PROGRESS IN COMPUTER GAMING AND ESPORTS: NEUROCOGNITIVE AND MOTOR PERSPECTIVES

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PROGRESS IN COMPUTER GAMING AND ESPORTS: NEUROCOGNITIVE AND MOTOR PERSPECTIVES

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EDITORIAL
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Editorial: Progress in Computer Gaming and Esports: Neurocognitive and Motor Perspectives

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Editorial on the Research Topic

Progress in Computer Gaming and Esports: Neurocognitive and Motor Perspectives

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This Research Topic covers the neurocognitive aspects of computer gaming and esports. Authors representing a broad spectrum of psychology and neuroscience have contributed, introducing empirical findings as well as conceptual and methodological innovations. In this Editorial we provide a thematic overview of the exciting and diverse contents of this Research Topic.

Video games have become a cultural phenomenon over the past 50 years and are now one of the most prominently chosen past times (Wagner, 2006; Hamari and Sjöblom, 2017; Lokhman et al., 2018). The use of dynamic visual displays, the demand on flexible attention allocation and the requirement for precise time-constrained bimanual motor control, make video games a unique medium for studying both cognition and motor control Bera et al. Over the past 20 years, neurocognitive research has demonstrated that habitual competitive video game players appear to display some superior cognitive attributes when compared to their non-video gaming counterparts (Colzato et al., 2013; Bediou et al., 2018; Kowal et al., 2018). Along with the increased recognition of esports as a sporting activity alongside traditional athletic sports, the unique cognitive skillset possessed by elite gamers has earned them the moniker of "cognitive athletes" (Campbell et al., 2018). This notion has led to an increased appetite toward understanding the cognitive benefits conferred from, and demanded by, video games.

A plethora of research has demonstrated that habitual action video gamers demonstrate superior information processing (Yuji, 1996; Dye et al., 2009; Kowal et al., 2018), attention Li et al.; Schenk et al., task switching (Colzato et al., 2010; Green et al., 2012; Toth et al., 2020), and memory abilities (Wilms et al., 2013; Waris et al., 2019), compared to non-gaming populations. Moreover, research has found these same cognitive skills can be enhanced when non-gamers engage with action video games in particular (Oei and Patterson, 2013; Clemenson and Stark, 2015). In fact, cognitive ability, in addition to past gaming experience, has even been found to predict one's ability to quickly learn new video games Smith et al. Alternatively, for some cognitive skills like response inhibition, gamers adopt a strategy that prioritizes speed over accuracy, showing no clear advantage (Kowal et al., 2018). This finding has been recently corroborated by Sousa et al., who demonstrated a decrease in inhibitory performance among participants following FPS and MOBA game play, which was larger in magnitude following FPS, compared to MOBA, play Sousa et al. Moreover, cognitive inhibition has also recently been shown not to differentiate ranking among gamers within a prominent FPS game (Colzato et al., 2013; Toth et al.). However, it is important to note that although classical tests of cognitive inhibition fail to differentiate gaming process, altering the context in which this skill is evaluated may also alter outcomes. For example, a gamified examination of cognitive inhibition may demonstrate performance differences among gamers, where classical standardized stroop tasks have failed to delineate differences. During F1 driving simulations for example, Eckardt et al. found that driving performance was largely tied to adaptive abilities and selective attention/inhibition ability Eckardt et al.

The recognized role of cognitive development and training in esports has extended to traditional sports, where superior executive function (EF) abilities can augment motor skill performance. For example, Beavan et al. share the importance of not only evaluating EF ability among soccer players, but also the set-up of consistent protocols and the effective communication of results to players. Traditional sport may also benefit from video games for motor learning too. In addition to the cognitive benefits that can be attained through video game play, video game environments have shown to promote motor skill practice away from the field of play. Michalski et al. demonstrate, in their recent review, that virtual environments (VE) now demonstrate a realism and flexibility that makes them potentially ideal and cost-effective for motor learning and the transfer of skill to the real world Michalski et al. Although work in this area is still sparse, early signs point to a promising role for VE to augment performance in traditional sports as well (Hülsmann et al., 2019).

In addition to the potential for video games to augment cognitive and motor abilities, they have also shown promise as a mental health tool as well (Kowal et al., 2021). Not only has this been significant in light of the recent COVID19 pandemic, but Tabacof et al. have demonstrated the critical role that video games can play in providing feelings of social connectedness among those who may have physical or mental disability Tabacof et al. In their study, they present solutions that can improve the accessibility of video games to those with spinal cord injury (SCI) and quadriplegia and how doing so significantly improves feelings of social connectedness among these individuals. Overall, this highlights the benefit that the digital nature of video gaming brings as a medium to remove barriers that may exist between individuals of varying sex, race, and physical ability.

Despite all the benefits to be had from video games, they are not without their pitfall. Their sedentary nature and the fact that users can find themselves staring at bright luminant screens for prolonged periods of time have been well cited as negative attributes (Lanningham-Foster et al., 2006; DiFrancisco-Donoghue et al., 2019; Yin et al., 2020). Therefore, some are now calling for a holistic approach to esports training and video game play in general Martin-Niedecken et al. In fact, new research is now altering the way esports players train, moving away from predominant full emersion training to adopting segmented skill based variable priority training strategies, prevalent in traditional sport (Toth et al., 2021). The role of physical exercise is also emerging as critical to the health and performance longevity in esports, despite physical exertion being a fraction of what is required at the elite level in traditional sports. Moreover, in addition to the well-established physical and mental benefits, physical exercise has been shown to augment the cognitive abilities which provide top video gamer players their advantage in the first place (Toth et al., 2020).

In conclusion, despite the prevalence and popularity of video games and esports worldwide today, we are still at the frontier of esports science and are only beginning to identify the key features that make elite esports athletes unique Smithies et al. Furthermore, the cognitive benefits conferred from engaging with video games, further social and physical benefits are likely to manifest as well, in addition to the development of a better understanding of how to mitigate health and performance pitfalls associated with video game play. As we embark on a new decade, we can expect to see a surge of new research on the role video games and virtual environments play in multiple facets of our lives, and this work is welcome now as we continue to place video games at the fore front of entertainment media in our digital world.

AUTHOR CONTRIBUTIONS

AT and MC wrote the first draft. CF and DP edited the draft. All authors contributed to and signed off on the final draft.

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Reduced Lateralization of Attention in Action Video Game Players

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There is increasing evidence that action video game players (AVGPs) possess superior performance in various tasks, especially those measuring attentional abilities. The current study aimed to examine the lateralization of attentional components in AVGPs. Twenty-nine AVGPs and twenty-six non-AVG players (NAVGPs) were recruited based on their frequency and intensity of playing action video games in the last 6 months. A lateralized attentional network test was used to measure the lateralization of attentional components in the two groups. The results showed that AVGPs exhibited comparable performance in the left and right hemispheres for reorienting and executive components. However, NAVGPs exhibited a significant difference between the two hemispheres for the two components. The findings indicate that AVG playing is closely associated with reduced lateralization of attentional networks.

Keywords: action video game playing, attention, lateralization, executive, reorienting

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INTRODUCTION

Increasing studies have revealed that compared to non-action video game players (NAVGPs), action video game players (AVGPs) perform better in various tasks (Powers et al., 2013; Wang et al., 2016; Bediou et al., 2018; Kowal et al., 2018; see Latham et al., 2013 and Green and Bavelier, 2015 for reviews). Attentional ability has been extensively examined in these studies, providing convergent evidence that AVG playing is associated with enhanced attentional capabilities (Green and Bavelier, 2003, 2012; Boot, 2015) and neural changes in the brain (Bavelier et al., 2012; Wu et al., 2012; Tanaka et al., 2013; Kühn et al., 2014; Gong et al., 2016), indicating an experience-based neural plasticity in attentional networks associated with AVG playing (Boot, 2015). The current study aimed to specifically examine the lateralization and efficiency of attentional networks associated with AVG playing.

Attention consists of three basic components, alerting, executive, and orienting (Posner and Boies, 1971; Posner and Petersen, 1990; Petersen and Posner, 2012). Alerting processes are involved in establishing and maintaining a state of sensitivity to surroundings, executive processes resolve cognitive conflicts evoked by multiple, incongruent attentional cues, and orienting processes direct individuals to a specific stimulus (Posner and Petersen, 1990; Corbetta and Shulman, 2002; Fan et al., 2005; Corbetta et al., 2008). A brief computerized battery, the attentional network test (ANT), has already been developed to assess the efficiency of the three components (Fan et al., 2002). In the test, different cue types are implemented to measure the efficiency of attentional components. Specifically, alerting effects are obtained by comparing no-cue with center/double-cue conditions, executive effects are obtained by comparing congruent with incongruent flanker conditions, and orienting effects are obtained by comparing valid-spatial-cue with center/double-cue conditions (Fan et al., 2002). Recent research has provided evidence for the association of AVG playing with the improvement of these attentional functions. Chisholm et al. (2010) and Mishra et al. (2011) found AVGPs outperformed NAVGPs in the suppression of distracting information, Green and Bavelier (2003) found that AVGPs showed better flanker compatibility effects, and Boot et al. (2008) found that AVGPs showed higher efficiency of task-switching. These findings indicate more efficient executive functions in AVGPs. As for orienting functions, it was found that orienting processes evoked by exogenous cues operate similarly in AVGPs and NAVGPs. Using a Posner cueing paradigm where an exogenous cue is briefly presented in one of two possible target locations before the target presented in either the cued location or the uncued location, Castel et al. (2005) found that AVGPs and NAVGPs benefited from the cue comparably, i.e., comparable exogenous orienting processes. Castel et al.'s finding is then supported by later studies that also applied a Posner cueing paradigm (Dye et al., 2009; Hubert-Wallander et al., 2011). But for alerting functions, no significant differences between AVGPs and NAVGPs were found in both children and adults (Dye et al., 2009). To summarize, the existing literature has revealed that extensive AVG playing is highly associated with the improvement of some facets of attention, especially executive component.

It has been established that the human attentional brain network is overall lateralized to the right hemisphere (Corbetta and Shulman, 2002; Corbetta et al., 2008; Vossel et al., 2014). Greene et al. (2008) and Asanowicz et al. (2012) added visual field (VF) factor to the ANT and developed a computerized tool, the lateralized attentional network test (LANT), to evaluate attentional functions in the two hemispheres. In the test, attentional components are obtained by comparing two of the four cue types, no-cue, center/double-cue, valid-cue, and invalid cue (see Fan et al., 2009 for the details). Reorienting effects (also called validity effects) are obtained by comparing invalid-cue with valid-cue conditions (i.e., reorienting to unexpected, but relevant stimuli from pre-cued locations). Disengaging effects are obtained by comparing invalid-cue with center/double-cue conditions (i.e., disengaging from pre-cued locations). The test has been used by later studies to determine the lateralization of the attentional functions (e.g., Marzecová et al., 2013; Spagna et al., 2016, 2018). It was found that in the general population, alerting functions were bilaterally implemented in the brain (Greene et al., 2008; Asanowicz et al., 2012; Spagna et al., 2016, 2018); orienting functions were biased to the right hemisphere (Experiment 1 in Greene et al., 2008; Spagna et al., 2016, 2018); reorienting functions were biased to the right hemisphere (Experiment 2 in Greene et al., 2008; Asanowicz et al., 2012; Spagna et al., 2016; but see Spagna et al., 2018); disengaging functions were bilateral (Spagna et al., 2016, 2018); and executive functions were biased to the right hemisphere (Asanowicz et al., 2012; Marzecová et al., 2013; Spagna et al., 2016, 2018; but see Experiment 2 in Greene et al., 2008). Interestingly, the right-hemisphere bias for reorienting functions observed above is broadly in line with earlier work by Evert et al. (2003), and Evert and Oscar-Berman (2001) who found a VF asymmetry for the invalid-cue condition of the Posner's cueing task. Collectively, these findings indicate that reorienting and executive functions are right-lateralized, and alerting functions do not show a lateralized pattern. These studies have demonstrated the feasibility and reliability of LANT in detecting the lateralization of attentional networks.

However, the lateralization of attentional networks in AVGPs is still poorly understood. A recent study revealed that AVG playing is associated with reduced response bias to the left VF (Latham et al., 2014). In this study, the authors used a line bisection task in which participants were asked to bisect horizontal lines printed on a paper. Typical middle points of lines bisected by normal right-handers are 2% left to the true middle point (Jewell and McCourt, 2000), reflecting the crucial role of the right hemisphere, especially temporoparietal junction, in visuospatial attention (Thiebaut de Schotten et al., 2011). The right temporoparietal junction is much involved in orienting and reorienting functions (Corbetta et al., 2008; Vossel et al., 2014). Therefore, the reduced leftward bias in AVGPs is more likely to be indicative of the reduced lateralization of visuospatial attention, especially orienting and reorienting functions. This finding could be interpreted by the nature of games. In the games full of competition and cooperation, AVGPs have to vigilantly monitor the computer screen with balanced visual monitoring and make fast, accurate responses to multiple various visual cues. In daily game playing, a bias to the left or right VF could be highly detrimental to performance, which has to be avoided by AVGPs. Thus, the right-lateralized attention observed in the general population would be altered to be more bilateral in AVGPs. However, this is not tested yet.

Using the LANT implementing a Posner cueing paradigm in the left and right VFs, this study aimed to test the lateralization of attentional components and its relationships with AVG playing. To measure the ability of AVGPs to reorient to an unexpected location from an expected location and disengage from an unexpected location, we added validity of spatial location, i.e., 20% of spatial cues were invalid, to the test. Effects of alerting, executive, orienting, reorienting, and disengaging were extracted by comparing different cue types (Fan et al., 2009; Spagna et al., 2018). According to the literature reviewed above, we hypothesized that long-term AVG playing would change the lateralization of attentional networks, more specifically reduce the lateralization of executive and reorienting functions.

MATERIALS AND METHODS

Participants

Twenty-nine AVGPs (mean age, 19.55 years; age range: 18–24 years; 13 females) and twenty-six NAVGPs (mean age, 19.11 years; age range, 18–22 years; 14 females) were recruited from Wuhan Polytechnic College, Wuhan, Hubei, China. Each of them participated in this study voluntarily and obtained no course credits or money. Each of them had normal or corrected-to-normal vision, and had no history of neurological impairments. The games played by AVGPs were but not limited to the following games: *The King of Fighters, Temple Run, Counter-Strike, Crossfire, Overwatch, and Need for Speed*, on their computers, tablets or mobile phones. They played games at least 2 h per day and 4 days per week in the last 6 months or more. The

NAVGPs didn't play any action video games in the last 6 months. This study was approved by the Institutional Review Boards of Qufu Normal University and each participant signed an informed consent form before the experiment.

The LANT

Building on the experimental paradigms used in two previous studies (Greene et al., 2008; Asanowicz et al., 2012), the present study used a LANT to measure the lateralization of alerting, conflict (i.e., executive), orienting, validity (i.e., reorienting), and disengaging effects in the two groups. Greene et al. (2008) and Asanowicz et al. (2012) have demonstrated the reliability of LANT in measuring the lateralization of attentional networks. This tool has also been used to detect the influences of bilingualism on the asymmetry of the networks (e.g., Tao et al., 2011; Marzecová et al., 2013).

The details of the LANT are provided in **Figure 1**. During this task, a fixation (black cross) was presented in the center of the screen, followed by an up- or down- pointing arrow appeared in the left or right VF with equal probability. The target arrow was flanked by two above arrows and two below arrows with their direction congruent or incongruent with the target arrow. Participants were instructed to indicate the direction of the target arrow by pressing buttons. Reaction times (RT) and accuracy were recorded. The difference in RT and accuracy between incongruent and congruent conditions reflects conflict effects (Fan et al., 2002, 2005). The efficiency of alerting, orienting, validity, and disengaging effects were measured by the differences in RT and accuracy between two of four types of cues. A no-cue is presented before the appearance of the target arrow; a center-cue is presented in the same location as the fixation; a valid-cue is presented in the left or right VF to indicate the location of the target arrow to be presented; an invalid-cue is presented in the left or right VF, but invalidly indicates the location of the target arrow to be presented, and this type of cue appeared 20% spatial cue trials. See the definition of each effect in Section "Data Analyses" below.

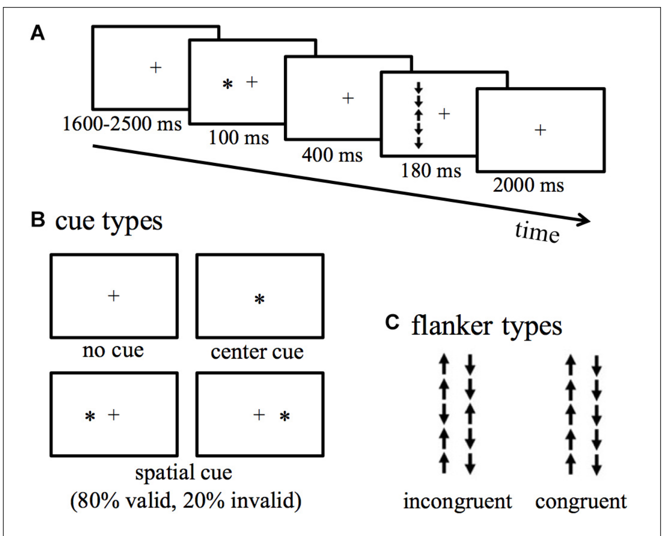

FIGURE 1 | The lateralized attentional network test (LANT). **(A)** Experimental procedure. **(B)** Cue types. **(C)** Flanker types.

Stimuli and Procedure

The fixation cross was 5 mm (0.47°) in width and 5 mm (0.36°) in length. The target arrow and arrows (flankers) around it were 7 mm (0.73°) in length, and an arrow chain (5 arrows) was thus 35 mm (3.65°). In the task, an arrow chain was presented 60 mm to the left or right VF of the screen. The cue was an asterisk of 5 mm diameter (0.47°) in width and 5 mm (0.36°) in length. The cue was presented in the center of the screen (center-cue), spatially at the same location as the following target arrow (valid-cue), or spatially at the opposite location to the following target arrow (invalid-cue). The distance between the screen and the participants' eyes was about 60 cm.

The experiment included 432 trials presented in six blocks with 72 trials in each block. In one-half of the trials, the target arrow was flanked by congruent arrows, and in another half flanked by incongruent arrows. Of all the trials, 192 trials were indicated by center-cue or no-cue; 192 trials were indicated by valid-cue presented in the left or right VF; 48 trials were indicated by invalid-cue, which accounts for 20% of all the spatial trials.

The entire procedure was compiled and controlled by E-Prime 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA, United States). For every single trial, a fixation was presented in the center of the screen for varying 1600–2500 ms duration (and the fixation remained through the entire trial), then one of the four types of cue was presented for 100 ms. After the offset of the cue, a blank was displayed for 400 ms, then a target arrow flanked by four arrows with the same or opposite pointing direction appeared for 180 ms. Participants were told that some of the locations of arrows were not predictable (i.e., cues were invalid), but they did not know the ratio (4:1) of valid and invalid conditions. Participants were instructed to indicate the direction of the target arrow by pressing buttons within 2000 ms as quickly and accurately as possible. Participant's right hand held the mouse of the computer to respond. The mouse was first placed at the middle line to the computer screen and rotated to be parallel to the screen. Participants pressed the right mouse key if the target arrow pointed up and pressed the left mouse key if the target arrow pointed down. This approach enabled participants to respond easily as the direction of the target arrow was spatially compatible with the button response. Before the actual experiment, a separated practice block was given to make participants familiarize with the procedure. Participants were allowed to have a short break between blocks. The entire experiment lasted for about 50 min.

Data Analyses

For the calculation of the RT and accuracy scores for the attentional networks for each group and VF, we adopted different strategies. For RT, we subtracted the center-cue condition from the no-cue condition to obtain *alerting* scores, subtracted the congruent from the incongruent conditions to obtain *conflict* scores, subtracted the center-cue from the valid-cue conditions to obtain *orienting* scores, subtracted the center-cue from the invalid-cue conditions to obtain *disengaging* scores, and subtracted the valid-cue from the invalid-cue conditions to obtain *validity* scores. Validity is also called reorienting as it reorients attention to unexpected, but behaviorally relevant stimuli. As for accuracy, we used subtractions that were inverse to the subtractions used for RT data to obtain scores. So for both RT and accuracy, a lower score was associated with a higher efficiency. Effects sizes were reported as partial eta squared (η_p^2). See Fan et al. (2009) for the details of the operational definitions for these effects.

