to non-gamers (0.023), $F(1, 38) = 6.95$, $p = .012$, $\eta_p^2 = 0.15$. Additionally, there was a significant main effect of phase: the normalized cueing effect was larger in the learning phase (mean = 0.097), relative to the relocation phase (-0.006), $F(1, 38) = 24.39$, $p < .001$, $\eta_p^2 = 0.39$. No other main effects or interactions reached significance (all *p*’s > 0.05). These results suggest that gaming experience has a strong association with the magnitude of contextual cueing. This is also illustrated in Figure 5 which shows that CC was larger for participants with vs. without gaming experience even if these individual participants had comparable overall reaction times.

### *Regression model*

In the second analysis, we used statistical modeling for examining how overall performance speed in both gaming and non-gaming participants impacted on contextual-cueing magnitude by applying quadratic functions (Darby et al., 2014) to the data. In more detail, our regression model (tries to) predicts the strength of contextual cueing in the last Epoch 5 of the initial learning phase (where reliable RT differences between repeated and non-repeated distractor-target arrays were observed) via inverse transformation of reaction times (1/RT). The inverse was used instead of raw RT values because of the positively skewed response time distributions due to prolonged responses. The quadratic fit was selected to model the tendency of intermediate search speeds to lead to a contextual cueing advantage, as proposed by Darby and colleagues. We found that the quadratic model was overall not significant, $F(2, 37) = 0.59$, $p > 0.5$, R2 = 0.031 as well as a second, linear regression model (which we conducted for control purposes), which was also non-significant $F(1, 38) = 1.05$, $p > 0.3$, R2 = 0.027. Also, a final model comparison revealed that there were no differences between the two models, $F = 0.15$, $p > 0.6$ (see Figure 5). This set of analyses implies that there was no strong dependency between the strength of contextual cueing effect and mean RTs. In other words, the observed contextual cueing difference between the two groups could not be explained by differences in overall speed of performance (i.e., faster responses in the group of gamers).