A mixed design was used in this experiment, with *cue type* (no-cue, center-cue, valid-cue, invalid-cue), *congruency* (congruent, incongruent), and *VF* (left, right) as within-subject factors, and *group* (AVGPs, NAVGPs) as between-subject factor. To investigate the interactions between these four factors (e.g., Callejas et al., 2004; Fan et al., 2009) and avoid misinterpreting the results by simply relying on the differences between conditions (Dye et al., 2009), we conducted an omnibus ANOVA, but focused on the significant interactions involving *group* factor. We further conducted simple effects analyses with Bonferroni correction to inspect significant interactions.

RESULTS

Analyses for RT and accuracy were separately conducted. Trials with RT shorter than 150 ms, longer than 1500 ms (~1% of correct responses), and trials with incorrect responses (~15% of all trials) from the RT analysis were excluded from the analyses. **Table 1** provides mean RT and accuracy for each condition in the two groups (also see **Supplementary Figure S1**).

Overall RT and Accuracy

The mean RTs of correct responses were 465 ms (±98 ms) for AVGPs and 485 ms (±98 ms) for NAVGPs. The mean accuracies were 0.876 (±0.056) for AVGPs and 0.85 (±0.061) for NAVGPs. *T*-tests revealed no significant group difference in both RT [$t(53) = -0.784$, $p = 0.125$] and accuracy [$t(53) = 1.639$, $p = 0.107$]. The accuracy of the right VF stimuli with invalid cue and incongruent flanker was significantly different from chance level (50%) in AVGPs ($p < 0.001$) but not in NAVGPs ($p = 0.743$; see **Supplementary Figure S1**). The performance of other conditions was significantly higher than chance level in the two groups ($p < 0.001$).

Alerting Effects

The difference between no-cue and center-cue conditions was calculated as an index of alerting effects. See **Supplementary Table S1** for the mean and standard deviation (SD) of RT and accuracy in the two groups. For RT, a 2 (*group*) × 2 (*VF*) mixed ANOVA revealed that all the *group* and *VF* effects and the interaction effect were not significant [$F(1,53) < 1.119$, $p > 0.295$, $\eta_p^2 < 0.021$; see **Figure 2A**]. Similarly, all the main effects and the interaction effect were not significant for accuracy [$F(1,53) < 0.13$, $p > 0.72$, $\eta_p^2 < 0.002$; see **Figure 2B**].

Conflict Effects

The difference between incongruent and congruent conditions were calculated as an index of conflict resolving (executive function). See **Supplementary Table S1** for the mean and SD of RT and accuracy in the two groups. For RT, a 2 (*group*) × 2 (*VF*) mixed ANOVA revealed that all the main effects and the interaction effect were not significant [$F(1,53) < 0.381$,

TABLE 1 | Mean reaction time of trials with correct responses and accuracy for each condition.

			Accuracy				Reaction time (ms)			
			AVGP		NAVGP		AVGP		NAVGP	
Cue	Flanker	VF	mean	SD	mean	SD	mean	SD	mean	SD
No-cue	Con	Left	0.96	0.04	0.92	0.07	456	100	483	92
		Right	0.94	0.06	0.93	0.08	476	105	483	86
	Inc	Left	0.81	0.12	0.78	0.14	521	103	542	97
		Right	0.75	0.15	0.75	0.13	532	108	541	95
Center-cue	Con	Left	0.97	0.05	0.94	0.04	413	100	452	107
		Right	0.95	0.08	0.96	0.05	421	98	438	94
	Inc	Left	0.89	0.10	0.87	0.11	497	107	519	88
		Right	0.85	0.11	0.83	0.10	505	91	524	99
Valid-cue	Con	Left	0.99	0.03	0.97	0.02	331	86	343	83
		Right	0.98	0.03	0.99	0.02	337	105	349	89
	Inc	Left	0.95	0.05	0.97	0.02	389	115	394	88
		Right	0.94	0.04	0.95	0.04	393	112	400	97
Invalid-cue	Con	Left	0.83	0.13	0.85	0.14	520	119	544	124
		Right	0.79	0.17	0.72	0.15	512	111	559	148
	Inc	Left	0.72	0.17	0.66	0.21	570	119	594	149
		Right	0.69	0.19	0.52	0.24	563	127	602	182

Con, congruent; Inc, incongruent; VF, visual field; AVGP, action video game players; NAVGP, non-action video game players.

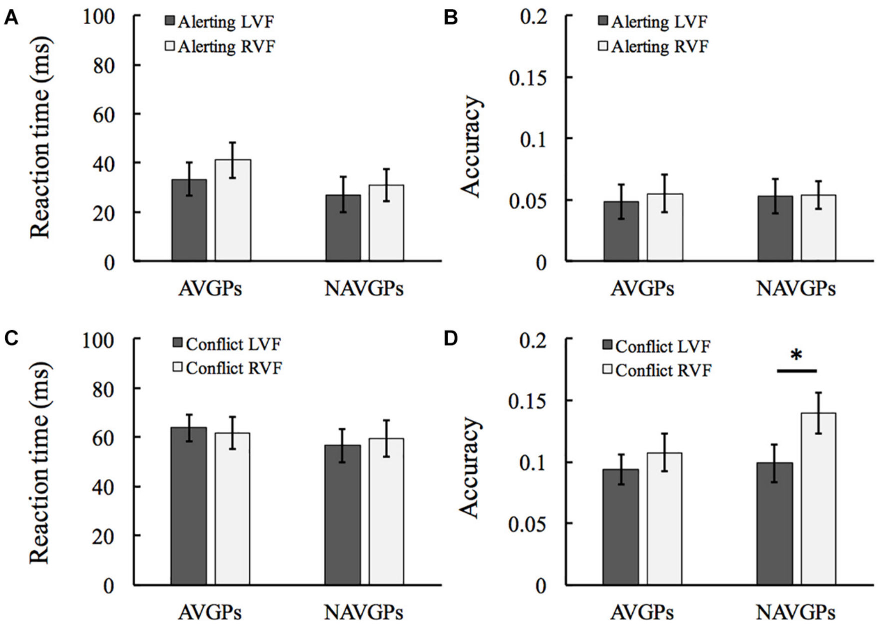

FIGURE 2 | Alerting effects in the left and right visual fields (L/RVF) in the action video game players (AVGPs) and non-action video game players (NAVGPs) **(A,B)**. Conflict effects in the left and right VFs in AVGPs and NAVGPs **(C,D)**. Note that a lower score indicates a higher efficiency for both reaction time and accuracy data. Error bars denote SEM. $^{*}p < 0.05$.

$p > 0.54$, $\eta_p^2 < 0.007$; see **Figure 2C**]. For accuracy, the *group* and interaction effects were not significant [$F(1,53) < 1.361$, $p > 0.296$, $\eta_p^2 < 0.025$]. The *VF* effect was significant [$F(1,53) = 5.465$, $p = 0.023$, $\eta_p^2 = 0.093$], indicating that the efficiency of right-hemisphere executive effect is higher than the left executive network. Further analyses with *T*-tests revealed a significant difference between the two VFs in NAVGPs [$t(53) = -2.399$, $p = 0.024$], but not in AVGPs [$t(53) = -1.076$, $p = 0.291$; see **Figure 2D**].

Orienting Effects

The difference between center-cue and valid-cue conditions were calculated as an index of orienting effects. See **Supplementary Table S1** for the mean and SD of RT and accuracy in the two groups. For RT, a 2 (*group*) × 2 (*VF*) mixed ANOVA revealed that the *group* effect was significant [$F(1,53) = 4.291$, $p = 0.043$, $\eta_p^2 = 0.075$; AVGPs, 96 ± 32 ms, NAVPs, 112 ± 22 ms; see **Figure 3A**]. Detailed inspection revealed that AVGPs had faster responses to the targets preceded by center-cues compared to NAVGPs, but the two groups benefited similarly from valid-cues. For accuracy, a 2 (*group*) × 2 (*VF*) mixed ANOVA revealed that all the effects were not significant [$F(1,53) < 2.07$, $p > 0.156$, $\eta_p^2 < 0.014$; see **Figure 3D**].

Validity Effects

The difference between invalid-cue and valid-cue conditions were calculated as an index of validity effects (i.e., reorienting). See **Supplementary Table S1** for the mean and SD of RT and accuracy in the two groups. For RT, a 2 (*group*) × 2 (*VF*) mixed ANOVA revealed that all the *group, VF*, and the interaction effects were not significant [$F(1,53) < 1.539$, $p > 0.22$, $\eta_p^2 < 0.028$; see **Figure 3B**]. For accuracy, the *VF* effect was significant [$F(1,53) = 25.265$, $p < 0.001$, $\eta_p^2 = 0.323$; see **Figure 3E**]; the *group* effect was significant [$F(1,53) = 4.955$, $p = 0.03$, $\eta_p^2 = 0.085$]; the interaction effect was also significant [$F(1,53) = 10.597$, $p = 0.002$, $\eta_p^2 = 0.167$]. Simple effects analyses with Bonferroni correction revealed that there was no significant difference between the left and right VF reorienting in AVGPs [$F(1,53) = 1.659$, $p = 0.203$, $\eta_p^2 = 0.03$; see **Figure 3B**]. But the validity score of NAVGPs was higher in the right than left VF [$F(1,53) = 32.52$, $p < 0.001$, $\eta_p^2 = 0.38$; see **Figure 3E**]. Furthermore, the validity scores of the right VF were significantly higher in NAVGPs than in AVGPs [$F(1,53) = 10.587$, $p = 0.002$, $\eta_p^2 = 0.167$], but there was no significant difference between the two groups in the validity scores of the left VF [$F(1,53) = 0.478$, $p = 0.493$, $\eta_p^2 = 0.009$; see **Figure 3E**].

Disengaging Effects

The difference between invalid-cue and center-cue conditions were calculated as an index of disengaging effects. See **Supplementary Table S1** for the mean and SD of RT and accuracy in the two groups. For RT, a 2 (*group*) × 2 (*VF*) mixed ANOVA revealed all the main or interaction effects were not significant [$F(1,53) < 2.44$, $p > 0.124$, $\eta_p^2 < 0.044$; see **Figure 3C**]. For accuracy, a 2 (*group*) × 2 (*VF*) mixed ANOVA revealed that the *VF* effect was significant [$F(1,53) = 20.67$, $p < 0.001$, $\eta_p^2 = 0.281$; see **Figure 3F**], indicating a left-VF bias for disengaging. The *group* effect was marginally significant [$F(1,53) = 3.914$, $p = 0.053$, $\eta_p^2 = 0.069$], indicating that the disengaging of AVGPs was more efficient than that of NAVGPs. Furthermore, the interaction effect was also significant [$F(1,53) = 17.028$, $p < 0.001$, $\eta_p^2 = 0.243$]. Simple effects

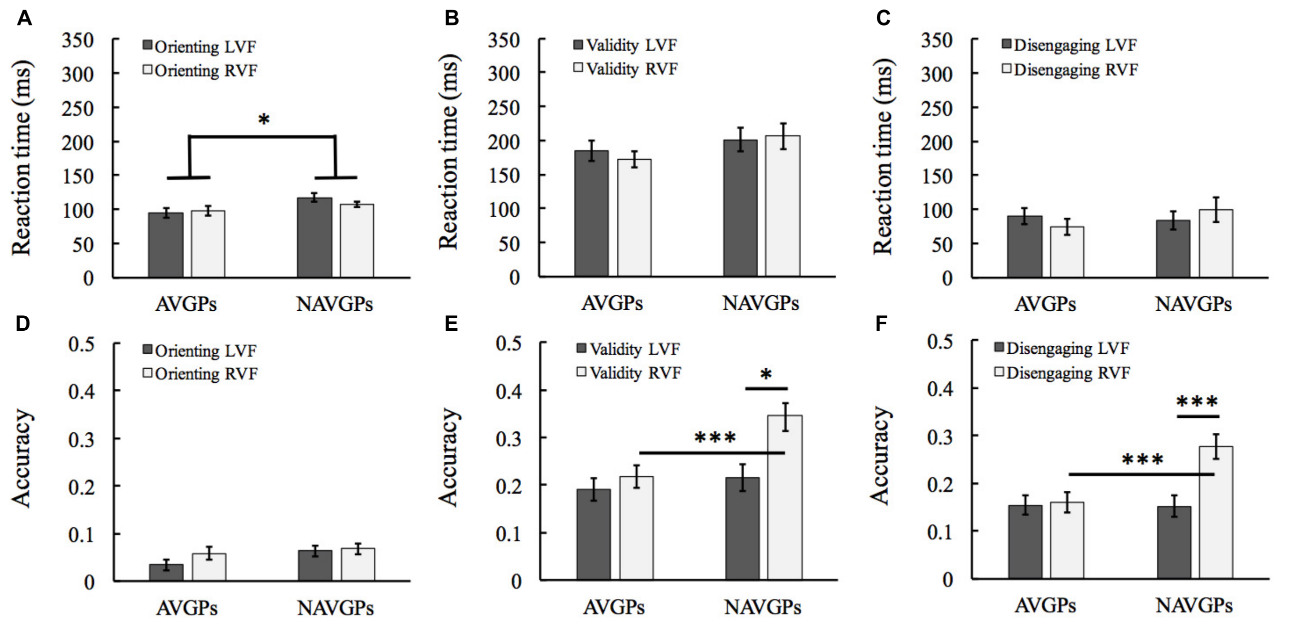

FIGURE 3 | Orienting **(A,D)**, validity (reorienting; **B,E**), and disengaging **(C,F)** effects in left and right visual fields (L/RVF) in the action video game players (AVGPs) and non-action video game players (NAVGPs). Note that a lower score indicates a higher efficiency for both reaction time and accuracy data. Error bars denote SEM. *$p < 0.05$, ***$p < 0.001$.

analyses with Bonferroni correction revealed that there was no significant difference between the left and right VFs in AVGPs [$F(1,53) = 0.093$, $p = 0.761$, $\eta_p^2 = 0.002$; see **Figure 3F**]. However, NAVGPs showed a higher disengaging in the right than left VF [$F(1,53) = 35.664$, $p < 0.001$, $\eta_p^2 = 0.402$; see **Figure 3F**]. Furthermore, the right-VF disengaging scores were significantly higher for NAVGPs than AVGPs [$F(1,53) = 12.077$, $p < 0.001$, $\eta_p^2 = 0.186$], but there was no significant difference between the two groups for the left-VF disengaging [$F(1,53) = 0.005$, $p = 0.944$, $\eta_p^2 = 0$; see **Figure 3F**].

Interactions Between Factors

A 4 × 2 × 2 × 2 ANOVA with *cue type* (no-cue, center-cue, valid-cue, and invalid-cue), *congruency* (congruent, incongruent), *VF* (left, right), and *group* (AVGPs, NAVGPs) as factors was conducted to extract interactions involving *group* (see **Supplementary Table S2** for the details of the main and interaction effects). Significant interactions involving *group* were only found in the accuracy data. The *cue by group* interaction was significant [$F(3,159) = 3.492$, $p = 0.017$, $\eta_p^2 = 0.062$]. Simple effects analysis further revealed that AVGPs were significantly higher than NAVGPs only in the invalid-cue condition [$F(1,53) = 4.207$, $p = 0.045$, $\eta_p^2 = 0.074$] but not in the other conditions [$F(1,53) < 0.905$, $p > 0.341$, $\eta_p^2 < 0.017$].

It was also found that the *cue by congruency by group* and *cue by VF by group* interactions were significant [$F(3,159) > 3.978$, $p < 0.009$, $\eta_p^2 > 0.07$]. The *cue by congruency* and *cue by VF interactions* were then conducted for each *group* to detail the significance of the interactions. The *cue by congruency* interaction was significant in both AVGPs [$F(3,84) = 12.763$, $p < 0.001$, $\eta_p^2 = 0.313$] and NAVGPs [$F(3,75) = 14.913$, $p < 0.001$, $\eta_p^2 = 0.374$]. Interestingly, the differences in accuracy between the congruent and incongruent conditions decreased from no/center/valid-cue to invalid-cue for both groups, but the decrease was larger for NAVGPs than AVGPs (**Figure 4A**). The *cue by VF* interaction was not significant in AVGPs [$F(3,84) = 1.082$, $p = 0.361$, $\eta_p^2 = 0.037$], but significant in NAVGPs [$F(3,75) = 20.002$, $p < 0.001$, $\eta_p^2 = 0.444$]. Specifically, the change in accuracy from no/center/valid-cue to invalid-cue conditions was smaller for AVGPs than NAVGPs when the cues were presented in the right VF, and the change in accuracy from the left to right VF was also smaller for AVGPs than NAVGPs when the cues changed from no/center/valid-cue to invalid cue (**Figure 4B**). As shown in **Figure 4**, the significance of the two interactions was mainly attributed to the invalid-cue condition.

DISCUSSION

The present study aimed to examine the lateralization and efficiency of attentional components, and their associations with AVG playing. We found that different from NAVGPs showing a right-hemisphere lateralized pattern for executive and reorienting components, AVGPs showed a bilateral mode (**Figures 2**, **3**). However, alerting component was comparable in the two groups, not showing a lateralized pattern. The findings are in line with a recent study wherein a reduced leftward bias of visuospatial attention in AVGPs was revealed (Latham et al., 2014). It has been reported that the alerting component is bilaterally implemented in the brain (e.g., Greene et al., 2008; Asanowicz et al., 2012; Spagna et al., 2016, 2018), which gets

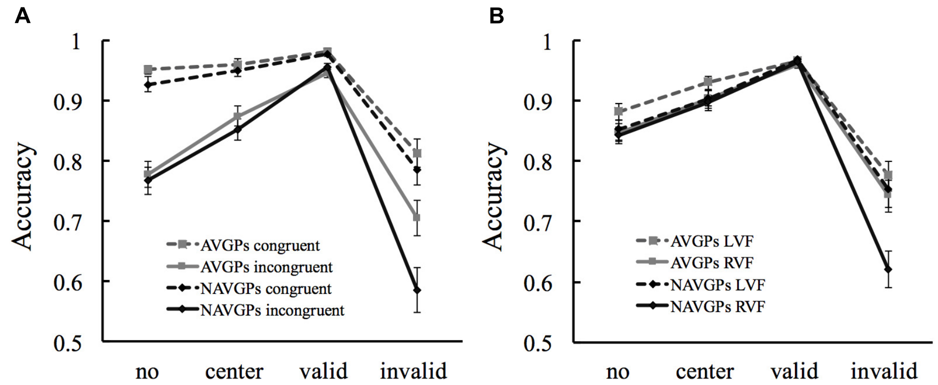

FIGURE 4 | Simple effects analyses for the *cue by congruency by group* interaction **(A)** and the *cue by VF by group* interaction **(B)**. L/RVF, left/right visual field. Error bars denote SEM.

supported by both the RT and accuracy results of alerting in NAVGPs. The absence of the differences between AVGPs and NAVGPs is consistent with a previous study showing no significant differences between the two groups for both children and adults (Dye et al., 2009). The finding that alerting was also comparable for the two groups in terms of lateralization suggests that AVG playing is not associated with alerting functions.

Previous studies have found that AVGPs have a more efficient executive function for resolving or suppressing cognitive conflicts as shown in different tasks compared to NAVGPs, (Chisholm et al., 2010; Mishra et al., 2011). Moreover, studies using the LANT revealed that executive functions show a bias to the right hemisphere in the general population (Greene et al., 2008; Asanowicz et al., 2012; Marzecová et al., 2013; Spagna et al., 2018), echoing the literature (Kondo et al., 2004; Levy and Wagner, 2011; Vallesi, 2012; Aron et al., 2014; Cai et al., 2014). The current study confirmed this finding. However, executive functions were comparable for both hemispheres of AVGPs, indicating a strong link between the bilateral executive functions and AVG playing. The bilateral executive functions of AVGPs likely reflects that neural resources are bilaterally recruited to detect and resolve cognitive conflict occurring in both VFs more efficiently. There were no significant differences between the left and right VFs of AVGPs, and no significant differences in the left VF between AVGPs and NAVGPs. These findings suggest that AVG playing is tightly associated with the efficiency of executive functions in the left VF such that executive functions could be performed comparably and unbiasedly for both VFs. Interestingly, a recent study found a larger conflict effect in AVGPs than in NAVGPs (Dye et al., 2009), but we did not (**Figure 2D** and **Supplementary Table S2**). Detailed analysis of Dye et al.'s data revealed that AVGPs responded more slowly to the incongruent flankers compared to the congruent flankers, leading to a larger conflict effect in AVGPs. This pattern was not observed in both RT and accuracy of the current study. The differences in results could be due to the age differences and the types of tasks in the studies. Dye et al. (2009) examined children aged 7–13 years using a child version of ANT, whereas our participants were adults who did a lateralized ANT.