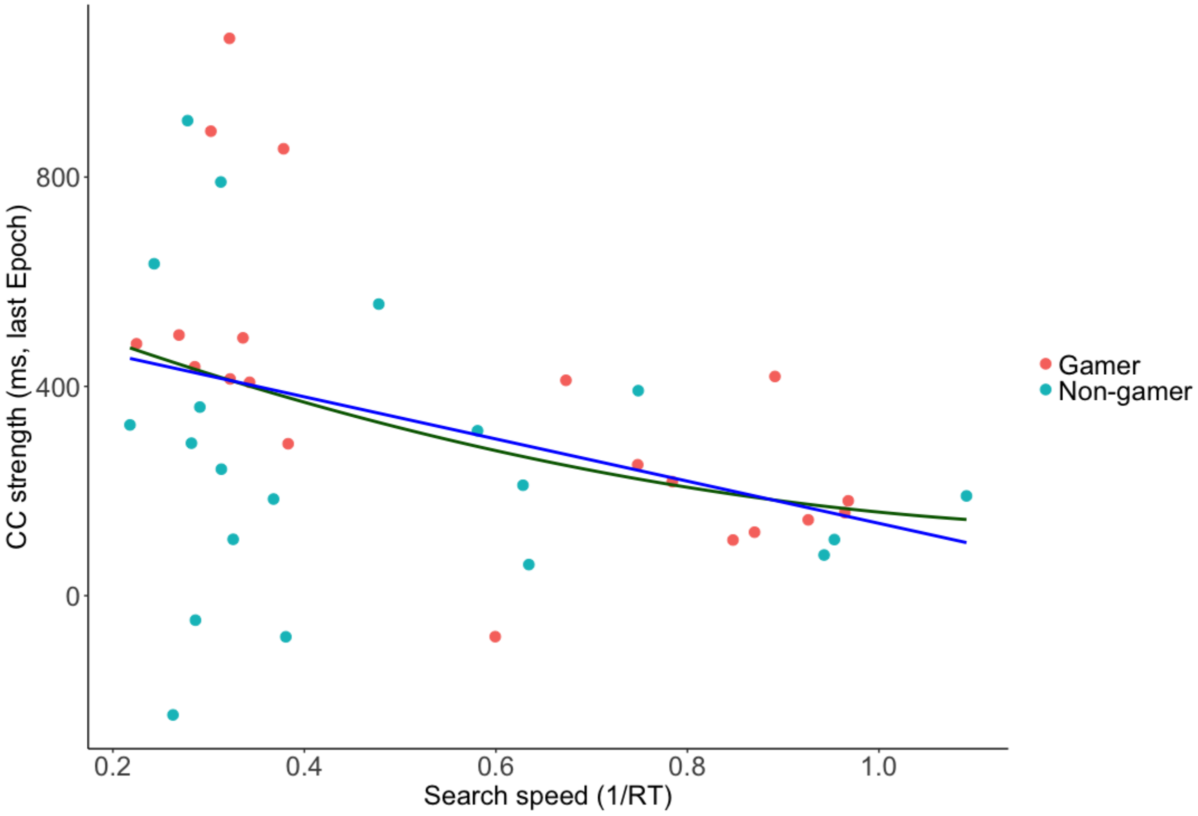

**Figure 5.** The scatter plot shows an association between speed of visual search (reciprocal of response time, in seconds: 1/RT) and the magnitude of the cueing effect (RT difference between non-repeated - repeated display in the last Epoch 5). The points represent data of individual participants in the two groups (Gamers, Non-gamers) from the initial learning phase (where the between-group RT differences were pronounced). The lines represent fitted linear (blue) and quadratic (green) model predictions.

### *Recognition test*

In the recognition test, conducted after the search task, there was no difference between the rates of hits (correct recognition of repeated displays as ‘repeated’: 49.21%) and false alarms (erroneous recognition of non-repeated displays as ‘repeated’: 51.56%; $t(15) = -0.39$, $p > 0.6$, Cohen’s $d = -0.14$). There was, thus, no evidence of explicit context memory in the current experiment, consistent with previous findings (e.g., Chun & Jiang, 1998).

## Discussion

The current study set out to examine whether the acquisition of context memories and subsequent contextual guidance of spatial attention are enhanced in action video game players (AVGP) relative to a control group of non-action video game players (NAVGP). Our study was based on prior findings showing that action video games improve selective-attention functions in search tasks. We used a novel, full factorial, training-phase/ relocation-phase design that could tease apart attentional guidance from learned search arrays and the ability to overcome visual distraction from these arrays. Such a design allowed us to verify, and thereby increase the reach of, prior conclusions on the facilitatory effects of action video game training on attention functions (of focusing on relevant vs. ignoring irrelevant information). Specific emphasis was given to search-task difficulty as it is possible that performance gains in AVGPs relative to NAGVPs unfold only with difficult, i.e., perceptually challenging, task conditions (see, e.g., Bavelier et al., 2012; Bejjanki et al., 2014; Chisholm & Kingstone, 2015; Green & Bavelier, 2003; Li et al., 2009; Li et al., 2010). To test this assumption and to further evaluate why previous studies did not show the gaming effect in contextual cueing (Schmidt et al., 2018), we used a well-established manipulation which has been shown to increase search task difficulty (Duncan & Humphreys, 1989): adjusting the offset of the line junction of the L-type letter distractors, making them overall more similar to the T-type target letter. Another important goal of the present study was to test whether the adaptation of existing contextual templates in the LTM is improved in individuals with higher attentional control function, e.g., action video game players. Specifically, there is consistent evidence in the literature that while acquisition of context-target associations is relatively effortless and requires just ~ 3 repetitions of repeated displays, updating these memories may require extensive training (Zellin et al., 2014; see also Annac et al., 2017 for a meta-analysis). We hypothesized that if the AVGP are superior at the updating their contextual LTM due to improved abilities to suppress the previously learnt, but no more relevant, target position and thus avoid attentional misguidance from this position (Zinchenko, Conci, Töllner et al., 2020), contextual cueing should recover rapidly in AGVPs (but not necessarily NAVGPs) in the relocation phase.

We found that the mean error rate was 7-10%, which is relatively high by the standards of a behavioral contextual-cueing experiment (~3%, Schmidt et al., 2018) and may index the overall higher difficulty of our task. In line with this interpretation, the average RTs were also numerically larger (> 2500 ms) relative to standard contextual-cueing studies (~ 1200 ms; Sisk et al., 2019; Zellin et al., 2014). Furthermore, and when using a relatively difficult task, we found that contextual cueing was 2.07 times larger in the AVGP relative to the NAVGP group in the initial learning phase, but not after the target was swapped to a different location (in the opposite hemifield) in the relocation phase. In the latter, there was no recovery of the contextual cueing effect in both groups.