The accuracy data of validity effects indicates that reorienting is dominantly supported by the right hemisphere. More specifically, the responses to stimuli preceded by invalid-cues were more accurate when stimuli were presented in the left VF than in the right VF. It concurs with several studies using the LANT (Greene et al., 2008; Asanowicz et al., 2012; Spagna et al., 2018). In this study, AVGPs showed a more efficient reorienting than NAVGPs; and AVGPs showed a bilateral reorienting function, but NAVGPs showed a reorienting biased to the right hemisphere (**Figures 3E,F**). It has been found that reorienting is dominantly implemented in the right hemisphere covering the temporoparietal junction and middle frontal cortex (Vossel et al., 2006; Petersen and Posner, 2012; Geng and Vossel, 2013; Krall et al., 2015). Therefore, the absence of the lateralization of reorienting in AVGPs exactly reflects the association of the improvement of the left hemisphere neural resources for reorienting functions with game playing, and the improvement could erase the differences in performance between hemispheres. It was proposed that reorienting is realized by the interplay between the dorsal system area, the intraparietal sulcus, and the ventral system area, the temporoparietal junction (Corbetta et al., 2008), so it is possible that AVGPs have more balanced interplays between the two systems of attention. Similar to the pattern of reorienting, AVGPs also showed a bilateral disengaging function while NAVGPs showed a disengaging function that is biased to the right hemisphere (**Figures 3E,F**). Both reorienting and disengaging reflects the capacity of responding to novel, unexpected but behaviorally relevant stimuli (Posner, 1980). The results of reorienting and disengaging collectively suggest a close relationship between game playing and the efficiency of capturing unexpected but behaviorally relevant stimuli.

There were no significant differences in orienting effects between the left and right VFs in both groups, indicating that game playing may not be related to hemisphere lateralization when the task is to capture cued, but always expected stimuli. Interestingly, AVGPs had faster responses to targets preceded by center-cues compared to NAVGPs, but the two groups benefited similarly from valid-cues, explaining why AVGPs had a lower score of orienting. The finding demonstrates the importance of separately analyzing the two conditions in interpreting orienting effects (Dye et al., 2009). The insignificant difference in only the valid-cue condition between the two groups is consistent with previous studies (Castel et al., 2005; Hubert-Wallander et al., 2011). However, using a temporal order judgment task West et al. (2008) found that AVGPs were more sensitive to early exogenous cues than NAVGPs, being opposite to the current finding. The reason could be that subjective report of temporal order judgment used in West et al. (2008) study might be much modulated by top-down attention rather than pure exogenous cue (Hubert-Wallander et al., 2011).

Unveiling how factors such as congruency, cue type, and VF interact with each other helps to better understand how the brain optimizes the processing of behaviorally relevant information (Callejas et al., 2004, 2005; Fan et al., 2009; Badre, 2011; Marotta et al., 2012; Xuan et al., 2016; Spagna et al., 2018). The finding that AVGPs had more efficient interplays between congruency or VF and cue type for a better attentional capacity (**Figure 4**) suggest that AVGPs are less susceptible to the factors, congruency, VF, and cue type. The results of the *cue by congruency by group* interaction is likely to indicate that NAVGPs' conflict resolving is not efficient during reorienting (Corbetta et al., 2008; **Figure 4A**). This is consistent with previous studies (e.g., Fan et al., 2009; Trautwein et al., 2016). However, AVGPs have optimized interplays between reorienting and conflict resolving such that conflicts could be efficiently resolved during reorienting to targets (**Figure 4A**), possibly reflecting the important role of anterior insula cortex in the interplays (Trautwein et al., 2016). The findings provide strong evidence for the association between AVG playing and the enhancement of the interplays between different factors.

Note that the enhanced attentional components of AVGPs observed in this study could be attributed to factors such as enhanced ability to "learning to learn" (Bejjanki et al., 2014; Green and Bavelier, 2015), better visuospatial resolution (Green and Bavelier, 2007), or larger useful field of view (Green and Bavelier, 2003, 2006; Feng et al., 2007). For example, Bejjanki et al. (2014) found that AVGPs and NAVGPs had similar performance on the earliest trials of a new task, but gamers showed steeper learning functions. Therefore, it is possible that the differences in the ability to "learning to learn" between the two groups contributed to the differences in performance, although participants knew little about the ratio of valid- and invalid-cue trials. It is also possible that AVGPs' larger useful field of view and lower threshold of visual resolution led to better performance, especially in detecting targets preceded by invalid-cues and resolving conflicts evoked by incongruent flankers.

The human brain is highly plastic. Reduced lateralization of visuospatial attention has been found in musicians (e.g., Patston et al., 2006, 2007) and bilinguals especially for executive functions (e.g., Marzecová et al., 2013), clearly indicating learning a second language and performing music instruments may reshape the lateralization of the human attentional networks. Extending the existing literature showing AVGPs have better attentional abilities (Green and Bavelier, 2012), the current study revealed that the lateralization of attentional networks is highly associated with AVG playing, contributing to a better understanding of improvement in attentional capacity, and more generally, neural plasticity benefiting from extensive game playing. However, the results do not indicate a causal relationship between AVG playing and the changes of attentional network. Future studies can take advantage of randomized control trial to examine how AVG playing changes or reshapes attentional networks, by which a causal inference can be made.

CONCLUSION

Using the LANT, we found that unlike NAVGPs possessing executive and reorienting functions being biased to the right hemisphere, the two were bilaterally implemented in the brain of AVGPs. But alerting functions were comparable for both populations in terms of lateralization. The results indicate that AVG playing is associated with the efficiency and lateralization of attentional networks, especially for executive and reorienting functions, and with overall reduced lateralization of visuospatial attention.

DATA AVAILABILITY

All datasets generated for this study are included in the manuscript and/or the **Supplementary Files**.

ETHICS STATEMENT

This study was approved by the Institutional Review Boards of Qufu Normal University and each participant signed an informed consent form before the experiment.

AUTHOR CONTRIBUTIONS

YL and DN designed the study and drafted the manuscript. XJ and YW collected the data. YL and XJ analyzed the data.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2019.01631/full#supplementary-material

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SYSTEMATIC REVIEW
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Using Virtual Environments to Improve Real-World Motor Skills in Sports: A Systematic Review

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In many settings, sports training can be difficult to organize, logistically complicated and very costly. Virtual environments (VE) have garnered interest as a tool to train real-world sports skills due to the realism and flexibility that they can deliver. A key assumption of VE-based training is that the learned skills and experiences transfer to the real world, but do they? Using PRISMA guidelines, this systematic review evaluated the available evidence regarding the transfer of motor skills from VE training to real-world sporting contexts. The initial search identified 448 articles, but only 4 of these articles met basic criteria necessary to assess real-world transfer. Key factors regarding the study design, learner characteristics and training environment of these studies are considered. In a relatively new area of research, the findings from these 4 articles are encouraging and provide initial support for the notion that skills training in a VE can improve real-world performance in sports. However, for a wider uptake of VEs in sports training, it is important that more research demonstrates real-world transfer. Study design recommendations are suggested for researchers, developers or trainers who are considering demonstrating real-world transfers from virtual to real-world environments.

Keywords: virtual environment, transfer, study design, training environment, learner characteristics

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INTRODUCTION

Practice makes perfect. Perhaps there is some truth in this popular phrase, as mastering any skill, be it performing a backflip, playing the guitar or serving a tennis ball requires practice. But what makes practice perfect? Despite over a century of research, it is still a matter of debate how training should be structured to maximize the potential for learning (Guadagnoli and Lee, 2004). What is clear is that to attain expertise in a sport, athletes must devote a considerable amount of time to training (Miles et al., 2012). Yet, often training can be difficult to organize, logistically complicated and very costly. Consider a quarterback who needs to pinpoint a pass amongst an entire field of players, a skier who needs access to a snow-covered mountain and a race car driver who needs access to a vehicle on a vacant race track. To overcome these barriers, heavy demands have been placed on finding contemporary, cost-efficient and flexible training methods (Gupta et al., 2008). Virtual environments (VE) have garnered interest as a tool for training real-world skills due to the realism and flexibility that they can deliver.

As technology is rapidly improving and becoming more affordable, many fields and professions have started using VEs as a tool to train real-world skills. A variety of professions such as surgeons (Seymour et al., 2002), pilots (Hays et al., 1992) and firefighters (Stansfield et al., 2000), to name a few, have been shown to benefit from training in a VE. Due to the inherent level of risk associated with such training programs, which typically involve "learning by doing," there is a growing trend in shifting toward VE-based training programs (Gavish et al., 2015). VEs promise a safe, realistic and interactive learning environment with the opportunity for repeated practice, supported by feedback and standards to measure performance. However, there is still a long way to go and further technological advances need to be made so that VEs can reach their full potential.

While VEs are becoming increasingly popular in fields such as aviation and surgery, its use in sports training is still rather limited. Yet, there are many potential advantages to VE-based training in a sporting context. VEs can be used to simulate the presence of team members and opponents, allow coaches to create personalized scenarios for players (Kim et al., 2013; Düking et al., 2018), practice can be designed relative to the skill level of the performer (Düking et al., 2018), users can log their performance and closely monitor their development (Neumann et al., 2018) and numerous sporting environments can be simulated. With the added benefit of being able to train in a safe and repeatable environment, VEs appear to be a promising platform to improve real-world motor skills in sports.

While promising, it is important to point out that VE training is not useful or practical for training in all sports. For example, water sports such as swimming cannot be trained in VEs. The current state of technology makes it also challenging to simulate training for skills relying on highly accurate haptic feedback and multiplayer interactions. The technical limitations and the costs associated with the creation of virtual training environments pose a significant barrier for an uptake in VE sports training. Overviews of technical requirements for VEs can be found in Miles et al. (2012) and Petri et al. (2018). However, it is important to note that even if some sports are currently too challenging and costly to simulate with high fidelity, VEs might be still useful for observational learning (Tanaka, 2017). Users can potentially improve their skills by passively viewing a skill demonstration or instructional video in which they can feel immersed.

An important prerequisite for a wider uptake of VE sports applications are demonstrations that the training leads to better performance in the real-world sport (Lathan et al., 2002; Neumann et al., 2018). That is, the trained skills can transfer to the real-world setting. Transfer has been defined as the process by which skills, abilities and knowledge developed through training are applied in a real-world situation or task (Baldwin and Ford, 1988). Burke and Hutchins (2007) propose three important factors to consider when evaluating transfer of training, including study design; learner characteristics; and training environment. Each of these factors will be addressed in turn.

An adequate study design is essential when evaluating transfer of training (Gray, 2017). Firstly, to determine the effectiveness of VE-based training, researchers must include a group to control for basic practice effects (Abernethy and Wood, 2001). Secondly, it is insufficient to assess the effectiveness of VE training by only quantifying the extent of improvement on the VE training task (near transfer) (Gray, 2017). This is because the results can almost always be expected to be positive, mainly due to practice effects. Thus, studies need to include an assessment of performance from the training task to the real-world sport (far transfer) (Abernethy and Wood, 2001; Gray, 2017).

Characteristics of the learner are important to consider when evaluating the effectiveness of training (Baldwin and Ford, 1988). Examples of characteristics which have been identified as affecting transfer of training include cognitive ability, motivation, personality and prior level of experience in the task (Sackett et al., 1998). One aspect to consider in relation to sports training is the user's prior level of experience in the sport being assessed. Guadagnoli and Lee (2004) suggest that training is optimal when the difficulty of the task is matched to the skill level of the individual. Adaptive training is based on this theory whereby training is appropriately matched to the user's level of success in a training bout. Adaptive training is when the difficulty of the task is constantly adjusted (usually by systematically increasing the difficulty) to ensure the training is always challenging and engaging. Perhaps the effectiveness of VE-based training does increase when the training is challenging (relative to the skill level of the individual).

The third factor identified which is necessary to consider when evaluating transfer is the training environment. The most compelling VEs give users a subjective experience of presence and immersion by engaging multiple sensory modalities, providing both a realistic and engaging experience in the training environment (Witmer and Singer, 1998). Presence refers to the subjective experience of "being there" in a VE, while immersion refers to the technological capabilities of delivering this experience (Witmer and Singer, 1998). Presence and immersion are highly related to one another, as they are both necessary to convey a realistic experience to the user (Slater and Wilbur, 1997). Based on advancements in VE technology in recent times, presence and immersion have become much easier to create (Fox et al., 2009). VEs are hypothesized to be better training tools in comparison to standard computer-based training programs and training using video because of the greater level of realism they can offer (Witmer and Singer, 1998). Perhaps, transfer of training is dependent upon the capabilities of the VE to create feelings of presence and immersion within the user (Vignais et al., 2015).

To maximize the effectiveness of VE training, the physical and cognitive fidelity of the training environment should also be considered. Hochmitz and Yuviler-Gavish (2011) proposed two complementary aspects. Firstly, it is assumed that for a positive transfer to occur, VEs must replicate high physical fidelity regarding the real-world environment. This involves the degree to which the VE looks, feels (via haptic rendering) and sounds (via auditory rendering) like the real-world situation (Alexander et al., 2005). Secondly, it has also been proposed that the VEs must replicate high cognitive fidelity regarding the real-world environment. This involves the degree to which VEs can engage users in the types of cognitive activities (i.e., stimulus-response relationship), such as the playing strategy and decision-making that is involved in the real-world task (Lathan et al., 2002). For example, a player in a competitive game of table tennis requires concentration (stimulus) and quick decision making (response). The underlying level of physical fidelity and cognitive fidelity should be evaluated as a potential factor affecting outcomes.

An additional factor that might influence the effectiveness of transfer are the characteristics of the sport trained. Broadly speaking, sports can be categorized into open and closed skills. Closed skill sports are defined as sports that involve a predictable, consistent and self-paced environment (e.g., cycling, golf, skiing) (Wang et al., 2013). Contrastingly, open skill sports are defined as sports that require players to engage in an unpredictable, constantly changing and externally-paced environment (e.g., soccer, cricket, rugby) (Wang et al., 2013). For example, having opponents or teammates can change the pace and predictability of sport interactions. Hence, a player must rely on open skills and their ability to quickly adapt to external changes in the competitive sport environment. Wang et al. (2013) suggest that open skill sports typically require athletes to exhibit greater flexibility in visual attention, decision making and action execution. An interesting question is thus whether the effectiveness of VE training differs between open and closed skills sports.

The aim of this review is to synthesize the evidence for the effectiveness of virtual environments as a tool to train real-world motor skills in sports. Although VEs offer potential as a tool for sports training, it is necessary to first establish whether VEs are an effective tool to improve real-world skills by reviewing articles that demonstrate real-world transfer. Factors related to the study design, learner's characteristics and training environment have been proposed to impact the transfer of trained skills. An investigation of these factors can add to both theoretical and practical knowledge to maximize the effectiveness of training in VEs for improving real-world sport skills.

METHODS

Search Strategy

The preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines were followed throughout the review process (Liberati et al., 2009). A literature search was performed on February 16, 2019, using the following databases: PsycINFO, SportDiscus and IEEE Explore. For all mentioned databases, the following search was conducted: [("virtual reality" OR "virtual environment") AND (sport* OR "motor skill*") AND (transfer OR learn* OR train*)]. Psychology, sports and engineering databases were used to cover the scope of this review, regarding transfer, sport and virtual technology.

Inclusion and Exclusion Criteria

Each article in this review must have included a VE and an assessment of real-world sports performance before and after VE training.

To have been considered a VE in this review, it must have included all the following components: (i) display or projection of an image e.g., head-mounted display (HMD) or Cave Automatic Virtual Environment (CAVE) or Powerwall; (ii) interactivity within the environment is essential via tracking of the user's movements; (iii) provision of sensory feedback (e.g., visual, auditory or haptic); (iv) software to render three-dimensional depth cues (Gray, 2017).

The definition by Oxford Dictionary of Sports Science and Medicine for sport was used in this review, "an activity involving physical exertion and skill in which an individual or team competes against another or others" (Kent, 2006).

An assessment of transfer must have included a group to control for basic practice effects and a measure of far transfer to assess the effect on real-world performance. These are the most basic elements necessary to assess transfer.

Only articles published in English were included, inclusive of articles from any year of publication. Each study must have included a healthy population. Articles were excluded in the review if a child or clinical sample were used and if it were not an original peer-reviewed research paper, such as a conference paper, dissertation or review.

Article Selection

Two reviewers completed the article selection and screening process in this review. Covidence (2018) was used throughout the screening process to manage articles. Titles and abstracts were screened to identify studies that appeared eligible for inclusion. Full-text articles were sourced and read for articles that appeared eligible, or for which eligibility could not be determined. During full-text reading, articles were either included in the review or excluded with reasons based on the criteria, listed in **Figure 1**. Additionally, reference lists of included articles were scanned for additional articles and entered the start of the review process. If a conflict arose during any stage during the article selection and screening process, the reviewers resolved the dispute via discussion; until consensus was reached.

Data Extraction

Data extracted from selected studies included: major findings, participant demographics, factors regarding the study design, learner characteristics and training environment. To determine the level of physical and cognitive fidelity in each study the two reviewers reached a consensus based on the information provided in the article.

RESULTS AND DISCUSSION

A total of 456 articles were selected for initial screening according to PRISMA protocol (Liberati et al., 2009). After removal of eight duplicates, 448 articles remained for screening. After screening titles and abstracts, 38 articles met inclusion criteria and were selected for review. Thirty four articles were excluded with reasons provided in **Figure 1**. In total four articles were included in this systematic review. A summary of the key characteristics and relevant findings of each of the included articles is included in **Table 1**.

Description of Studies

Of the four articles included in this review, one reported multiple experiments (Todorov et al., 1997), resulting in a total of five studies included in the review. Out of the five studies there is a combined total of 189 participants. The earliest studies were

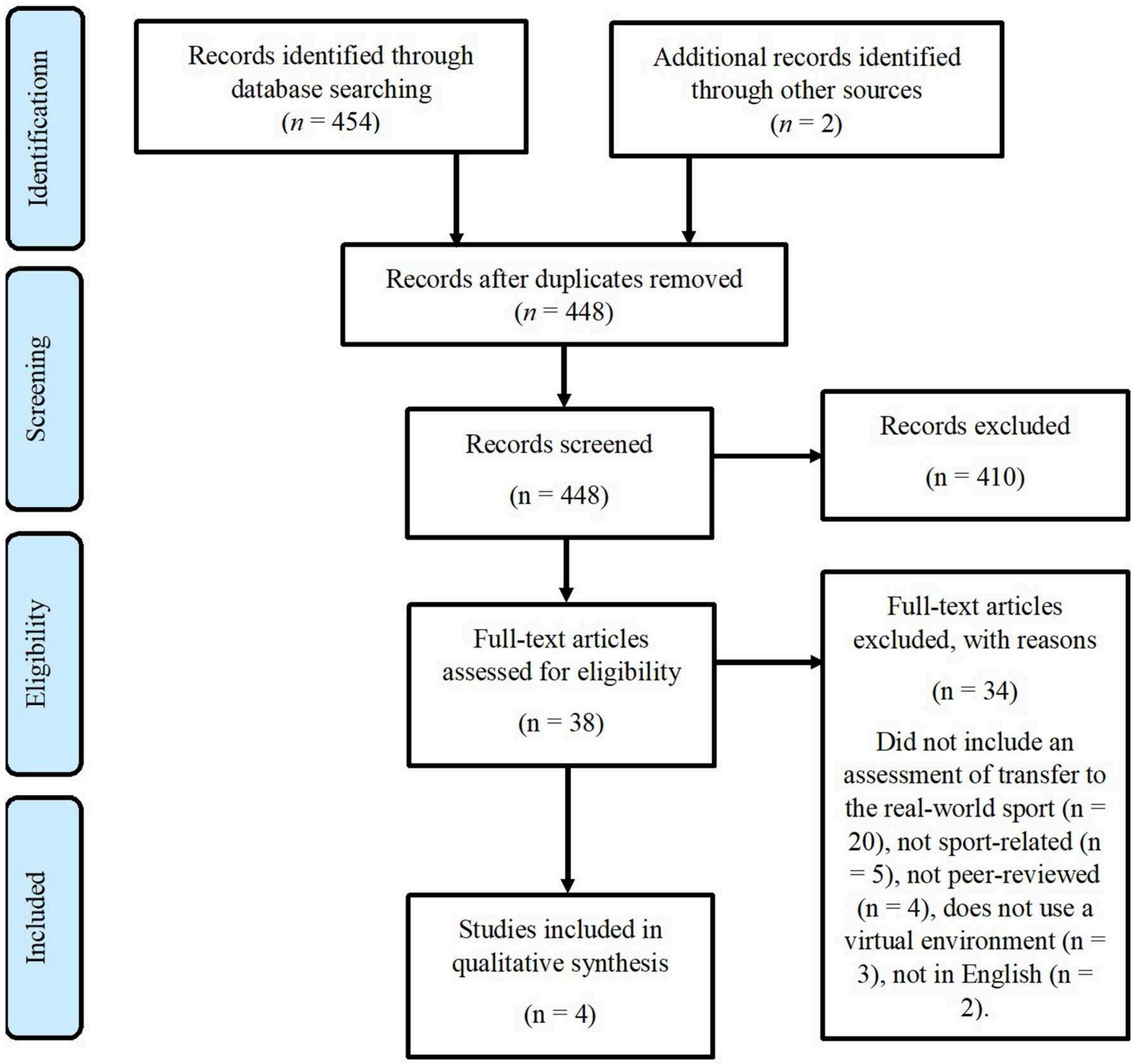

FIGURE 1 | The article selection and screening process using the PRISMA flow diagram (Liberati et al., 2009). Databases searched included PsycINFO, SportDiscus via EBSCOhost and IEEE Explore.

published in 1997 (Todorov et al., 1997), while the remaining studies were published between 2013 and 2017. In the five studies included in this review, sample sizes ranged from 8 to 80. The length of the VE intervention varied between studies. The longest time spent training in a VE was reported as a total of 9 h (Gray, 2017), while the shortest time reported was 10 min (Experiment 1) (Todorov et al., 1997). Two studies did not specify the length of VE intervention.