The current factorial experimental design set out to contrast different mnemonic and attentional (or learn-to-learn) mechanisms that may be involved during the initial context learning and subsequent context re-learning or adaptation. Based on the observed dissociation between AGVPs and NAGVPs in the learning vs. relocation phases, gaming experience seems to specifically up-modulate the former function, while leaving the latter adaptation mechanism unaffected in the AGVP group. In other words, it is possible that the game-related trained perceptual processing facilitates the establishment of context memories, while it does not affect the frequently observed lack of adaptation of these formed memories. Linking this to enhanced attention capabilities in AGVPs, the current findings suggest that a specific form of –memory-based– attention is improved in AVGPs – assuming the existence of other forms of attention control relating to salient stimulus properties and participants' strategic goals (e.g., Corbetta & Shulman, 2002).

However, once learnt, repeated layouts trigger attentional- priority signals from memory that, after target relocation, interfere with contextual re-learning. Interestingly, participants in the AVGP group experienced similar difficulties in contextual adaptation than those in the NAGVP group. This is in contrast to other [gaming] studies reporting that gamers can limit distraction coming from salient, unexpected stimuli (e.g., Chisholm & Kingstone, 2015). That is, these studies revealed that the AGVP group had enhanced mechanisms of distractor inhibition - the capability to detect and actively suppress further processing of the irrelevant items (see Chelazzi et al., 2019 for review). Critically, however, these studies have typically tested search tasks in which both a physically salient feature- singleton target and a physically (more) salient, but task- irrelevant, feature-singleton distractor were present in the display (e.g., Geyer et al., 2008; Theeuwes, 1992). Accordingly, AGVPs enhanced attentional control capabilities observed previously may primarily be applied in a more bottom-up fashion, that is, in presence of physically 'salient' stimulation. This [bottom-up] mechanism contrasts with a more top-down process, when distraction arises from within LTM contextual memory in the form of a bias towards the previously learnt – but now no longer valid – target position.

Not mutually exclusive with this view is the idea that AVGPs improve in their ability for controlling procedural-motor (saccadic) events, but not necessarily the allocation of focal attention in the visual perceptual array. Specifically, previous contextual cueing studies additionally measured participants' eye-movements and revealed that repeated contexts were associated with reduced number of saccades, i.e., participants needed fewer eye-movements to locate the target item (e.g., Manelis & Reder, 2012; Manginelli & Pollmann, 2009; Tseng &

Li, 2004). This means that participants may have learned the sequence of motor eye-movements that lead to the target in repeated displays, and this mechanism could be specifically enhanced in AVGPs relative to NAVGPs. However, after the target has been relocated, the advanced procedural eye-movement sequences may become detrimental for visual search and hinder successful adaptation.

Note also that the current work has several important limitations. Specifically, the study used relatively broad sample criteria (e.g., 5+ hours per week for the AVGP group), which could also limit the sensitivity of statistical analyses. That is, it could be beneficial for future studies to split the group into those who played 5 to 10 hours per week vs. those gaming significantly above 10 hours, and examine the relationship between the number of hours spent gaming and behavioral performance. Please note that this comparison could not be made in the present investigation due to unequal distribution of those participants who reported playing 5 to 10 hours weekly (37.5%) vs. 10+ hours per week (12.5% of all participants). Further, such a comparison would also be important since 5-10 hours of video games per week may not be considered “heavy gaming” anymore, due to widespread and easy access to gaming devices in the last decades. Therefore, future studies should consider and account for these limitations. Additionally, to support the causal relationship between AVGP and cognitive performance, future studies should consider training designs in which non-gamers are trained on action video games and compared with control group in their pre and post-test contextual cueing performance (see Safaei et al., 2022 for example of such design with other types of games and spatial tasks).