While there are only four articles included in this review, there is an abundance of research assessing sports training in a VE (Bideau et al., 2003; Croft et al., 2011; Zaal and Bootsma, 2011; Marchal-Crespo et al., 2013; Miles et al., 2013), although these studies demonstrate an improvement in the VE-based sport task, the researchers do not assess the impact that the training had on real-world performance. A measure of real-world performance is essential in determining the benefit and value of the training. Notably, 20 out of 34 studies were excluded during full-text screening as they did not include a measure of far transfer. These elements are the minimum requirements to assess VE transfer in sports, yet only five studies in four articles met this search criteria.

Out of the five studies included in this review, a total of four different sports have been assessed, including darts (Tirp et al., 2015), rowing (Rauter et al., 2013), baseball (Gray, 2017) and table tennis (Todorov et al., 1997). In this review, all sports were eligible for inclusion. Thus, it may surprise that only four different sports assessed far transfer. A key reason for the limited number of sports might be that with the current state of technology, VEs are not ideal training platforms for all sporting interactions, particularly for in-water and interactive multi-player activities. The high costs for creating VEs with high levels of realism combined with uncertain VE training benefits may have been another reason for a slow uptake of

TABLE 1 | Summary of included articles.

Authors	Gray (2017)	Rauter et al. (2013)	Tirp et al. (2015)	Todorov et al. (1997)	
				Experiment 1	**Experiment 2**
Participants	$n = 80$ Age: 17–18 Sex: Male = 80, Female = 0	$n = 8$ Age: 28–45 Sex: Male = 4, Female = 4	$n = 38$ Age: ($M = 25.2$) Sex: Male = 26, Female = 12	$n = 42$ Age: N/A Sex: N/A	$n = 21$ Age: N/A Sex: N/A
Sport	Baseball batting	Rowing	Dart throwing	Table Tennis	Table Tennis
Level of experience in the sport being assessed	Intermediate. Participants were baseball players who played competitive high school baseball in the United States at the time of training	Intermediate. Participants were recreational rowers without competition experience and complete <2 h of training per week	Novices. All participants were inexperienced in dart throwing	Novices. Information regarding participants table tennis experience was not specified	Novices. Information regarding participants table tennis experience was not specified
Task in VE training	Hit virtual baseball with a real baseball bat	Training co-ordination of body movement and handling oars	Throwing darts at a bullseye	Returning shots and hitting targets	Returning shots and hitting targets
Measure of real-world sports performance for pre- and post-test	Hitting real baseballs via pitching machine	Quantitative biomechanical performance measures and qualitative video evaluation	15 throws at a dart board	50 attempts to hit targets on a real-world table tennis table	50 attempts to hit targets on a real-world table tennis table
Virtual technology used in the study	LCD screen placed in front of the participant. The VE projected an incoming baseball, pitcher and the playing field	A custom-built rowing machine was placed in a CAVE display	A dartboard was projected on the wall and Xbox Kinect sensors were used to track participant's actions	Participants stood next to a computer screen that simulated a table tennis table, moving paddle and ball	Participants stood next to a computer screen that simulated a table tennis table, moving paddle and ball
Length of VE intervention	9 h	3 h, 20 min	Did not report	10 min	Did not report
Research Designs	Experimental (between-subjects)	Experimental (between-subjects)	Experimental (between-subjects)	Experimental (between-subjects)	Experimental (between-subjects)
Groups in study	1) Adaptive training in VE; 2) Extra batting sessions in VE; 3) Extra batting in real-world; 4) No training.	1) VE training; 2) Real-world training (on open water).	1) VE training; 2) Real-world training; 3) No training.	1) VE training; 2) Real-world training (coaching).	1) VE training; 2) Real-world training (extra practice).
Real-world sports performance significantly improved pre-post virtual training	Yes	No	Yes	Yes	Yes
VE training group significantly improved in comparison to a control group receiving no training.	Yes	N/A	Yes	N/A	N/A
VE training group significantly improved in comparison to a control group receiving real-world training.	Yes	No	No	Yes	Yes
Physical fidelity	High	Moderate	Low	Low	Low
Cognitive fidelity	Moderate	Low	Moderate	Low	Low
Open or closed skill training	Closed	Closed	Closed	Closed	Closed
Adaptive training	Yes	No	No	No	No

M, Mean; SD, Standard Deviation; N/A, Not available.

VEs across sports. It is noteworthy, however, that the included studies comprised rather distinct simulations (e.g., darts and rowing). Although many of the sports in this review were comparably different, important comparisons regarding the study design, learner characteristics and training environment can be made.

Study Design

The findings from studies assessing real-world performance improvements after VE-based training from pre-test to post-test, compared to no-training and compared to real-world training are considered in turn. Four out of five of the studies included in this review found that VE-based training led to a significant improvement in real-world performance from pre-test to post-test, as illustrated in **Table 1**. Though, considered by Abernethy and Wood (2001), to effectively assess transfer of training, studies need to include controls to rule out basic practice effects.

Two out of two studies found that training in a VE led to a significant improvement in real-world performance in comparison to a control group receiving no-training (Tirp et al., 2015; Gray, 2017). All available (however, limited) evidence suggests that VE-based training can enhance real-world performance compared to no training. This supports the growing interest in using VEs as a tool for training, especially as a complementary tool for when training in the real world is logistically difficult, dangerous or impractical to organize. While all current findings suggest that VE-based training improved real-world performance relative to no-training, it was found in three out of five studies that the amount of real-world improvement was significantly greater following VE training as compared to real-world training. Whether these findings are positively skewed due to a file drawer problem cannot be answered in this review.

Assessing transfer in a sport can be challenging when there are various aspects of sports performance to consider. Our results support the notion that motor skills can be improved after VE training. Although positive transfer was found in most studies, often the assessments utilized were narrow, involving trivial performance tasks to assess real-world performance. Todorov et al. (1997) found mixed effects in their study, as while target accuracy improved after VE training it was also found that their technique degraded. This highlights the importance of obtaining a comprehensive assessment of sports performance which future studies could consider to understand the true impact of the VE training.

Gray (2017) was the only study included in this review that assessed the impact of VE-based training in a competitive setting. In this study, 80 competitive baseball players were used (Gray, 2017). Each participant's league batting statistics (as assessed by on-base percentage) for the season following the training and their level of competition reached at a 5-year follow up was assessed. After training in a VE, participant's real-world batting performance and level of competition reached at the 5-year follow up were significantly higher when compared to groups that received no training and real-world training (Gray, 2017). These findings demonstrate the positive real-world implications that VE-based training can have in terms of athletic development and achievement in real competition with athletes of an intermediate level of experience. More comprehensive research is required, analyzing changes in real-world competitive situations which would provide further insight into the benefits that VE training can have on performance.

Learner Characteristics

Sackett et al. (1998) proposed that learner characteristics affect transfer outcomes. For example, it has been found by numerous researchers that people with higher cognitive ability are better able to process and retain information in training (Colquitt et al., 2000; Velada et al., 2007; Grossman and Salas, 2011). However, none of the studies included in this review directly assessed learner characteristics such as cognitive ability, motivation and personality.

Two studies included participants with an intermediate level of experience in the sport being assessed (Rauter et al., 2013; Gray, 2017), while the remaining studies assessed novices. The skill level of the individual and the difficulty of the task in training are essential in the promotion of skill learning (Guadagnoli and Lee, 2004). Termed the challenge point framework, Guadagnoli and Lee (2004) propose that training is optimal when the level of challenge is relative to the skill level of the performer. Adaptive training is based on this concept, where the level of difficulty is suitably matched to the individual's level of success during training.

Gray (2017) investigated transfer of training from virtual to real-world baseball batting in athletes with an intermediate level of experience. A group that received adaptive training in a VE was compared to groups that received repetitive batting practice which involved hitting balls of the same speed and trajectory as released by a pitching machine (irrespective of the user's skill level) in both the real world and in a VE. In the VE adaptive training group, factors such as pitch speed and spin would regularly increase based on success or alternatively, decrease based on failure. Gray (2017) found that when training was adaptive (as constantly adjusted to the performer's skill level), it resulted in significantly greater improvements in real-world performance as compared to both groups that received the repetitive practice (in both the virtual environment and in the real world).

VE training has found to be most beneficial when taking advantage of the simulation to devise methods of training (i.e., adaptive training) which are difficult to implement in the real world. Gray (2017) attributed the improvement in the VE adaptive training group to the combination of ball types (i.e., speed, spin and trajectory) which is more realistic to the range of conditions players face in real-world gameplay. Perhaps, the added value is in being able to take advantage of the flexibility of VEs, rather than simply trying to recreate training in the real world. However, Gray (2017) is the only study included in this review to have assessed the effect of adaptive training as compared to other forms of training and more research comparing training forms are needed.

Training Environment

The degree of physical fidelity and cognitive fidelity in the VEs varied considerably in each of the included studies. It might seem that the more similar the VE is to the real world the better the transfer of training (Miles et al., 2012). Yet, this review found that even simple displays and tasks were found to be beneficial, suggesting that perhaps a high degree of detail is not necessarily crucial to the success of skill acquisition. While Hochmitz and

Yuviler-Gavish (2011) proposed that a high level of cognitive and physical fidelity is essential to the success of transfer of training, the results from this review suggest that fidelity is not a vital component to the overall success of transfer. It is important to note that fidelity may still potentially be an important factor in promoting transfer, however, no studies in this review had directly manipulated fidelity in training.

Although the level of fidelity may not be vital, fundamental differences in VEs compared to the real world could lead to negative transfer. In the case of Rauter et al.'s (2013) rowing study, participants in the VE training group showed an offset in their oar handling skills as compared to a real-world (on water) training group. In terms of biomechanical measures the VE training group degraded in 35%, stayed indifferent in 50% and improved in 15% (Rauter et al., 2013). In terms of a qualitative video analysis, the VE training group degraded in 21.4%, stayed indifferent in 53.5% and improved in 25% (Rauter et al., 2013). Perhaps if the training environment is too dissimilar to the real-world environment (e.g., lack of resistance while rowing in water) the training can lead to negative skill transfer. In the case of Todorov et al. (1997) study, the training task was uncharacteristic to the real-world task as participants had to focus on a computer screen while trying to connect with a ball and hit a target on a real table. In this study, negative transfer also occurred perhaps as participants performed a specific movement noticeably different to what occurs in the real world.

All the studies included in this review trained sports as closed skills, as conducted within a stable and predictable environment, unaffected by the presence of an interactive opponent or externally-paced condition. Tirp et al. (2015) studied transfer of dart throwing in a VE, which is a sport that utilizes closed skills by nature. However, the method that the remaining studies have used to study rowing (Rauter et al., 2013), baseball (Gray, 2017) and table tennis (Todorov et al., 1997) have also been assessed as closed skills, which is different to how they are played in real-world competition.

Due to the realism and flexibility of VEs, users can immerse in various game-like interactions among the presence of opponents and/or team members. Yet, to date, no studies have assessed the transfer of open skills to the real world (after training in a VE) to a control group. Wang et al. (2013) suggest that open skill sports require athletes to exhibit a higher level of concentration and speed in response, relative to athletes in closed skill sports. However, the value of VEs in open skill situations is unknown as sports which require interactive actions are likely to differ from static (closed skill) sports.

Streuber et al. (2012) tested this assumption as participants performed table tennis strokes in a VE while viewing an interactive virtual opponent and responding to their hits. Having the ability to see an opponent's body and their paddle was found to improve decision-making and preparation in their own stroke response (Streuber et al., 2012). This study was not included in the present review based on the absence of a measure of real-world sports performance. However, these findings suggest that there is value in VE-based training to train open skills, as it was found that people can improve by observing an opponent's movements and adapting to unpredictable responses in a VE (Streuber et al., 2012).

For the two studies which included participants with an intermediate level of experience, there is a rationale for training involving open skills. However, in consideration of the four studies in this review which used novices, there is basis for training involving closed skills. This is based on the consideration that learning the fundamentals (i.e., basic strokes and movements) in a competitive (open skill) environment might not be ideal for a novice. Future research is needed to investigate further if the open-closed factor in VE training is more so dependent upon the stage of learning of the player, and the skill set that is intended to be trained.

SUMMARY AND FUTURE DIRECTIONS

In this review, we evaluated peer-reviewed research measuring the effectiveness of using VEs to improve real-world motor skills in sports. Collectively the evaluated studies support the notion that skills training in a VE can improve real-world sports performance. Notably, studies like Gray (2017) using complex adaptive training strategies show large real-world performance improvements thus demonstrating the potential value in VE based programs. VEs provide users with the flexibility to conveniently practice a wide range and number of skills, though this flexibility has not been entirely explored.

Few studies measured transfer and even fewer studies met the basic criteria for measuring real-world transfer. As a result, there was a lack of consistency regarding study design factors including

TABLE 2 | Summary of factors to consider when assessing transfer of training from a virtual environment to the real world.

Factor	Explanation
Real-world assessment	An assessment of real-world performance on a task related to the one performed during VE training, both before and after training
Control group	A group which completes either no training or another form of VE training must be included to control for basic practice effects. A real-world training control group is needed if the goal is to compare the effectiveness of VE and real-world training. A no-training control group could be utilized to assess if VE training is greater than no training and to determine the minimal detectable change
Random allocation of participants	Random allocation of groups is essential to counter bias during the selection of the different groups
Blinding of assessor	The real-world assessor should remain blinded, meaning unknowing of which condition each participant has been assigned to limit bias during an assessment
Comprehensive assessment (additional)	In addition to pre- and post-assessments, other skills should be considered including performance under competitive conditions, such as in-game statistics for athletes involved in amateur/professional competitions

the VE technology, length of the VE intervention, real-world performance measures and the presence or absence of a control group. As these factors were categorically different between studies it made comparisons and recommendations difficult. This limitation suggests that there is an immense need for such research, particularly for researchers considering VE training or companies developing VE-based training programs. Several companies' (such as STRIVR Willage, 2017, EON Sports, Beyond Sports, LucidCam and NeuroTrainer) market custom VEs and may make claims about the benefits of sports training in a VE, however, there is very little publicly available data supporting real-world improvements from VE sports training programs.

While there is some evidence that more basic closed skills are transferable from VE to the real-world, it remains to be established to what degree the current VE technology can be used to develop the more complex open skills. Researchers should consider introducing more competitive elements to training programs, such as opponents or teammates that match real world competitive environments. Including elements that mimic a real world competitive environment could further enhance open skills development. Some VE experiences aim to train open skills and incorporate an element of unpredictability, for example, interactions with an artificial intelligence opponent (Streuber et al., 2012). What is lacking, however, is controlled research studies that demonstrate transfer of open skills to the real-world.

Achieving an accurate in-game real-world performance assessment would be more challenging as the assessor/s would have less control over the events during gameplay. For example, in a football game with various opponents and teammates a player's performance is likely to vary to some degree on each occasion due to the interactions from both opponents and teammates. One approach that has been used successfully to analyse real-world performance was Gray (2017) whereby participants' league statistics and level of competition was assessed 5 years post VE training. Additional factors such as a player's in-game performance statistics and league rankings over a period of time can provide a more comprehensive overview though this can be both costly and time consuming.

There are a multitude of possibilities that may account for the limited number of studies measuring real-world transfer from a VE. Transfer is not a new term, but high quality VEs that have the capability to be used for sports training is still a relatively novel concept. One possibility is that research has not yet caught up with the influx of new virtual reality devices entering the consumer market. Another possibility is that assessing transfer of training has not been a research priority as some VEs have been developed as pure recreational games (e.g., Eleven: Table Tennis VR; developed by Fun Labs). Furthermore, some types of sports (e.g., water and interactive multiplayer sports) are costly and difficult to simulate with the current state of the technology. For a wider uptake of VE in sports training, it is important that real-world transfer is demonstrated. We have summarized important factors for measuring real-world transfer in **Table 2**. Researchers that may be interested in using VEs as a tool for training could incorporate these factors in their study design or build upon this research.

AUTHOR CONTRIBUTIONS

SM and AS: article selection and screening, writing, and analysis. TL: writing and analysis.

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OPINION
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Taking the First Steps Toward Integrating Testing and Training Cognitive Abilities Within High-Performance Athletes; Insights From a Professional German Football Club

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INTRODUCTION TO EXECUTIVE FUNCTIONS

Executive functions (EFs) are higher-level cognitive functions which refer to the family of top-down mental processes that sub serve goal-directed behavior (Miller and Cohen, 2001), and are relevant in situations that require a fast and flexible adjustment of behavior to the changing demands of the environment (Zelazo et al., 2003). There is a general agreement that the three core EFs are: inhibition, working memory, and cognitive flexibility (Diamond, 2013). Previous research has proposed that EFs play an essential role in sport, connecting successful athletes with greater cognitive abilities (Jacobson and Matthaeus, 2014). Therefore, academics and practitioners alike are implementing EF testing batteries as an additional measure of performance. During the planning and implementation of EF assessments, there are obstacles that may be encountered by practitioners and coaches throughout all levels of play (i.e., amateur to professional leagues), such as the choice of assessments, the financial and opportunity costs, how to convey the data into meaningful results to the team, and what assumptions can currently be made from the data that is supported by research. By using the experience that we have gained by testing and training EFs for over 5 years at a professional 1st division football (Association Football) club in Germany, we aim to share our opinion on how to tackle these issues. We also aim to discuss the remaining barriers in EF research in hope of having more researchers and practitioners working together to collectively overcome them.

SETTING UP A PROTOCOL

The choice of assessments is the foundation that all future assumptions are based upon, and it is recommended to have a test measuring each EF independently. However, a large hurdle that clubs will inevitably encounter is the financial cost of implementing new assessment tasks. Despite some companies marketing their cognitive testing for upwards of $30,000 (i.e., CANTAB), this does not mean that cognitive batteries should only be implemented by the teams with larger budgets. Assessments such as the Design Fluency task to assess cognitive flexibility, and the

Digit Symbol Substitution task to assess working memory can both be completed by pen and paper, whereas the N-back task to assess working memory and the Stroop Task to assess response inhibition can be created using PowerPoint. Furthermore, establishing mutualistic relationships with universities can provide opportunities for teams to either use the psychological tools owned by the university in exchange of participants' data for research purposes, and/or to help develop their own EF assessments.

DATA COLLECTION

Our club assesses every players' EFs once during the pre-season and once halfway through the season. We further recommend collecting contextual information about each player such as: birthdate, birth quartile and birthplace, intelligence quotient (IQ) or a similar academic grading score, history questionnaires on their years of experience playing both their main sport and any additional sports participation, and hours of training per week both in structured and unstructured playing environments (Mann et al., 2017). Contextual information can help improve our understanding of whether high-level athletes display better EFs than their lower-level and non-athletic counterparts because they were either born with greater cognitive abilities (i.e., nature), or whether their higher cognitive abilities are sport/environmentally-induced (i.e., nurture; Scharfen and Memmert, 2019).

COMMUNICATING THE RESULTS

Measuring EFs requires multiple complex assessments in a psychological domain and ensuring that the results are understood by the intended audience can be difficult (Eisenmann, 2017). Some strategies have been recommended in the literature. For example, Sakamoto et al. (2018) created a composite score by changing the results of each individual test into a *z*-score and then adding the z-scores together. In a practical sense, the idea of creating a single number that encompasses different scales for each variable can make the results easier to interpret and can be relatively easy to implement. However, caution should be taken in this approach as it may under-power the changes for each test. A more complex method that this club developed is an "EF sum score," which combines all results into one total value (Beavan et al., 2019). **Figure 1** displays the practicality of the sum score to provide a smoother translation of the relevant results to the intended audience (Buchheit, 2017).