To conclude, contextual cueing is an important statistical learning mechanism characterized by facilitation of target-related responses in repeated search arrays. As such, contextual learning of these arrays can be well up-modulated by gaming-related changes for how to (more effectively) scan the current sensory environment and allocate attention to critical display events, eventually also including the adaptation of existing memories due to improved reactive attention control mechanisms. Our findings support the former hypothesis. Contextual facilitation of search reaction times was 2.07 times greater in AVGPs relative to NAVGPs during learning, while the cueing effect was comparable (and almost non-existent) between the two groups in the target relocation phase. We propose that action-game experience might enhance the detection/ acquisition of and subsequent attentional guidance from statistical LT contextual memories about the consistent placement of the target in a consistent configuration of distractor elements, while leaving the ability for active suppression of ongoing attention biases arising from the learned target position in contextual LTM uninfluenced. However, training studies are needed in order to draw this kind of conclusions. Our findings thus clearly dissociate effects of action-game experience on attention guidance during contextual learning vs. reactive attention control during context adaptation, demonstrating that action-gaming trains different facets of attentional function, even within the same task. This highlights the importance of investigating gaming related performance improvements of attention functions in fully factorial designs. Our study also has practical implications. We found that more effective allocation of attention based on the acquisition of distractor-target scene memory happened by just playing action video games. That is, gaming benefits in the learning where to allocate attention to important information in the visual array clearly occurred outside of explicit, i.e., effortful, learning – the latter realized, e.g., by dedicated computerized cognitive tasks (Green & Bavelier, 2003; Tang & Posner, 2009).

## References

Annac, E., Conci, M., Müller, H. J., & Geyer, T. (2017). Local item density modulates adaptation of learned contextual cues. *Visual Cognition*, 25(1-3), 262-277.

Bavelier, D., Achtman, R. L., Mani, M., & Föcker, J. (2012). Neural bases of selective attention in action video game players. *Vision research*, 61, 132-143.

Bavelier, D., & Green, C. S. (2019). Enhancing attentional control: lessons from action video games. *Neuron*, 104(1), 147-163.

Bediou, B., Adams, D. M., Mayer, R. E., Tipton, E., Green, C. S., & Bavelier, D. (2018). Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychological bulletin*, 144(1), 77.

Bejjanki, V. R., Zhang, R., Li, R., Pouget, A., Green, C. S., Lu, Z. L., & Bavelier, D. (2014). Action video game play facilitates the development of better perceptual templates. *Proceedings of the National Academy of Sciences*, 111(47), 16961-16966.

Brainard, D. H., & Vision, S. (1997). The psychophysics toolbox. *Spatial vision*, 10(4), 433-436.

Carrasco, M., Penpeci-Talgar, C., & Eckstein, M. (2000). Spatial covert attention increases contrast sensitivity across the CSF: support for signal enhancement. *Vision Research*, *40* (10-12), 1203-1215.

Chen, S., Shi, Z., Müller, H. J., & Geyer, T. (2021b). Multisensory visuo-tactile context learning enhances the guidance of unisensory visual search. *Scientific Reports*, 11(1), 1-15.

Chelazzi, L., Marini, F., Pascucci, D., & Turatto, M. (2019). Getting rid of visual distractors: the why, when, how, and where. Current opinion in psychology, 29, 135-147.

Chisholm, J. D., & Kingstone, A. (2015). Action video games and improved attentional control: Disentangling selection-and response-based processes. Psychonomic Bulletin & Review, 22(5), 1430-1436.

Chun, M. M., & Phelps, E. A. (1999). Memory deficits for implicit contextual information in amnesic subjects with hippocampal damage. *Nature neuroscience*, 2(9), 844-847.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive psychology*, 36(1), 28-71.

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed  and stimulus- driven attention in the brain. *Nature reviews neuroscience* , *3* ( 3), 201-215.

Darby, K. P., Burling, J. M., & Yoshida, H. (2014). The role of search speed in the contextual cueing of children's attention. *Cognitive development*, 29, 17-29.

Denton, S. E., & Kruschke, J. K. (2006). Attention and salience in associative blocking. *Learning & behavior*, 34(3), 285-304.

Duckworth, A. L., Quirk, A., Gallop, R., Hoyle, R. H., Kelly, D. R., & Matthews, M. D. (2019). Cognitive and noncognitive predictors of success. *Proceedings of the National Academy of Sciences*, 116(47), 23499-23504.

Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96* (3), 433.

Erickson, K. I., Boot, W. R., Basak, C., Neider, M. B., Prakash, R. S., Voss, M. W.,et al. (2010). Striatal volume predicts level of video game skill acquisition. Cereb. Cortex 20, 2522–2530. doi: 10.1093/cercor/bhp293

Föcker, J., Cole, D., Beer, A. L., & Bavelier, D. (2018). Neural bases of enhanced attentional control: Lessons from action video game players. *Brain and behavior*, 8(7), e01019.

Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. *Journal of neuroscience*, 34(16), 5658-5666.

Geng, J. J., & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. *Perception & psychophysics*, 67(7), 1252-1268.

Geyer, T., Müller, H.J., & Krummenacher, J., & Geyer, T. (2008). Expectancies modulate attentional capture by salient color singletons. *Vision Research*, 48, 1315-1326.

Geyer, T., Zehetleitner, M., & Müller, H. J. (2010). Contextual cueing of pop-out visual search: When context guides the deployment of attention. *Journal of vision*, 10(5), 20-20.

Geyer, T., Rostami, P., Sogerer, L., Schlagbauer, B., & Müller, H. J. (2020). Task-based memory systems in contextual-cueing of visual search and explicit recognition. *Scientific Reports*, 10(1), 1-13.

Geyer, T., Seitz, W., Zinchenko, A., Müller, H. J., & Conci, M. (2021). Why are acquired search-guiding context memories resistant to updating?. *Frontiers in Psychology*, 12, 650245.

Goujon, A., Didierjean, A., & Thorpe, S. (2015). Investigating implicit statistical learning mechanisms through contextual cueing. *Trends in cognitive sciences*, 19(9), 524-533.

Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, 423(6939), 534-537.

Green, C. S., & Bavelier, D. (2012). Learning, attentional control, and action video games. *Current biology*, 22(6), R197-R206.

Hout, M. C., & Goldinger, S. D. (2012). Incidental learning speeds visual search by lowering response thresholds, not by improving efficiency: evidence from eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, 38(1), 90.

Jiang, Y., & Chun, M. M. (2001). Selective attention modulates implicit learning. *The Quarterly Journal of Experimental Psychology: Section A*, 54(4), 1105-1124.

Kiili, K. (2005). Digital game-based learning: Towards an experiential gaming model. The Internet and higher education, 8(1), 13-24.

Koepp, M. J., Gunn, R. N., Lawrence, A. D., Cunningham, V. J., Dagher, A., Jones, T.,et al. (1998). Evidence for striatal dopamine release during a video game. Nature 393, 266–268. doi: 10.1038/30498

Kühn, S., Romanowski, A., Schilling, C., Lorenz, R., Mörsen, C., Seiferth, N., ... & Gallinat, J. (2011). The neural basis of video gaming. Translational psychiatry, 1(11), e53-e53.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance* , *21* ( 3), 451.

Li, R., Polat, U., Makous, W., & Bavelier, D. (2009). Enhancing the contrast sensitivity function through action video game training. *Nature neuroscience*, 12(5), 549-551.

Li, R., Polat, U., Scalzo, F., & Bavelier, D. (2010). Reducing backward masking through action game training. *Journal of vision*, 10(14), 33-33.

Liesefeld, H. R., & Müller, H. J. (2019). Distractor handling via dimension weighting. *Current Opinion in Psychology*, 29, 160-167.

Lorenz, R. C., Gleich, T., Gallinat, J., & Kühn, S. (2015). Video game training and the reward system. *Frontiers in human neuroscience*, 9, 40.

Makovski, T., & Jiang, Y. V. (2010). Contextual cost: When a visual-search target is not where it should be. *Quarterly Journal of Experimental Psychology*, 63(2), 216-225.

Manginelli, A. A., Langer, N., Klose, D., & Pollmann, S. (2013). Contextual cueing under working memory load: Selective interference of visuospatial load with expression of learning. *Attention, Perception, & Psychophysics*, *75*(6), 1103-1117.

Manginelli, A. A., & Pollmann, S. (2009). Misleading contextual cues: How do they affect visual search?. *Psychological Research*, 73(2), 212-221.

Manelis, A., & Reder, L. M. (2012). Procedural learning and associative memory mechanisms contribute to contextual cueing: Evidence from fMRI and eye-tracking. *Learning & Memory*, 19(11), 527-534.

Mishra, J., Zinni, M., Bavelier, D., & Hillyard, S. A. (2011). Neural basis of superior performance of action videogame players in an attention-demanding task. Journal of Neuroscience, 31(3), 992-998.

Pelli, D. G., & Vision, S. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial vision*, 10, 437-442.

Pessoa, L.,  Padmala, S., &  Morland, T.  (2005). Fate of  unattended fearful  faces in the amygdala is  determined by  both attentional resources and  cognitive  modulation. *Neuroimage* , 28 (1),  249-255.

Peterson, M. S., & Kramer, A. F. (2001). Attentional guidance of the eyes by contextual information and abrupt onsets. *Perception & Psychophysics*, 63(7), 1239-1249.