WHAT INFERENCES CAN CURRENTLY BE MADE FROM EF RESULTS?

We evaluate our players' EF performance relative to their age group norms. However, there is a high variation between players on EFs across each age group, and this has similarly been reported in another study (Sakamoto et al., 2018). Our practitioners report that players who are the true elite academy players that

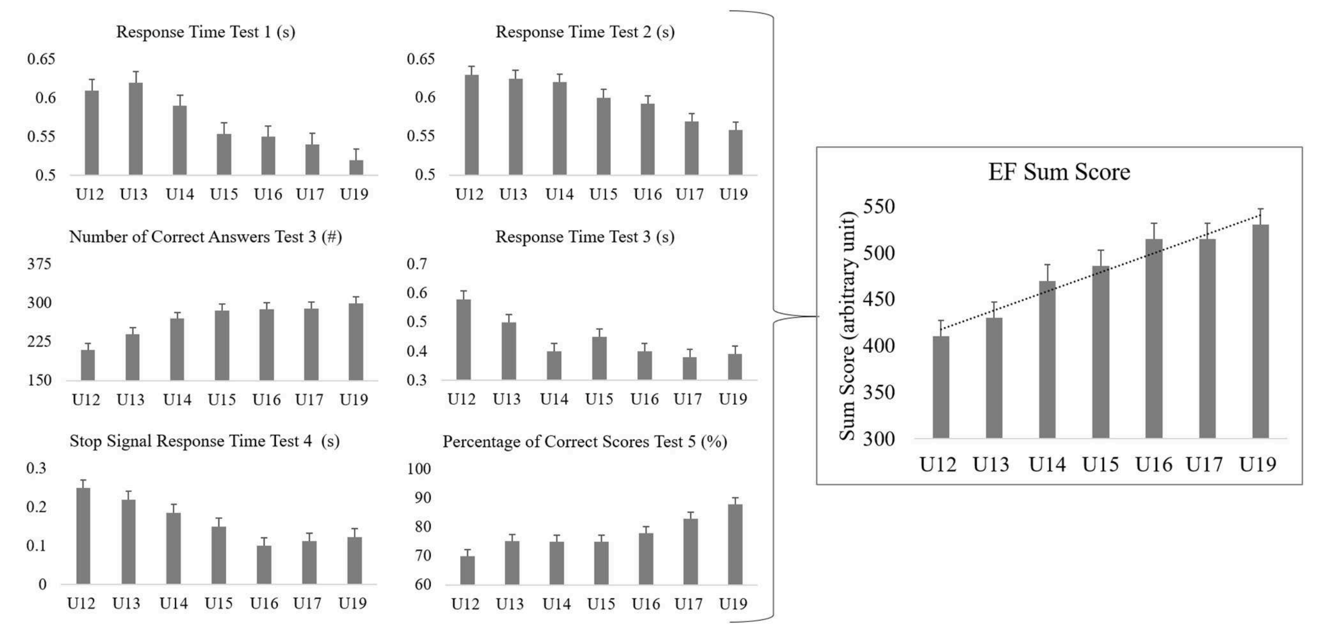

FIGURE 1 | Mock data demonstrating how the results from individual assessments with various units can be combined in one summary graph. Values were normalized and then used in a two factor analyses to develop a total executive function sum score (EF sum score) for all players. A new EF variable was developed using each individual item's factor loading as a weighting system, so each change in one unit of performance was equal across each assessment. Our equation unique to our assessments (and serves only as an example) are: EF sum score = (0.720*Response Time Congruent Inverse) + (0.699*Response Time Incongruent Inverse) + (0.756*Determination Test Number of Correct Answers) + (0.828*Determination Test Response Time Inverse) + (0.853*SSRT Inverse) + (0.766*Response Inhibition Time Inverse).

yield the potential to make it to the adult professional level are also the players who are outperforming their age-group in the EF assessments, and the variation is caused by the many athletes that do not yet hold this "elite" status amongst coaches. Longitudinal data is needed in order to support this standpoint, but an interesting next step is to relate EFs to a panel of coaches' ratings of skill and potential of each player to reach the professional level rather than their age. Furthermore, various levels of motivation may influence the attainment of scores across the battery, specifically in EF assessments where athletes may be disinterested in performing non-sport specific testing. Although this remains difficult to account for, the underlying principle is that practitioners should consider the subjective contextual variables when interpreting their team's EF results. Variables such as the presence of a coach, motivation, players' contract situations, wellness, and whether the participants understand why they are doing the assessments all may influence the test results (Stiroh, 2007); but these variables have remained difficult to account for objectively in scientific research that may help explain the observed variance.

Despite these obstacles, a recent meta-analysis reported that a positive finding exists regarding the importance of EFs in football (Scharfen and Memmert, 2019). Higher-level athletes demonstrated better EFs than lower level athletes, and it has therefore been advocated that EF testing could play a role within the talent identification process (Huijgen et al., 2015; Sakamoto et al., 2018; Montuori et al., 2019). Yet additional research outside of football did not confirm the generalization of better EFs linked with expertise, where no differences between different levels of expertise in tennis (Kida et al., 2005), ice hockey (Lundgren et al., 2016), or basketball (Nakamoto and Mori, 2008) were reported. Therefore, there is a lack of agreement in the literature on whether EFs as a prognostic tool for football talent has practical validity. Albeit, previous research has attempted to understand if EFs could help identify talent. For example, Sakamoto et al. (2018) reported that players who were accepted into an academy exhibited better EFs than players who were rejected. Yet we need to assess whether these statistically significant differences are also practically relevant. The between-group difference on a Stroop task was on average +3 correct answers out of 100 (rejected group: 31.3 ± 9.6; approved group: 34.5 ± 8.6; $p = 0.001$; effect size = 0.35). In other words, the groups that were accepted and not accepted into the academy overlapped by about 86% (Magnusson, 2014). Although the differences reached statistical significance, whether they are large enough to help a coach distinguish between a player that should be accepted or rejected from an academy remains questionable.

To date, longitudinal studies in athletic populations are lacking, leaving only weak generalizations of the EF developmental trajectories from existing longitudinal studies in general populations. Therefore, longitudinal research is needed to understand if assessments of EFs are able to help practitioners predict talent in young athletes. For example, does assessing EFs have more value to help in the detection of potential talent from a heterogenous cohort that does not yet compete at a high-level (i.e., a large group of school kids), or in the identification of the best performers within a homogenous cohort of already competing athletes (i.e., high-level academy players likely to become adult-professionals)? Currently, no study has yet to demonstrate that athletes with higher EF scores become more successful in their sport.

COGNITIVE TRAINING

The cognitive training approach stems from the "broad training hypothesis" which states that training basic cognitive skills could improve EFs and would therefore translate into better performances when utilizing EFs (Walton et al., 2018). For example, 10 sessions of cognitive training in a laboratory improved football players' on field passing decision-making accuracy by 15% (Romeas et al., 2016) and Ducrocq et al. (2016) reported the possibility to enhance sporting performance by improving the inhibitory control of tennis athletes. Importantly, there remains a large debate on whether training with computer-based cognitive tasks can broadly transfer into real-world performances. An extensive review by Simons et al. (2016) conveyed that no compelling evidence currently exists showing a true positive transfer of cognitive training interventions to real-world tasks. Recently, Harris et al. (2018) mentioned that although the lack of evidence across the literature is not an encouraging sign that it would work for athletes, only one study directly examined the benefits of a cognitive training program on sporting transfer task. Seemingly, if academics and practitioners are wanting to overcome this paucity of knowledge directly in sport, they are recommended to read Walton et al. (2018) who provides recommendations of how to best explore the link between cognitive and sporting abilities.

It is important that if clubs decide to invest in training EFs, the staff should further discuss both the financial cost of purchasing the equipment and the opportunity cost of spending the time and money on a different task (Simons et al., 2016). In order to reduce the opportunity cost, we emphasize the importance of cognitive training toward players who are: (i) regressing from their previous EF scores, (ii) wanting to engage in cognitive training, (iii) injured, and (iv) scoring in the lowest third within their age norms. The reason behind training players who performed in the lowest third is based on previous non-sporting literature reporting that a threshold effect may exist with natural abilities and expertise, where any improved ability beyond the requirement to compete at a high-level (i.e., the threshold) may not further improve performance (Terman and Oden, 1959). Contrastingly, this also means that players who are under the threshold may yield the potential to enhance their performance by improving their EFs (Diamond, 2016). Diamond (2016) advocated that training EFs are important to the future success of individuals and should begin as young as possible; especially in individuals that yield the lowest scores to ensure that their deficiencies are not enlarged over the coming years. Although the threshold hypothesis is still relatively new when explaining the role of EFs in sport, it has been used to explain differential correlations between intelligence (i.e., IQ), creativity (Jauk et al., 2013), and future career achievement (Terman and Oden, 1959; Baird, 1985; Gagné, 2004).

CONCLUSION

Practitioners are commonly the first to apply and test new methods with science following in attempt to examine their practices. The measurement and training of cognitive abilities such as EFs are becoming a popular new approach in sporting clubs. However, with EF research being a relatively young area of research, the importance of EFs in sport remains widely unknown, and it remains unclear if the measurement and training of EFs are justifiable to help predict future talent. Pending further research, a current focus on EF development in the lower achieving athletes may be a more suitable use. Being well-informed of the scientific literature will help in overcoming the delicate balancing act between administering good scientific practice methodology and what is functional for the club with respect to the aforementioned hurdles of implementing the testing and training of EFs. Therefore, new research-practitioner relationships are a cornerstone to furthering our understanding of the role that EFs play in sport. Collectively, a promising opportunity exists to help overcome the limitations in the literature if research informed protocols are put in place with a purpose of improving the support toward the testing and training EFs.

AUTHOR CONTRIBUTIONS

AB, JS, and JM contributed toward the conception and ideas presented of the opinion piece. AB wrote the majority of the manuscript. JS wrote sections of the manuscript. All authors contributed to the manuscript revisions, read, and approved the submitted version.

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The Color-Word Stroop Task Does Not Differentiate Cognitive Inhibition Ability Among Esports Gamers of Varying Expertise

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This study set out for the first time to identify whether gamers of low, intermediate, and elite skill level in a prominent esports game, Counter-Strike: Global Offensive, demonstrated increasingly superior performance on a test of a specific cognitive skill (cognitive inhibition). Here we tested low, intermediate, and high ranked gamers and compared their performance on a color-word Stroop Task and also compared the performance of players in each gaming rank group to non-gamers. Contrary to our hypothesis, the Stroop Task did not differentiate significantly gamers of varying expertise. Although, we found that when considering both accuracy and response times, elite gamers performed significantly better than both intermediate and low ranked gamers on the simple choice reaction time condition and both elite and novice gamers performed significantly better than intermediate ranked gamers on the incongruent condition (a measure of cognitive inhibitory ability).

Keywords: Stroop, counter-strike:global offensive, esport science, cognitive control, action video games, FPS

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INTRODUCTION

Competitive video gaming, or esports (electronic sport), is a phenomenon that has grown dramatically over the past decade. From the development of professional gaming leagues, to the staggering numbers of spectators drawn to watching players compete, to the ever rising revenues every year, esports are solidifying their place in competitive sport culture (Wagner, 2006). Typically, sport involves the display of elite physical and cognitive skill in competition for entertainment purposes (Campbell et al., 2018). However, where traditional sports to a great extent rely on the development and performance of complex motor skills for success, gamers seem to rely more on cognitive skills (Himmelstein et al., 2017). As society continues to rely on digital technology for its entertainment, platforms such as twitch have revealed the immense popularity of watching elite gaming across the world. As we enter what may be the era of the cognitive athlete, the scientific investigation of esports must continue to grow.

Previous research on video gaming has debated numerous topics including the potential negative effects of action video gaming on behavior (Ferguson, 2007) and the effects of screen time on our physiology (Swing et al., 2010). However, a growing body of research has emerged demonstrating the benefits of video games for cognition. For example, a meta-analysis conducted by Bediou et al. (2018) demonstrated positive effects of gaming on cognitive abilities such as spatial memory, multi-tasking, and inhibition. Moreover, recent evidence has demonstrated that when compared to non-gamers, action video gamers display enhanced cognitive ability when evaluated using standardized cognitive measures of processing speed, visual search, and response inhibition (Kowal et al., 2018). However, despite the recent evidence in support of the effects of gaming on cognitive ability, no research to date has investigated whether superior cognitive ability is a hallmark of elite gaming performance.

Counter-Strike (now Counter-Strike:Global Offensive; CS:GO) is a first-person shooter computer game that has been one of biggest success stories for esports. Released in 1999, there have been a number of game releases prior to the current version and the game has been played professionally since 2012. In CS:GO, two teams of five players battle on a small map to either plant (terrorists) or diffuse (counter-terrorists) a bomb. Players are armed with weapons and while weapon proficiency is important, so are cognitive abilities like decision-making and response inhibition as friendly fire, an enabled feature of competitive CS:GO, makes recognizing the difference between friend and foe crucial for success. Despite the fact that anecdotally, elite players have a learned understanding of some of the important fundamentals to play CS:GO at a high level, gamers at all levels tend to practice very little on those specific abilities but rather, simply play more matches (Campbell et al., 2018). By better understanding the specific skills required for success in esports, players would be better able to comprehend the areas of strength and weakness in their performance, which has the potential to completely alter how esports athletes train and would align esports training with the type of training observed in traditional skill-based sports.

The purpose of this study is to identify whether gamers of low, intermediate, and elite skill level in a prominent esports game demonstrated increasingly superior performance on a test of a specific cognitive skill (cognitive inhibition). To address this purpose, we will evaluate the color-word Stroop performance (Stroop, 1935) among three groups of CS:GO gamers: those with low, intermediate, and elite level competitive game rankings. The Stroop Test is believed to measure a key cognitive inhibitory ability: response inhibition (MacLeod, 2007). Inhibition, traditionally considered as a critical component of executive functioning, is seen as the active suppression of task-irrelevant information from working memory, or the ability to inhibit an overlearned response (Strauss et al., 2006). We hypothesize that CS:GO gamers in higher ranking groups will demonstrate superior cognitive inhibitory ability compared to those in lower ranking groups evidenced by higher accuracy and faster response times, specifically on incongruent stimuli in the test.

METHODS

Participants

One hundred and twenty-nine CS:GO players (N = 129; 126 males, 3 females) were recruited from attendees at the 2018 Gamescom and PAX gaming conference in Cologne, Germany, and Melbourne, Australia, respectively. Each provided informed consent prior to voluntarily participating in the study. The Research Ethics Board at the University of Limerick authorized approval for the study in accordance with the Declaration of Helsinki.

Participants began by completing a survey that gathered demographic information regarding their age, sex, handedness, and color vision. It also gathered data regarding their gameplay, including the average number of hours per week they estimated they spent playing CS:GO and their current competitive CS:GO ranking. Following completion of the survey, participants sat in front of a computer with a 24-inch monitor, were instructed to wear headphones to reduce the volume of external noise, and asked to complete a Color-Word Stroop Test.

Stroop Test

The keyboard Color-Word Stroop Test used in this study was administered using Inquisit 4 software by Millisecond with the same test design used by Kowal et al. (2018). Participants were presented with either the word "red," "green," "black," or "blue" on a white screen in either red, green, black, or blue colored font. In Congruent trials, the printed word and the color in which it was printed matched. Incongruent trials were those in which the printed word on screen and the font color it was printed in did not match. In addition to Congruent and Incongruent trials, Control trials were also included and consisted of a colored box presented on screen. In total, seven trials of each of the four colors within each condition (84 total trials) were presented randomly to participants during the test (see **Figure 1**). In every trial, participants were instructed to respond to the color of the ink used to present the word or box on screen and not the written word on screen. Participants were instructed to respond as quickly and accurately as they could using the keyboard keys "d," "f," "j," and "k," which corresponded with answers red, green, blue, and black, respectively. To aid participants, the key bindings were indicated in 18% neutral gray ink along the top of the screen throughout the test (see **Figure 1**). For each trial, the response was recorded as well as the reaction time (RT), in milliseconds, between the presentation of the stimulus and the participants' response.

Participants' data were excluded from analyses if they were under 16 or over 35 years of age (n = 7), indicated they were colorblind (n = 8) or were left-handed (n = 13). As evidence exists suggesting a female advantage on color-word Stroop Tasks (Golden, 1974) and due to our inability to compare male and female performance (low female n), we also excluded the data from the three female participants from further analyses. We additionally verified that no difference existed between our gamers from the Gamescom and PAX gaming conferences for Stroop accuracy [Site: $F(1, 1{,}542) = 0.589$, $p = 0.443$; Site*Condition: $F(2, 1{,}542) = 1.434$, $p = 0.239$] and RT [Site: $F(1, 1{,}542) = 0.283$, $p = 0.595$; Site*Condition: $F(2, 1{,}542) = 0.010$, $p = 0.990$] measures. The remaining participants were categorized based on their in-game competitive ranking. In total, there are 18 competitive CS:GO rankings (see **Figure 2**). We grouped participants based on their individual CS:GO ranking into one

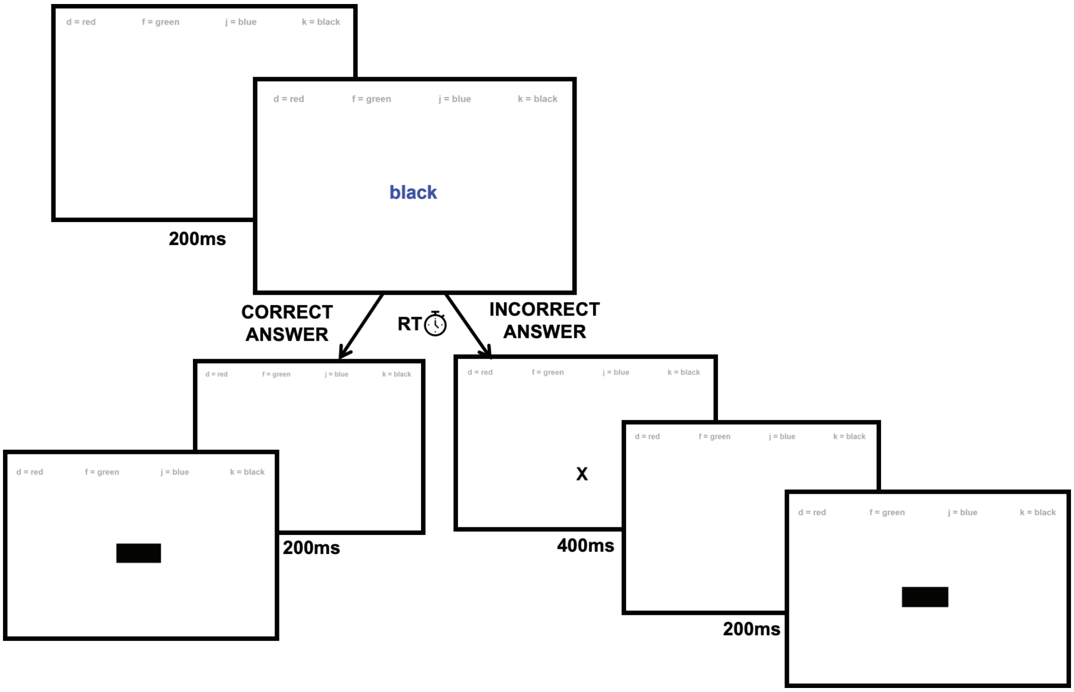

FIGURE 1 | Example trial for the Color-Word Stroop Test. Participants are presented with a control, congruent, or incongruent trial after a brief 200-ms baseline (top left). If a participant responds correctly (left), the next trial is presented in identical fashion. If a participant responds incorrectly, a brief 400-ms × is shown on screen (right) to provide feedback prior to the presentation of the next trial.

FIGURE 2 | The 18 current competitive skill rankings for first-person shooter esports game, Counter-Strike:Global Offensive (CS:GO).

of three Rank groups. The Low Skill group consisted of gamers with rankings from Silver 1 to Silver Elite Master (n = 12, Age = 19.42 ± 3.44; Mean ± SD). The Intermediate Skill group contained gamers with rankings from Gold Nova 1 to Master Guardian 2 (n = 26, Age = 20.46 ± 4.16). Finally, the Elite Skill group consisted of gamers between the Master Guardian Elite to The Global Elite rankings (n = 60, Age = 19.77 ± 3.84).

Although previous work has determined that action video gamers display enhanced cognitive ability compared to non-gamers, this work never compared non-gamers to gamers of a specific game nor has it evaluated whether only gamers of a particular ranking showed superior performance. In order to address these questions, we also included Stroop performance data from a group of non-gamers published in a previous study (Kowal et al., 2018) and compared the performance of the 29 male participants in this group (Age = 21.28 ± 2.05) to the performance of ranked CS:GO players. Data for trials across each participant were also excluded if the response time (RT) for that trial exceeded that participant's overall average by two standard deviations. The average (±SE) percent correct and average (±SE) response times are reported for each condition and each rank group.

Statistical Analyses

In order to compare Stroop performance between the three CS:GO rank groups, we conducted two-way ANCOVAs on both Accuracy (Number Correct) and Reaction Time (RT; milliseconds) dependent variables with Condition (Control, Congruent, and Incongruent) and Rank group (non-gamers, Low Skill, Intermediate Skill, and Elite Skill) as independent variables. We also conducted one-way ANCOVAs on Stroop Interference Accuracy and Reaction Time dependent variables with Rank Group as an independent variable. Here, Stroop Interference is calculated as the average difference score between color-matched Incongruent and Control stimuli. Previous work has demonstrated superior cognitive performance with greater time allocated to gaming (Kowal et al., 2018). Therefore, the average number of hours reported gaming per week by participants was used as a covariate in the ANCOVAs. *Post hoc* analyses were performed with Tukey's correction for multiple comparisons and significance was determined at an alpha level of 0.05. Descriptive metrics for rank groups and Stroop conditions are presented in **Table 1**.

RESULTS

Response Accuracy

Participants responded with accuracies of 94.4, 95.3 and 91.0% on Control, Congruent, and Incongruent trials respectively with response accuracy on incongruent trials being significantly poorer compared to those on control ($p < 0.001$) and congruent trials ($p < 0.001$). Although there were significant main effects for both rank group [$F(3, 1{,}434) = 10.298$, $p < 0.001$, $\eta^2 = 0.021$] and condition [$F(2, 1{,}434) = 15.823$, $p < 0.001$, $\eta^2 = 0.022$], there was a significant interaction between condition and rank group on response accuracy when controlling for the average hours per week participants gamed for [$F(6, 1{,}434) = 3.918$, $p = 0.001$, $\eta^2 = 0.016$]. *Post hoc* comparisons revealed that non-gamers were significantly more accurate than CS:GO gamers across all Stroop conditions (**Figure 3**). Also, while no difference in accuracy was found between CS:GO rank groups for Congruent trials, Intermediate ($p = 0.008$) and Elite ($p = 0.025$) ranked CS:GO players were significantly more accurate than Low ranked gamers in the Control condition. In the Incongruent condition, Elite ranked gamers were significantly more accurate compared to intermediate ranked gamers ($p < 0.001$) but not Low ranked gamers ($p = 0.723$) (**Figure 3**). A significant main effect for Rank group was also found when analyzing Stroop Interference [$F(3, 523) = 4.057$, $p = 0.038$, $\eta^2 = 0.016$] (see **Supplementary Figure S1**).

Response Times

A significant main effect of condition [$F(2, 1{,}443) = 13.49$, $p < 0.001$, $\eta^2 = 0.018$] was found and *post hoc* comparisons demonstrated that although participants responded to congruent and control trials with average latencies of 778.939 and 779.364 ms, respectively, they took significantly longer to respond to Incongruent trials (855.683 ms; $p < 0.001$). There was also a main effect of rank group [$F(3, 1{,}442) = 17.962$, $p < 0.001$, $\eta^2 = 0.036$] whereby non-gamers were significantly slower than gamers in all CS:GO rank groups (Low; $p < 0.001$, Intermediate; $p = 0.027$, Elite; $p < 0.001$) and Elite ranked gamers showed significantly faster response times compared to Intermediate ranked

TABLE 1 | Accuracy (number correct) and response time (RT) descriptive metrics for rank groups and Stroop Task conditions.

Rank group	Condition	Number correct	SD	SE	95% CI	RT	SD	SE	95% CI
Non-gamers	Congruent	6.80	0.49	0.08	6.65, 6.95	884.42	247.79	23.62	838.12, 930.72
	Control	6.86	0.38	0.08	6.71, 7.01	864.50	239.41	23.73	818.00, 911.00
	Incongruent	6.67	0.59	0.08	6.51, 6.83	941.79	232.53	25.28	892.24, 991.34
Low skill	Congruent	6.53	0.72	0.11	6.32, 6.74	730.55	240.60	32.23	667.38, 793.72
	Control	6.32	0.84	0.11	6.11, 6.53	748.67	230.80	32.24	685.49, 811.85
	Incongruent	6.36	0.93	0.11	6.15, 6.57	814.84	229.00	32.94	750.27, 879.41
Intermediate skill	Congruent	6.72	0.60	0.07	6.58, 6.86	789.35	216.01	21.65	746.92, 831.78
	Control	6.65	0.62	0.07	6.51, 6.79	785.38	216.46	21.34	743.55, 827.21
	Incongruent	6.05	1.26	0.07	5.90, 6.20	889.21	248.67	22.53	845.04, 933.38
Elite skill	Congruent	6.64	0.67	0.05	6.55, 6.73	719.95	214.48	14.36	691.80, 748.10
	Control	6.58	0.69	0.05	6.49, 6.67	727.02	190.82	14.37	698.85, 755.19
	Incongruent	6.40	0.82	0.05	6.30, 6.50	784.59	218.02	14.89	755.41, 813.77

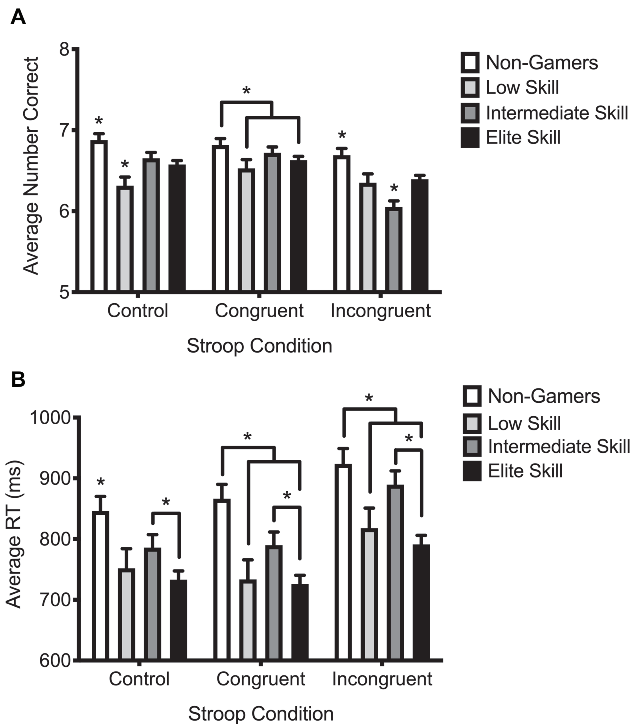

FIGURE 3 | Average number of correct responses **(A)** and average response latencies in milliseconds **(B)** for Non-Gamer (white bars) and Low ranked (silver bars), Intermediate ranked (charcoal bars), and Elite ranked (black bars) CS:GO gamers across Control, Congruent, and Incongruent Stroop conditions. Error bars represent ±SE. *indicates significant differences from all other bars unless asterisk brackets indicate otherwise.

gamers ($p < 0.001$). No interaction was found between condition and rank group [$F(6, 1{,}434) = 0.382$, $p = 0.891$, $\eta^2 = 0.002$]. Finally, no effect for Rank group was found for Stroop Interference [$F(3, 523) = 1.070$, $p = 0.361$, $\eta^2 = 0.006$] (see **Supplementary Figure S1**).

DISCUSSION

This study set out to identify whether gamers of low, intermediate, and elite skill level in a prominent esports game demonstrated increasingly superior performance on a test of a specific cognitive skill, previously suggested to be relevant for gaming performance. To do this, we tested gamers of the FPS game, CS:GO, on a standardized Color-Word Stroop Test and found evidence that elite ranked gamers show superior cognitive ability compared to lower ranked gamers. Specifically, we found that elite gamers have higher accuracy and faster response times for simple choice reaction time stimuli (control trials). However, contrary to our hypothesis, Stroop performance did not appear to differentiate cognitive inhibition among our three rank groups. Specifically, low and elite skill gamers performed better on incongruent stimuli compared to intermediate skilled gamers. These findings were also apparent when observing Stroop Interference measures. Finally, we corroborate previous work by demonstrating that gamers of all rankings prioritize speed over accuracy as a strategy when performing the Stroop Task (Kowal et al., 2018).

Traditional sport science, motor learning, and neuro-psychology research have demonstrated the importance of identifying and training the individual fundamental skills required for high performance (Mané et al., 1989; Boot et al., 2010; Conte et al., 2016). It is through the identification of an individual's competency with the many physical and cognitive skills required for elite sports performance that tailored training plans can be developed to more rapidly improve performance. In fact, this has been shown using a game developed for psychological research called Space Fortress (Boot et al., 2010). Previous research used this game to show that those players who practiced the individual skills of the game in isolation improved their in-game performance significantly faster and to a greater extent compared to those who spent their training time simply playing the game. In addition to improving individual performance, knowledge of the unique combination of strengths and weaknesses across skills for all players of a team allows for the development of superior strategies that utilize players to maximize strengths and mitigate the effects of weaknesses during matches. Currently, very little research to date has attempted to identify the crucial cognitive and physical skills associated with elite esports performance. Moreover, competitive players often cite their practice regimen to involve a steady diet of matches or scrimmages to improve performance with little to no objective approach to training the fundamental skills required for high performance at their chosen game (Hollist, 2015). As esports performance research grows and competitive franchises begin to identify player skillsets and alter training strategies to improve performance, we may observe a significant evolution in esports and the quality of play required to compete at a high level.

In this study, we focused on the cognitive ability of cognitive inhibition, which has been identified as a skill superiorly displayed by action video gamers when compared to non-gamers. However, previous research has often combined gamers of different action video game genres. Previously, Campbell et al. (2018) suggested that esports games or genres should be viewed separately from one another, similar to the differentiation of different traditional sports. Here, we examined the performance on a well-known and widely utilized cognitive inhibition task among a homogeneous group of gamers of the FPS game CS:GO and compared their performance to a non-gaming sample. The apparent importance of cognitive inhibition for CS:GO and first-person shooter games in general may be tied to the importance of this cognitive skill for military personnel (Irgens-Hansen et al., 2015; Makhani et al., 2015). The scenario where distinguishing between friend and foe and deciding quickly and accurately whether to engage a target occurs regularly during CS:GO matches and often has a significant consequence to the outcome of a match.

This research is the first to attempt to quantify the influence that an individual's cognitive skill has on differentiating players of different expertise level in a prominent esport. However, many more cognitive and physical abilities are likely to be important indicators of performance, and, by identifying the key skills and attributes that differentiate esports players of varying expertise, we may better understand how to develop training programs and in-game strategies to improve the probability of success for these individuals. To determine additional cognitive abilities associated with esports expertise, we may look to previous research that has identified specific cognitive abilities that are enhanced through gaming or which gamers show superiority with compared to non-gamers. For example, the meta-analytic work by Bediou and colleagues found that gamers were superior to non-gamers in the cognitive domains of inhibition, verbal cognition, perception, top-down attention, and spatial cognition (Bediou et al., 2018). These findings are supported by experimental work showing gamers possess enhanced spatial memory (Clemenson and Stark, 2015; Bonny et al., 2016) as well as visual attention and processing speed (Kowal et al., 2018) compared to non-gamers, but also that some of these cognitive aspects can be improved by gaming (Green et al., 2010; Boot et al., 2011; Green and Bavelier, 2012).

In addition to the cognitive skills that may mark performance, there remains a gap in esports performance science highlighting the physical skills and attributes that highlight expertise within different games. For example, it has been well established that elite players of the game *Starcraft* possess a unique ability to output a significantly higher number of actions per minute compared to low ranked players and non-gamers (Hotz, 2012). In CS:GO, players have highlighted skills such as "flicking" and "tracking" to be key mouse control skills allowing players to hit and kill targets with the greatest speed and efficiency. However, no research into the biomechanical and motor control skills displayed by elite esports players has been conducted to date and the area would immensely benefit from experiments that aim to quantify the magnitude of effect that different physical skills have on gaming performance.

Interestingly, among our sample of CS:GO players, we did not see that performance on the Stroop Task was better among individuals strictly in the higher ranking groups. Specifically, elite ranked gamers significantly outperformed intermediate ranked gamers but not those in the lowest rank group on incongruent stimuli. This may be due to the fact that the Stroop Task does not have the sensitivity to differentiate cognitive inhibitory ability among a homogeneous group of esports gamers or quite simply there were no cognitive inhibition differences in the first place among the groups. We encourage future work to investigate more aspects of cognition among esports players. Alternatively, the observed finding may be due to a differential influence that the many esports skills have on one's performance as they gain expertise in the game. For example, a lack of expertise across a number of mechanical skills using their mouse and keyboard may more strongly differentiate low from intermediate ranked players. In this way, low ranked players may be more largely differentiated during gameplay by their physical, rather than cognitive, ability. As mechanical skill develops and becomes less influential on overall ranking differences among intermediate players, perhaps cognitive abilities, such as cognitive inhibition, become more important and thus the main obstacle for those unable to achieve an elite ranking status. In order to address this hypothesis, we recommend future research to identify the likely many more cognitive and physical markers of esports expertise, particularly in FPS games, and establish the other skills that differentiate specifically low ranked gamers and those in both intermediate and higher rankings.

This study tested whether cognitive inhibition, the mind's ability to disregard stimuli that are irrelevant to the task at hand, and a known attribute of successful action video gaming could differentiate expertise among players of one of the most popular first-person shooter esports, Counter-Strike: Global Offensive. We encourage future research to continue toward the identification of the outstanding skills and characteristics underlying optimal esports performance. It is our hope that the current study helps to accelerate a new and emerging body of esports performance research that aims to revolutionize the methods used by gamers to train and prepare for elite competitive esports competitions.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Faculty of Education and Health Sciences (EHSREC), University of Limerick. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MC and AT conceptualized and drafted the article and revised it critically for important intellectual content; gave final approval of the version to be published; and were accountable for all aspects of the work. MK conceptualized and revised the study critically for important intellectual content, gave final approval of the version to be published, and was accountable for all aspects of the work.

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SUPPLEMENTARY MATERIAL

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MINI REVIEW
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Let the Body'n'Brain Games Begin: Toward Innovative Training Approaches in eSports Athletes

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The phenomenon of eSports is omnipresent today. International championships and their competitive athletes thrill millions of spectators who watch as eSports athletes and their teams try to improve and outperform each other. In order to achieve the necessary cognitive and physical top form and to counteract general health problems caused by several hours of training in front of the PC or console, eSports athletes need optimal cognitive, physical and mental training. However, a gap exists in eSports specific health management, including prevention of health issues and training of these functions. To contribute to this topic, we present in this mini review possible avenues for holistic training approaches for cognitively, physically and mentally fitter and more powerful eSports athletes based on interdisciplinary findings. We discuss exergames as a motivating and promising complementary training approach for eSports athletes, which simultaneously combines physical and cognitive stimulation and challenges in an attractive gaming environment. Furthermore, we propose exergames as innovative full-body eSports-tournament revolution. To conclude, exergames bring new approaches to (physical) eSports, which in turn raise new topics in the growing eSports research and development community.

Keywords: eSports, exergaming, effectiveness, attractiveness, cognition, physical activity, performance, health

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INTRODUCTION

In today's digital age, eSports is an up-and-coming, widely discussed and yet mostly recognized new sports genre that is increasingly gaining social, cultural, economic, and scientific interest (e.g., Hallmann and Giel, 2018). eSports (electronic sports) – a form of sport where the primary aspects of the sport are facilitated by electronic systems and the input of players and teams as well as the output of the eSports system are mediated by human-computer interfaces (Hamari and Sjöblom, 2017) – have become a significant part of today's sports and gaming culture. Teams of players all over the world meet online or, even more spectacular, at big international tournaments to compete against others in a video game battle. According to the International eSports Federation, eSports is officially accepted as a sport in more than 60 countries. Recently, the Olympic Council of Asia approved eSports to be part of the Asian Games in China 2022. Scientists underline this development with scientific rationales for eSports as a showcase of the merit of enhancing cognitive abilities to increase sports performance (Campbell et al., 2018). However, according to

Abbreviations: BDNF, brain-derived neurotrophic factor; IGF-1, insulin-like growth factor 1.

the current state of knowledge, much is still unclear if one considers physical and cognitive processes, strains and general health-related issues in eSports athletes as well as specific methods to train, prevent or treat them. With the rise of eSports and the continued emergence of professional eSports leagues, a huge demand exists for new research and development aimed toward understanding and supporting the performance and health-related factors behind this special profession.

To contribute to this uprising topic, we reviewed existing literature in eSports and related fields such as cognitive and movement science as well as interdisciplinary game research. Following, we illustrate how this interdisciplinary knowledge can help to understand and support cognitive, physical and mental processes in eSports athletes and thus serve as a basis for new training approaches towards optimal performance and health in eSports athletes. Finally, we elaborate on and suggest potential avenues, how to compose interdisciplinarily inspired exergame-based training for (physical) eSports athletes.

eSPORTS ATHLETES

Several hours per day, professional eSports athletes play the video games they specialized in to improve specific gaming skills including gamepad and keyboard handling, game knowledge as well as strategy and tactics. These long-term cognitive, physical and mental tenses can favor the development of negative health-related side effects.

Status Quo: eSports Athletes' Health

On the bodily level, eSports athletes are susceptible to chronic overuse or (sports) injuries such as eye fatigue [excessive exposure to light-emitting diodes (LEDs)] as well as neck, back and wrist pain (Brautigam, 2016; DiFrancisco-Donoghue et al., 2019). These conditions are close to conditions seen in sedentary desk jobs (DiFrancisco-Donoghue et al., 2019). In general, eSports athletes tend to have a higher risk for a diminished health status due to characteristics of eSports (e.g., long-lasting sitting position in front of screens) (Brautigam, 2016; DiFrancisco-Donoghue et al., 2019). On the mental level, eSport athletes might also suffer from diseases such as depression (Rudolf et al., 2016) and burn-out symptoms (Pérez-Rubio et al., 2017). Moreover, psycho-social components can include addictive behavior, personal hygiene issues, social anxiety, and sleep disturbances (DiFrancisco-Donoghue et al., 2019), which in turn can affect the physical, cognitive and mental health state of eSports athletes. Among others, certain cognitive issues are associated with gaming addiction such as cognitive deficits (e.g., impaired executive functioning, hazardous decision-making or deliberative processes) and cognitive biases (e.g., attentional biases, cognitive distortions and dysfunctional cognition) (Billieux et al., 2020). Regarding sleep disturbances, the screen light can impact the natural circadian rhythm and this, in turn, might affect the sleep behavior as well (Tosini et al., 2016). Furthermore, sleep disturbances seem to be related to depression and cognitive impairments, although this relationship varies by age (Alfano et al., 2009). Overall, these health constraints lead to a high drop-out rate and career-ending injuries in professional eSports athletes (DiFrancisco-Donoghue et al., 2019).

eSports-Specific Performance Requirements

As mentioned before, eSports performance is demanding on several levels and requires different abilities to sustain strenuous tournaments as well as long-lasting, regular daily training sessions. An electronic survey study showed that average eSports athletes train between 3 and 10 h per day (DiFrancisco-Donoghue et al., 2019). Another study surveyed that professional and high-level eSports athletes train 5.28 h every day (Kari et al., 2019). Such a training session can last 3 or more hours in sitting position without standing to take a break (DiFrancisco-Donoghue et al., 2019). Furthermore, eSports performance demands physical effort. Especially during stressful tournaments, the heart rate can extremely increase, e.g., up to 160 to 180 beats per minute (Rudolf et al., 2016). Moreover, supporting musculature of the back and neck are continuously tense in the sitting position and hand muscles are ongoingly needed for fine motor skills. eSports athletes reach up to 400 klicks or keystrokes per minute showing augmented manual dexterity (Green and Bavelier, 2006a; Rudolf et al., 2016). Furthermore, those athletes show highly complex and coordinated skills and movement patterns to interact with their controller devices (e.g., keyboard) (Hilvoorde and Pot, 2016; Campbell et al., 2018).