Rescorla, R. A., & Wagner, A. R. (1972). A theory of Pavlovian conditioning: Variations in the effectiveness of reinforcement and nonreinforcement. In A. H. Black & W. F. Prokasy (Eds.), Classical conditioning II: Current research and theory (pp. 64-99). New York: Appleton-Century-Crofts.

Safaei, A., Rahmanian, M., Oraki, M., & Zinchenko, A. (2022). Video Game Play Does Not Improve Spatial Skills When Controlling for Speed-Accuracy Trade-Off: Evidence From Mental-Rotation and Mental-Folding Tasks. Perceptual and Motor Skills, April 2022, https://doi.org/10.1177/00315125221078982.

Sawaki, R., & Luck, S. J. (2010). Capture versus suppression of attention by salient singletons: Electrophysiological evidence for an automatic attend-to-me signal. *Attention, Perception, & Psychophysics*, 72(6), 1455-1470.

Sewell, D. K., Colagiuri, B., & Livesey, E. J. (2018). Response time modeling reveals multiple contextual cuing mechanisms. Psychonomic Bulletin & Review, 25(5), 1644-1665.

Schankin, A., & Schubö, A. (2009). Cognitive processes facilitated by contextual cueing: Evidence from event-related brain potentials. *Psychophysiology*, 46(3), 668-679.

Schankin, A., & Schubö, A. (2010). Contextual cueing effects despite spatially cued target locations. Psychophysiology, 47(4), 717-727.

Schmidt, A., Geringswald, F., & Pollmann, S. (2018). Spatial contextual cueing is not a limiting factor for expert performance in the domain of team sports or action video game playing. *bioRxiv*, 267872.

Schmidt, A., Geringswald, F., & Pollmann, S. (2019). Spatial contextual cueing, assessed in a computerized task, is not a limiting factor for expert performance in the domain of team sports or action video game playing. *Journal of Cognitive Enhancement*, 3(3), 281-292.

Schmidt, A., Geringswald, F., Sharifian, F., & Pollmann, S. (2020). Not scene learning, but attentional processing is superior in team sport athletes and action video game players. *Psychological research*, 84(4), 1028-1038.

Sisk, C. A., Remington, R. W., & Jiang, Y. V. (2019). Mechanisms of contextual cueing: A tutorial review. *Attention, Perception, & Psychophysics*, 81(8), 2571-2589.

Stokes, M. G., Atherton, K., Patai, E. Z., & Nobre, A. C. (2012). Long- term memory prepares neural activity for perception. *Proceedings of the National Academy of Sciences* , *109* (6), E360-E367.

Tang, Y. Y., & Posner, M. I. (2009). Attention training and attention state training. *Trends in cognitive sciences*, 13(5), 222-227.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & psychophysics,* 51(6), 599-606.

Tseng, Y. C., & Li, C. S. R. (2004). Oculomotor correlates of context-guided learning in visual search. *Perception & Psychophysics*, 66(8), 1363-1378.

Vadillo, M. A., Konstantinidis, E., & Shanks, D. R. (2016). Underpowered samples, false negatives, and unconscious learning. *Psychonomic Bulletin & Review*, 23(1), 87-102.

Wolfe, J. M. (2021). Guided Search 6.0: An updated model of visual search. *Psychonomic Bulletin & Review,* 1-33.

Wolfe, J. M., & Horowitz, T. S. (2017). Five factors that guide attention in visual search. *Nature Human Behaviour*, 1(3), 1-8.

Zang, X., Jia, L., Müller, H. J., & Shi, Z. (2015). Invariant spatial context is learned but not retrieved in gaze-contingent tunnel-view search. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 41(3), 807.

Zellin, M., von Mühlenen, A., Müller, H. J., & Conci, M. (2014). Long-term adaptation to change in implicit contextual learning. *Psychonomic Bulletin & Review*, 21(4), 1073-1079.

Zellin, M., Conci, M., von Mühlenen, A., & Müller, H. J. (2013). Here today, gone tomorrow–adaptation to change in memory-guided visual search. *PloS one*, 8(3), e59466.

Zinchenko, A., Conci, M., Hauser, J., Müller, H. J., & Geyer, T. (2020). Distributed attention beats the down-side of statistical context learning in visual search. *Journal of Vision*, 20(7), 4-4.

Zinchenko, A., Conci, M., Töllner, T., Müller, H. J., & Geyer, T. (2020). Automatic guidance (and misguidance) of visuospatial attention by acquired scene memory: Evidence from an N1pc polarity reversal. *Psychological Science*, 31(12), 1531-1543.