Even more pronounced in eSports are the cognitive challenges, which is why eSports players are also referred to as "cognitive athletes". Cognitive resources are needed to learn, train and consolidate specific cognitive abilities, which are necessary to build the cognitive expertise or skill set of eSports athletes. The cognitive workload during eSports game sessions demands various cognitive domains including attention (e.g., dividing and switching attention), perception and information processing (e.g., fast reaction time) and visuo-spatial skills (e.g., navigating in a virtual environment) (Green and Bavelier, 2003, 2006a,b,c, 2007; Bavelier et al., 2012; Bejjanki et al., 2014; Bediou et al., 2018; Chopin et al., 2019; Torner et al., 2019). Furthermore, habitual video game players benefit from enhanced hand-eye coordination (Green and Bavelier, 2006c). To keep in mind, the respective skill set varies depending on the characteristics of the played video game. To properly recall these cognitive skills and to achieve optimal performance, eSports athletes also need a strong foundation of mental and psychological skills (e.g., emotional regulation and attentional control) (Himmelstein et al., 2017).

A clear mind, optimal cognitive abilities and a proper working physical system can be the crucial difference between eSports athletes who win or lose a tournament. Thus, preventive and therapeutic approaches to counteract health-related issues and support long-term health are needed, but also innovative training approaches that specifically train the athletes on the cognitive, physical and mental level. A survey revealed that 55.6% of professional and high-level eSports athletes believe that physical exercise enhances their eSports performance (Kari et al., 2019). Nowadays, professional and high-level eSports athletes perform approximately 1.08 h of physical exercises per day, but rather to increase their healthy lifestyle than to improve their eSports performance (Kari et al., 2019). Nevertheless, a recent study showed that still 40% of the eSports athletes do not participate in any form of physical exercise or have less than 60 min of daily activity (DiFrancisco-Donoghue et al., 2019) indicating that physical exercising is not yet on the daily agenda of every eSports athlete. Regarding cognitive training, besides the daily gaming routine, there is currently no literature discussing potential complementary brain training approaches while some indications exist for mental training in eSports athletes (Nilsson and Lee, 2019). Furthermore, little knowledge exists on the topic of preventive and therapeutic approaches as well as performance-related training (frequency, intensity, time and type of exercises) for eSports athletes (Kari et al., 2019). A current study recommends developing and incorporating a health management model for eSports athletes as well as defining and understanding the medical needs of eSports athletes as it is standard for other athletes (DiFrancisco-Donoghue et al., 2019). As indicated before, one part of such a health management model would include attractive and effective (training) approaches that meet the specific needs of eSports athletes in terms of overall health and gaming performance. To this day, however, no eSports-specific, well-founded and scientifically proven training approaches are known. A promising training approach that could be a beneficial part of a health management model in eSports athletes is combined physical-cognitive training.

General Beneficial Mechanisms of a Combined Physical-Cognitive Training

Of great interest for eSports athletes are proper cognitive functioning and existing cognitive reserves that could boost gaming performance. Physical exercise can positively affect cognitive functioning by triggering different metabolic brain pathways and mechanism (Thomas et al., 2012; Hötting and Röder, 2013; Voelcker-Rehage and Niemann, 2013; Bamidis et al., 2014; Erickson et al., 2015; Ballesteros et al., 2018; Netz, 2019). Aerobic exercise elevates serum BDNF levels (Vaynman et al., 2004; Knaepen et al., 2010; Lafenêtre et al., 2010; Huang et al., 2014). BDNF is a crucial mediator of the exercise-induced neuroplasticity, and the magnitude of its increase seem to be exercise intensity-dependent (Cotman and Berchtold, 2002; Huang et al., 2014). Further growth factors that might facilitate the effects of aerobic exercise on neuroplasticity are IGF-1 and vascular endothelial growth factor (Trejo et al., 2001; Voss et al., 2013; Maass et al., 2016). In addition, physical exercise has been shown to affect neurotransmitter systems (Lista and Sorrentino, 2010). Moreover, aerobic exercise can increase brain perfusion leading to enhanced supply of oxygen and nutrients (Hötting and Röder, 2013; Maass et al., 2016). Additionally, strength training can create a supportive brain environment via e.g., increased IGF-1 production (Cassilhas et al., 2007; Vega et al., 2010). However, animal studies showed that physical exercise combined with enriched environments (and thus increased cognitive stimulation) might potentiate the positive training effects (Kempermann, 2002; Fabel et al., 2009; Kempermann et al., 2010). Physical exercise facilitates neuroplastic processes while cognitive exercise guides the plastic changes (Fissler et al., 2013; Bamidis et al., 2014). A further crucial factor seems that both components, physical and cognitive, need to be simultaneously present to get the best output (Fissler et al., 2013). A recent review speculated that "[. . .] incorporating cognitive tasks into motor tasks, rather than separate training of mental and physical functions is the most promising approach to efficiently enhance cognitive reserve [. . .]" (Herold et al., 2018). Next to the cognitive improvement by a combined physical-cognitive approach, exercising can also trigger general physical effects depending on the physical components that are integrated into the training [e.g., aerobic components can enhance the cardiovascular system (Cornelissen and Fagard, 2005), strength components can improve the musculoskeletal system (Kristensen and Franklyn-Miller, 2012; Ciolac and Rodrigues-da-Silva, 2016), and motor components can influence coordination and balance skills (Pless and Carlsson, 2000; Kümmel et al., 2016)]. For eSports athletes, these potential adaptations can positively influence their general health status and that, in turn, can support their gaming performance in training and tournament situations.

An innovative training approach that could take up the holistic body'n'brain training in the field of eSports athletes and that could be a combined physical-cognitive and motivating addition to the conventional training approaches are exergames. Due to their playful training approach and the typical setup, exergames could offer a somewhat familiar and thus particularly attractive training approach for eSports athletes while potentially achieving effective cognitive, physical and mental outcomes for eSports athletes.

PERSPECTIVES ON EXERGAMES IN eSPORTS

Exergames are single or multiplayer games that are controlled by physically active body movements (Oh and Yang, 2010; Mueller et al., 2016). Some require more physical effort than others (full-body movements versus moving single body parts). Exergames, which are also known as movement-based games (Isbister and Mueller, 2015), active video games (Biddiss and Irwin, 2010) or exertion games (Mueller et al., 2016), can be played in different settings. Typically, a player who physically interacts with a motion-based controller technology moves in front of a screen, which displays a virtual game scenario. Thus, commercially available exergame platforms such as the Nintendo Wii, the Sony Move or the Microsoft Kinect and their corresponding games have successfully been turning living rooms into playful training settings for about 10 years now (Mueller et al., 2016; Martin-Niedecken and Mekler, 2018). Besides virtual exergame environments, we also find exergame scenarios, which, similar to classic sports games, can be played analogously in the physical space with optional technical aids (e.g., physical obstacles or devices) and thus completely do without the classic player-screen setting (e.g., Segura et al., 2013). Apart from the entertainment market, game-based training and therapy applications further establish themselves in the fitness and rehabilitation industry (e.g., Martin-Niedecken et al., 2019).

Evidence in Exergame Training

So far, studies in the field of exergaming have investigated various effects of commercially available and specifically developed exergames in different target population such as children, adolescents, seniors or patients. Results deliver indications for effects on the cognitive (e.g., executive functions, attention and visual-spatial skills) (Staiano and Calvert, 2011; Best, 2015; Benzing et al., 2016; Mura et al., 2017; Stojan and Voelcker-Rehage, 2019; Xiong et al., 2019), physical (e.g., energy expenditure, heart rate, and physical activity) (Staiano and Calvert, 2011; Sween et al., 2014; Best, 2015; Kari, 2017) and mental (e.g., social interaction, self-esteem, motivation, and mood) (Staiano and Calvert, 2011; Li et al., 2016; Joronen et al., 2017; Lee et al., 2017; Byrne and Kim, 2019) level. Generally, exergames are very well known for their playful combination of physically and cognitively challenging tasks and thus provide dual domain training, which indicates to have greater effects compared to traditional training approaches (Schättin et al., 2016; Ballesteros et al., 2018; Egger et al., 2019; Stojan and Voelcker-Rehage, 2019). Nevertheless, more studies are needed that examine the effects of long-term training periods.

Besides the cognitive, physical and mental effectiveness of exergame training, it is further known for its appealing and motivating impact, especially in physically less active populations (e.g., Lu et al., 2013; Kappen et al., 2019). By offering different players [with different motivational types (Tondello et al., 2019)] an audio-visual and narrative appealing, immersive game scenario, exergames enable a shift of the (cognitive) focus of the player to the playful experience, making it easy to engage in a physically challenging training (Martin-Niedecken et al., 2019). Exergames have successfully been shown to increase training adherence (e.g., Valenzuela et al., 2018), long-term motivation (e.g., Macvean and Robertson, 2013), engagement (e.g., Lyons, 2015), immersion (e.g., Lu et al., 2013), and flow experience (e.g., Martin-Niedecken and Götz, 2017) in players from different populations. However, further research and development work is needed to fully explore and understand the effects of various exergame design elements on players' gameplay and training experience considering the physical, cognitive and mental level.

Exergames – Innovative Training Tools in eSports Athletes

If designed properly in terms of effectiveness and attractiveness, exergames allow for innovative, motivating and holistic training approaches, which may be extremely suitable and beneficial in eSports athletes to keep and maintain their cognitive, physical and mental processes and thus to increase their eSports-related performance and health. Multiple interdisciplinary design guidelines provide well-funded recommendations and considerations for the design of effective (Wüest et al., 2014; Hardy et al., 2015; Hoffmann et al., 2016; Benzing and Schmidt, 2018) and attractive (Sweetser and Wyeth, 2005; Sinclair et al., 2007, 2009; Segura et al., 2013; Mueller and Isbister, 2014; Kajastila and Hämäläinen, 2015; Isbister, 2016; Mueller et al., 2016) exergames, which immerse the player in a motivating and flowing workout experience in front of a screen or in a physical play space. In the context of eSports, however, exergames are not yet used or evaluated as potential training tools. In order to meet the previously described diverse physical, cognitive and mental needs of eSports athletes, exergames must meet certain requirements that are aimed at the specific requirements and general health aspects, which in turn have a positive influence on eSports performance. Following exemplarily avenues for potential eSports-specific exergame concepts including physical, cognitive and mental components are described (**Figure 1**).

Generally, exergames allow for the development of target audience-specific holistic body'n'brain training concepts featuring full-body movements which follow specific design and training principles. To counteract health-related symptoms of eSports athletes' mainly sedentary activities and one-sided physical strain, exergames could feature full-body functional movements (Weiss et al., 2010) with a strong focus on strength training (e.g., holding musculature, trunk musculature, and strength endurance) and flexibility elements (e.g., coordination and stretching). To support performance-related physical-cognitive processes particularly during tournament situations, exergames should further feature cardio-vascular training elements (e.g., high intensity interval training) (Farrow et al., 2019). On the cognitive level, exergames provide several options to train executive functions (e.g., inhibition and flexibility) and attentional functions (e.g., divided and selective attention) via various multi-sensory stimuli on the audio-visual (Ekman, 2008), haptic (Shaw et al., 2017) or proprioceptive level (Moran et al., 2016). Exergames further allow for real-time adaptations of both the cognitive and the physical challenge, based on each player's personal fitness, gaming skills and performance and thus can provide an individualized, optimally balanced training mode (Sinclair et al., 2007).

Furthermore, due to the combination of gaming and exercising, exergames can positively affect eSports athletes' mental state, especially if they suffer from depression and thus feel completely unmotivated to participate in any physical activity (Li et al., 2016). The implementation of specific game mechanics, feedback loops and design parameters may further be suitable to train certain game tactics/strategies, which are needed in eSports games and to extend the very specific skill profile of eSports athletes. Among others, exergames allow simulating socially and bodily competitive multiplayer situations. This might help eSports athletes to mentally handle stressful situations (Argelaguet Sanz et al., 2015) and train mental strength (Kamel Boulos, 2012) by triggering bodily security and self-esteem (Gerling et al., 2014), which are valuable attributes when it comes to eSports tournaments. The implementation of more calming and active relaxation training concepts such as yoga or breathing exercises could further help to target anxiety, stress and other psychophysiological, psychosomatic and mental issues (Van Rooij et al., 2016; Patibanda et al., 2017). Moreover, eSports athletes could benefit from more analogous exergame designs,

Key Influencing Component	Exergame Training & Design Requirements		Potential Positive (Component-Specific) Effects on...
Physical	• Endurance, strength, motor and stretch training • Full-body functional movements • High Intensity Interval Training • Active relaxation training such as yoga and breathing exercises	• Simultaneously vs. sequential • Coupled vs. uncoupled • Distribution of training components determines training focus	• Gaming performance (e.g., information processing, executive and attentional functions, perception, and visuo-spatial skills • Lifestyle (e.g., counteract sedentary behavior) • Musculoskeletal system (e.g., holding musculature of neck and trunk) • Balanced physical strain • Mental strength (e.g., counteract depression and burn-out) • Self-esteem and bodily security • Gaming behavior (e.g., counteract effects of addictive behavior such as loss of reality and social isolation)
Cognitive	• Multisensory stimulation: audio-visual, haptic, proprioceptive level • Game tactics and strategies		
Mental	• Digital/virtual detox: exergaming in the physical space • Simulation of mentally challenging situations • Psychophysiological and psychosomatic training		

FIGURE 1 | Summary of avenues for the development of eSports-specific exergame concepts and the effects of selected physical, cognitive and mental training as well as design components on eSports athletes' performance and health.

FIGURE 2 | Augmented, virtual and mixed reality technologies make eSports more and more physical. **(A)** Echo Arena, **(B)** Beat Saber, **(C)** Hado AR, **(D)** Icarace, and **(E)** the ExerCube are examples of exergames, which require not only fine motor and cognitive skills, but also certain levels of physical effort and which are or will be performed in eSports tournaments. Hence, new physical-cognitive training approaches are not only needed to sustain and improve eSports athletes' gaming performance and general health, but also to develop physical eSports concepts.

as they take the players out of the often very engaging virtual world and focus on the real environment, while still maintaining the playful character and thus particularly counteract potential negative effects of gaming addiction.

Finally, exergames can also serve as assessment tools. Next to various physical and game performance-related input parameters, exergames could track training effects on specific skill levels or allow for planning and analyzing individual training sessions. Thus, the body-centered characteristics of exergames may also be a supportive tool for eSports coaches. However, not every commercially available exergame can be used as an additional eSports training tool. To provide a benefit for eSports athletes' gaming performance and health, specifically modified or newly developed, effective and attractive exergames are needed, which are co-designed and evaluated by an interdisciplinary team of experts from the fields of eSports, game design and research, movement and cognitive science as well as psychology.

eSports Becomes Physical – The Exergame-Based Future of eSports?!

Besides their potential application as an additional training tool in eSports athletes, exergames further open up new possibilities for physical eSports leagues (Kajastila and Hämäläinen, 2015). To be suitable as a competitive discipline, exergames again must fulfill certain requirements such as standardized setups and scenarios or multiplayer balancing (e.g., Bayrak et al., 2017). Today, immersive Virtual and Augmented Reality technologies allow players to physically engage in games. eSports is following this trend and thus more and more physical game genres are establishing themselves in professional leagues, which are played against each other in the context of larger tournaments (**Figures 2A–E**).

Given the current trend, it is even more important to provide athletes with specific exergame training tools besides the games they specialized into. One exergame example which unites various of the previously mentioned requirements, such as an effective full-body functional training, is scalable from moderate to high intensity, provides an attractive and physically immersive gaming environment, and was designed and evaluated by an interdisciplinary team of sports scientists and game designers, is the ExerCube (Martin-Niedecken and Mekler, 2018; Martin-Niedecken et al., 2019) by Sphery Ltd. (**Figure 2E**).

CONCLUSION

Today eSports is a widely discussed and omnipresent phenomenon. eSports athletes compete in major tournaments in front of an audience of millions. To be in top form and able to cope with this situation as well as to counteract general health issues caused by the very special athlete profiles, eSports athletes need optimal cognitive, physical and mental abilities. However, a holistic health management system for eSports athletes is missing. Findings from interdisciplinary work in related fields such as cognitive and movement science or game research will provide potential avenues for the development of holistic body'n'brain training approaches for eSports athletes. A very promising and innovative training approach is exergaming, which combines physical and cognitive training in an attractive gaming environment. Considering the game design and training principles as well as eSports specific requirements, exergames could serve as an additional training option to holistically support gaming performance and general health in eSports athletes. However, further interdisciplinary research and development work is needed to understand and meet the various requirements of eSports athletes and to unite them into exergames, which then may serve as a training tool and an eSports genre. To conclude, exergames bring new approaches to (physical) eSports, which in turn raise new topics in the growing eSports research and development community.

AUTHOR CONTRIBUTIONS

AM-N and AS equally contributed to the conceptualization of the mini review, compilation and review of relevant related work, and writing of the manuscript.

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OPINION
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Life After Esports: A Grand Field Challenge

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INTRODUCTION

Esports has experienced unprecedented growth recently and with it, the proposition for aspiring gamers to pursue a professional esport career has become increasingly attractive. "Esports" are video-games played competitively (and often professionally) through the means of cyberspace (Campbell et al., 2018) and are an important fixture in the overall gaming industry, which is estimated to be worth more than 120 billion US$ (Takahashi, 2020). The exponential rise in popularity has led to the inclusion of two esports (Rocket League and Street Fighter V) in an International Olympics Council sanctioned tournament before the 2020 Tokyo Olympic games (Martinello, 2019).

Despite the appeal of esports as a profession, aspiring esport athletes face many obstacles that can threaten their prospective career timespan, and present post-career difficulties. To date, very limited formal exploration exists into this challenge; thus, this grand field challenge aims to explore the difficulties faced by esport athletes. It also highlights the unique skillsets and experience acquired during a professional esports career, and the value these could offer to alternate high performance professions.

Like all occupations, an esports career depends on financial and job security. Although some professional athletes in tier-1 (the highest level of competition) leagues within popular esports enjoy financial stability from yearly contracts (Esports Mention, 2019), athletes in less popular esports and aspiring gamers not yet competing in tier-1 leagues are not afforded this luxury. Additionally, outside tier-1 tournaments, prize money distribution is such that winners are more greatly rewarded at the expense of other participants (Coates and Parshakov, 2016). Moreover, protections are limited for esport athletes as they have not yet been able to unionize. This makes job security remarkably fragile, particularly given the high athlete replaceability, with extreme cases of top esport athletes being dropped from teams at post-victory celebrations (Van Allen, 2018).

To further compound these challenges, the average career of typical esports athletes' is remarkably short; with about one-in-five professional esport athletes' careers lasting 2 years or longer (Ward and Harmon, 2019). This short career length is largely due to the difficulty of becoming and remaining a top esport athlete, particularly given the volatility of team rosters. Esports performance is reliant on the ability to rapidly and accurately respond to complex visual stimuli, which begins to decline past 24 years of age (Thompson et al., 2014). As such, one's timeframe for peak esports performance is limited. The time commitment and rigor required for elite esports performance has resulted in many cases of burnout and injury, causing early retirement (Salo, 2017). Additionally, adolescent esport athletes often sacrifice educational opportunities to pursue their careers (Hollist, 2015), hampering their ability to pursue alternate careers post-retirement. In summary, there appears to be a narrow timeframe for financial success for esports athletes, who may jeopardize their post-retirement opportunities to take that window.

SKILLS AND EXPERIENCE OF AN ESPORT ATHLETE

Despite the current pitfalls of an esports profession, esports athletes possess a unique range of specialized skills and experiences that we argue are highly sought after in many contemporary professions. Such attributes include digital intelligence, experience and expertise in prolonged human computer interaction performed in a seated posture, skillful and efficient communication, and perhaps most notably, enhanced cognitive abilities. In this section, we outline some of these traits that this population possess.

Digital Intelligence and the Workplace Environment—Esport Athletes

Fundamentally, esports involve human-computer interactions with an adapting computer program to produce outcome-defining events within a virtual gameplay environment (Hamari and Sjöblom, 2017). Higher-level esport athletes perform faster and with more complexity than their less-skilled counterparts (Avontuur et al., 2013; Buckley et al., 2017). Esports are a type of high-performance computing that requires "digital intelligence" to provide a competitive advantage, such as knowledge of, and proficiency with, hardware components (Claypool and Claypool, 2007). Additionally, esports athletes undertake long continuous bouts (often >3 h) fixating on computer monitors in a seated posture during training and competition (DiFrancisco-Donoghue et al., 2019). It is well-established that this prolonged sitting can result in lower back discomfort and impaired vascular function (Dunk and Callaghan, 2010; Credeur et al., 2019). Moreover, frequent computer monitor use can lead to "computer vision syndrome," associated with temporary eye discomfort (Blehm et al., 2005). Although little work has investigated these physiological effects in esports athletes, it may be that esports athletes have developed strategies to maintain performance despite these issues.

Communication—Esport Athletes

Esport teams are a unique hybrid of a high-performance action team engaging in computed supported cooperative work (CSCW), a combination not regularly seen in more traditional team environments (Freeman and Wohn, 2019). Given that most esports are team-based, effective team cohesion and communication are essential for success. Communication within elite esports is overwhelmingly verbal (Lipovaya et al., 2018). To maximize efficiency and effectiveness of this communication, athletes must be proficient in utilizing rigid phraseologies (Lipovaya et al., 2018; Freeman and Wohn, 2019). Team strategies and individual roles must be effectively communicated prior-to and during competition to ensure successful performance (Lipovaya et al., 2018; Freeman and Wohn, 2019).

Cognitive Skills—Esport Athletes

First Person Shooter (FPS) and Multiplayer Online Battle Arena (MOBA) games, which collectively comprise the majority of major esports and are known as action video-games (AVGs), are cognitively demanding (Campbell et al., 2018). The demand that esports places on athletes has resulted in a growing body of research demonstrating that gamers possess enhanced cognitive abilities compared to non-gamers (Kowal et al., 2018; Large et al., 2019); due to this, esport athletes have been referred to as "cognitive athletes" (Campbell et al., 2018).

Existing literature indicates that experienced AVG players (AVGPs) have enhanced spatial and temporal visual perception (Green and Bavelier, 2007; West et al., 2008; Li et al., 2009, 2010; Appelbaum et al., 2013). Further, AVGPs possess greater attentional resources, facilitating performance improvements on tasks with large attentional-demands (Bavelier et al., 2012a; Krishnan et al., 2013). Additionally, AVGPs can also better control their attentional resources (Chisholm et al., 2010; Mishra et al., 2011; Bavelier et al., 2012a; Chisholm and Kingstone, 2012; Green et al., 2012; Krishnan et al., 2013; Cain et al., 2014; Föcker et al., 2018) and allocate them over a wider visual field-of-view (Dale et al., 2019). Lastly, AVGPs demonstrate high capacity to integrate visual and auditory information (Donohue et al., 2010).

In addition to enhanced perception and attentional capabilities, AVGPs have been demonstrated to have faster overall response times across a diverse range of tasks, which is believed to represent general enhancements in cognitive throughput (Castel et al., 2005; West et al., 2008; Dye et al., 2009; Hubert-Wallander et al., 2011; Bavelier et al., 2012a; Green et al., 2012; Wu and Spence, 2013; Föcker et al., 2018). It has been suggested that these improved perceptual, attentional, and processing speed abilities provide gamers an enhanced capacity to learn as well (Bavelier et al., 2012b).

THE TRANSLATION OF THE ESPORT SKILLSET TO ALTERNATE PROFESSIONS

Although their careers are tenuous and short-lived, the inherent skill-sets possessed by esports athletes are highly desirable in multiple contemporary professions. To demonstrate this, we queried the Occupational Information Network to determine professions sharing expertise and experience with esport athletes (O*net, queried 12/12/19). O*net is a free database of occupation-specific descriptors, developed with the sponsorship of the U.S. Department of Labor/Employment and Training Administration (USDOL/ETA), to help jobseekers match careers to their skill-sets. Within the database, almost 1,000 professions are ranked according to defined categories of abilities/experience; we queried those categories related to the expertise of esport athletes.

Following our searches, two professions very regularly (over 40%) appeared (top 30 most relevant occupations; see **Supplementary Table 1** for search details): aircraft pilots (hereafter simply referred to as "pilots") and air traffic controllers (ATCs). Additionally, previous research demonstrating comparable performance of AVGPs to military combat pilots on simulated Unmanned Aerial System (UAS) operations (McKinley et al., 2011) led us to include this profession. The following sections explore how the skill-sets and experience

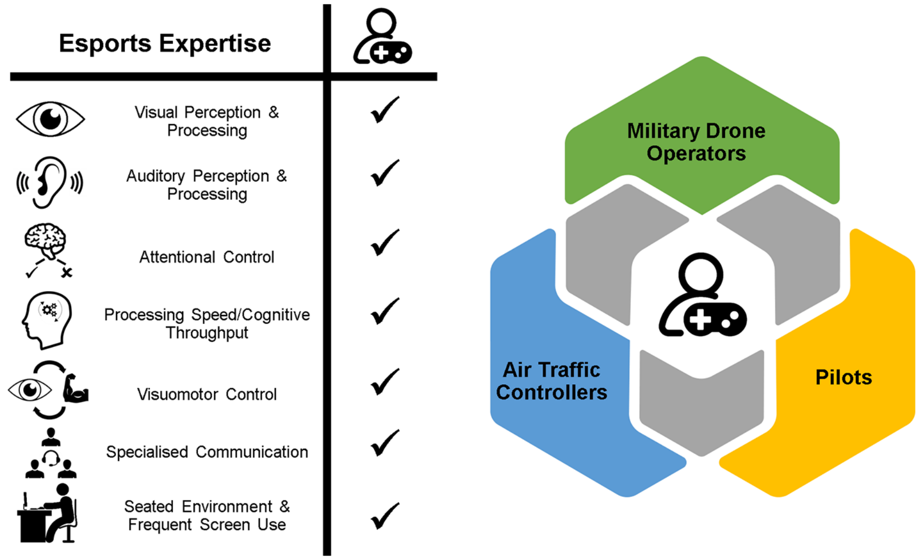

FIGURE 1 | Prominent skills and experiences possessed by esport athletes (left) and a Venn diagram (right) visually demonstrating the mutual desire for esport-related skill and experience by military UAS (drone) operators, air traffic controllers, and pilots.

required for success in esports could be highly valued in these professions (see **Figure 1**).

Digital Intelligence and Workplace Environment—Pilots, ATCs and UAS Operators

Expert interfacing with complex computerized systems is essential for the outlined professions, with ATCs and UAS operators, in a similar manner to esports, using computer monitors as primary outputs. For ATCs, the quality of such human-computer interface interactions is integral to overall performance (Chang and Yeh, 2010). Furthermore, McKinley et al. (2011) noted that gamers were highly proficient at using "game-like" UAS interfaces, supporting the performance benefits of interface familiarity. All of the outlined professions are also performed while seated, with pilots specifically remaining in such a posture for several hours at a time (Lusted et al., 1994). While pilots do not fixate on screens for prolonged periods, ATCs and UAS operators do, and may experience "computer vision syndrome" as a result. Given that esport athletes often perform during long bouts of sitting and screen fixation, they may be better suited to maintaining high task performance in jobs that appear to also have these challenges.

Communication—Pilots, ATCs and UAS Operators

Pilots and ATCs must work synergistically to maximize safety in operations where communication, much like esports, is primarily digital (CSCW). Very specific phraseology is used in aviation to optimize communication efficiency (Campbell-Laird, 2004). Such consistency is vital, as coordination and communication errors are the leading cause of air traffic accidents (Isaac and Ruitenberg, 2017). Similarly, UAS operators are required to have frequent and concise verbal communication with ATCs, ground units, and other aircraft (McKinley et al., 2011).

Cognitive Skills—Pilots, ATCs and UAS Operators

The key similarities between esports athletes, pilots, ATCs and UAS operators lie in their cognitive abilities. Rapid identification (perception and attention) and processing (cognitive throughput) of information is vital for safety and operational performance. For ATCs and pilots, timely recognition and response to warnings on one of many displays (often in visual peripheries) can prevent hundreds of casualties, while timely localization and action toward a target can define operational success or failure among UAS operators. Important information for all three professions is invariably concealed among an array or "clutter" of stimuli, rendering attentional control as critical. Moreover, individuals in these professions are often required to simultaneously attend to multiple stimuli at once (multitasking); particularly ATCs, who constantly must manage airspaces containing numerous aircraft. Information may be visual (displays), haptic and auditory (alarms, warnings, and verbal), placing importance on multisensory integration.

Given such intense demands, attentional errors are among the most common errors for ATCs (Pape et al., 2001), and cognitive processing/decision making errors constitute most "pilot error" accidents (Adams and Ericsson, 2000); both of which can result in numerous casualties. To mitigate such risks, pre-training assessments for these professions regularly include assessing these aforementioned cognitive attributes; given the cognitive proficiency of esport athletes, they may perform well on such tests, demonstrating high suitability for these professions.

It must be acknowledged that the skill-sets/experiences possessed by esport athletes are not exclusively beneficial for pilots, ATCs, and UAS operators, and may be favorable for any occupations which share similar workplace demands, communication, and cognitive requirements.

FIELD CHALLENGE

The rise of esports has resulted in the emergence of a population of uniquely skilled young individuals. These "cognitive athletes" can quickly perceive and process large amounts of information, while simultaneously demonstrating better attentional control. Moreover, they are strong communicators and work well in team environments, particularly through digital means and in high-performance computing contexts. Lastly, they are notably proficient with human-computer interfaces, and are experienced with working in a seated posture for extended periods. Unfortunately, given the nature of esports as a profession, most esport athletes experience a short, financially unstable career, with limited post-retirement opportunities.

Here, we have highlighted the shared importance of the unique skills and experiences possessed by esport athletes and how they may be preferentially valued for three exemplar professions; pilots, ATCs, and military UAS operators. High-performance in these three professions is critical, as errors can pose large financial and human costs. Overall, this work poses a challenge to the esports, scientific and industrial communities, to demonstrate how best to leverage the unique abilities of esports athletes to facilitate their life after esports and add value to professions seeking individuals with these unique skillsets. Doing so could result in more suitable personnel occupying the abovementioned industries and would be highly beneficial to the distinctly vulnerable population of esport athletes.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception of the field challenge. TS wrote the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Play to Win: Action Video Game Experience and Attention Driven Perceptual Exploration in Categorization Learning

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Categorization learning is a fundamental and complex cognitive ability. The present EEG study examined how much action video gamers differ from non-gamers in the usage of visual exploration and attention driven perceptual analyses during a categorization learning task. Seventeen healthy right-handed non-gamers and 16 healthy right-handed action video gamers performed a visual categorization task with 14 ring stimuli, which were divided into two categories. All stimuli had the same structure but differed with respect to their color combinations and were forming two categories including a prototype, five typical stimuli and one exception. The exception shared most similarities with the prototype of the opposite group. Prototypes and typical stimuli were correctly categorized at an early stage of the experiment, whereas the successful categorization of exceptions occurred later. The behavioral data yield evidence that action video gamers perform correct categorizations of exceptions earlier than non-gamers. Additionally, groups differed with respect to differential expressions of the attention related P150 ERP component (early perceptual analysis) and the N170 ERP component, which reflected differential processing demands for the stimulus material. In comparison to non-gamers, the analyses of the eye movements yield for action video gamers different, more central fixations possibly indicating covert peripheral processing. For both groups fixations as well as saccades decrease and in the case of exceptions, one of the two segments that are decisive for correct categorization shows higher fixation rates at the end of the experiment. These findings indicate for both groups a learning process regarding the stimulus material. Regarding the group differences, we interpret the results to indicate that action video gamers show a different stimulus exploration, use an enhanced early perceptual analysis of the stimulus material and therefore may detect changes in objects faster and learned the belonging of the stimuli to their categories in an earlier trial phase.

Keywords: categorization learning, visual attention, perceptual processing, action video games, exception-based strategy, abstraction-based strategy

INTRODUCTION

Categorization learning is a basic cognitive ability that determines everyday life. It is a cognitive function that helps us to assign objects as well as abstract concepts to specific categories (Smith and Minda, 1998; Zentall et al., 2008; Sloutsky, 2010). By using categorizations, hazards can be detected and successfully avoided (Smith et al., 2012), for example potentially toxic plants (Ashby and Maddox, 2005). Furthermore, the ability to categorize improves over the lifespan and is modulated by experiences (Quinn et al., 1993).

Based on the importance of categorization learning, it is not surprising that many theoretical models have been published (Ashby and Maddox, 2005; Ashby and Maddox, 2011; Lech et al., 2016; Schenk et al., 2016). For example, Cook and Smith (2006) concluded from their study that within the learning of categories a psychological shift from an early abstraction-based strategy to a later exception-based strategy takes place. This combination of strategies enables the categorization of realistic categories with a nuanced feature structure that consist of prototype-like stimuli and exceptions. In the current study we focused on the theoretical model of Cook and Smith (2006).

In general, cognitive flexibility as well as generalization processes are essential mechanisms that underlie categorization learning (Sloutsky, 2010). Focusing on category-typical features and ignoring all irrelevant information are necessary aspects of these processes. They are influenced by visual perception and supported by selective attention (Nosofsky, 1986; Thompson and Oden, 2000; Sloutsky, 2010). Visual attention is one of the main areas of investigation in categorization learning. But although selective attention is a part of many models of categorization learning (Nosofsky, 1986; Kruschke, 2001; Love et al., 2004), the effect of attention on categorization learning had not been investigated using the individual differences approach.

In our present work we compared the categorization performance of two groups who are thought to differ with respect to their attentional capacities. Based on previous studies, which have shown the positive impact of action video games on visual information processing (Green and Bavelier, 2006a,b, 2007; Feng et al., 2007), reaction times (Boot et al., 2008), multi-tasking (Green and Bavelier, 2006b; Strobach et al., 2012; Chiappe et al., 2013) and attention capacity (Green and Bavelier, 2003; Rosser et al., 2007; Hubert-Wallander et al., 2011; Bavelier et al., 2012), we compared action video gamers with non-gamers in a categorization learning task. Kühn et al. (2014) could show that even playing video games like Super Mario induces structural brain plasticity. These studies show that different types of video games have different effects on cognitive abilities and neurocognitive correlates. Besides, playing action video games appears to reduce gender differences in visual search and attention tasks (Stoet, 2011). Since playing action video games reduces gender differences (Stoet, 2011) and enhances selective visual attention and attention allocation (Rosser et al., 2007; Bavelier et al., 2012), it appears to be reasonable to make this comparison.

However, there are not many studies that shed light on the implications of these attentional benefits of action video gamers in categorization learning together with the underlying neurocognitive correlates. Categorization includes the combination of cognitive domains like attention, cognitive flexibility and visuospatial processing and visual perception. Palaus et al. (2017) reviewed the effect of video gaming on different cognitive functions in video gamers showing different effect of video gaming on each of these functions. The investigation of a task that combines these different cognitive functions, like it is realized during categorization, in video gamers provides a useful and important next step. Therefore, the investigation of visual attention during categorization related electrophysiological correlates appears to be of special interest. One of these event-related potentials (ERP) is the P150 component. This component has its focus at posterior electrode positions, is associated with a perceptual analysis of stimulus material and depends on the number of shared features within a category. The P150 reflects an early perceptual analysis and attention direction to specific stimulus segments (Johnson and Olshausen, 2003; Bigman and Pratt, 2004; Long et al., 2010). Additionally, we could already show in a former study (Schenk et al., 2016), that the P150 amplitude was higher in elderly subjects during categorization if compared to younger participants. Results of this study further suggest that the P150 amplitude reflects critical processes in categorization at least when exploring categorization using the paradigm introduced by Cook and Smith (2006). An additional ERP is the N170. It reflects visual expertise with non-face objects and early categorization related perceptual processes in the occipito-temporal cortex (Rossion et al., 2004). Inversion-effects (Diamond and Carey, 1986; Tarr and Gauthier, 2000), as well as behavioral (Gauthier and Tarr, 1997) and neuroimaging studies (Gauthier et al., 1999; Gauthier, 2000) indicated that N170 arises as a function of perceptual processing of expertise objects, such as Greebles (Tanaka and Curran, 2001; Rossion et al., 2002; Gauthier et al., 2003).

This study aimed to investigate how individual differences in visual exploration and attentional processing influence the performance and the electrophysiological correlates of categorization learning. For this, we used electroencephalography (EEG), eye-tracking, the same behavioral paradigm as Cook and Smith (2006) and compared two groups with different visual attention capacities. In reference to previous findings we compared action video gamers, who have an enhanced visual attention capacity, and non-gamers, who have a normal visual attention capacity. We expected that the behavioral results of Cook and Smith (2006) can be replicated. Furthermore, we expected that action video gamers use an enhanced perceptual analysis, detect relevant information faster and therefore show a faster and better learning performance. The faster detection of relevant information and the enhanced perceptual analysis should be accompanied by higher P150 amplitudes of action video gamers. Additionally, it is assumed that action video gamers exhibit less scattered and more center focused eye movements than non-gamers.

MATERIALS AND METHODS

Participants

Seventeen subjects without action video game expertise (mean age 22.53 years; 3 male/14 female; non-gamers) and 16 subjects with high expertise in action video games (mean age 23.94 years; 14 male/2 female; action video gamers) participated in the current study. Participants with high action video game experience formed the group of the action video gamers. They were assigned to this group by fulfilling the criterion of playing a first-person shooter game for more than 20 h per week using a self-designed questionnaire (**Supplementary Datasheet 1**). The group of non-gamers consisted of subjects without any game experience playing not video games at all. All subjects were right-handed, neurologically healthy and had normal or corrected-to-normal vision. The neurological health and handedness were recorded via a self-report questionnaire. After a detailed explanation of the procedure all subjects gave informed written consent. The Ethics Committee of the Faculty of Psychology, Ruhr University Bochum, Germany approved the study.

Stimuli and Task

The participants performed an adapted version of the visual categorization task from Cook and Smith (Cook and Smith, 2006), with two categories and ring stimuli with six color features (768 × 768 pixels). These ring circles had a radius of 12.95° visual angle. Color features located at the outer side of the circle had a width of 1.74° visual angle. The stimuli of both categories had the same structure but differences in the combination of color features. Participants had no prior knowledge about the stimuli or categories. Both categories consisted of seven stimuli: one prototype, five typical stimuli and an exception. The typical stimuli shared five color features with the prototype of their own category. The exception shared five color features with the prototype of the other category (Cook and Smith, 2006; Schenk et al., 2016). An overview of the stimulus material, including the delineation of the two categories and the labeling of the stimulus types, as well as the numbering of the color features is shown in **Figure 1**. Subjects were not informed about the existence of exceptions. Since the exclusive usage of an implicit abstraction-based strategy would lead to errors in the categorization of the exceptions, the participants had to realize the existent of exceptions and had to explicit remember both exceptions, to correctly categorize all stimuli (Lech et al., 2016).

In the center of a white background, the ring stimuli were presented with a screen resolution of 1024 × 768 pixels. The left and right CTRL keys were used as response buttons. Each button corresponded to one of the two categories. After the response the participants received immediate feedback ("right" or "wrong"). If the subjects react too slowly (more than 1.8 s after stimulus presentation), they were given an information via the feedback to react faster ("Please react faster!"). After the feedback presentation (1 s) a fixation cross was presented for a variable inter trial interval of 1 to 2 s before the next trial started. The learning process is taught through feedback. The experiment consisted of a total of 490 trials, divided into five blocks each, containing 98 that were presented in a random order (14 prototypes, 70 typical stimuli, and 14 exceptions). After every block the participants were allowed to take a short break (**Figure 2**).

EEG Recording

The experiment was performed at the Ruhr University Bochum in an EEG laboratory using Presentation® 16.2 software package[1] (NeuroBehavioral Systems, Inc.). During the experiment, EEG was recorded from 30 electrodes according to the international standardized 10–20 system. For the recording a BrainProducts Amplifier (BrainAmp, BrainProducts, Munich, Germany) and the appropriate software package "BrainVision Recorder" were used with a sample rate of 500 Hz. A ground electrode was placed at FCz and the reference electrodes were placed at the mastoids. The impedances of the electrodes were kept below 5 kΩ.

Eye-Tracking

Eye position data of participants' right eye were captured during the stimulus presentation with a sampling rate of 500 Hz. For the recording of the fixations a video-based iView XTM Hi-Speed system (Senso Motoric Instruments, Berlin, Germany) was used. A calibration of the eye-tracker to the individual eye position of the participants was implemented at the beginning of each block (**Figure 2**).

Data Analyses

The recorded EEG dataset was analyzed with the BrainVision Analyzer Software of Brain Products (BrainVision Analyzer, Package 2.0, Brain Products, Munich, Germany). A band-pass filter with cutoffs of 0.5 and 40 Hz (order 2; Time Constant = 0.3 s) were used. Blink artifacts and vertical eye movements were removed from the EEG data of each subject after individual independent component analyses (ICA). Components reflecting eye movements were removed from the EEG signal. Because of their similarity prototypes and typical stimuli were combined (prototypical stimuli). Segments for both stimulus types (prototypical stimuli and exceptions), followed by a baseline correction relative to 200 ms preceding the stimulus presentation were created. Trials with data points exceeding an absolute amplitude value of 150 μV were excluded by automatic artifact detections (see **Supplementary Table 1** for the numbers of included EEG trials). Single subject averages were created for both stimulus types (prototypical stimuli, exceptions).

The P150 ERP component is related to early selective visual attention and has its focus at posterior electrode positions. In the categorization paradigm introduced by Cook and Smith (2006) it is a critical component for the categorization performance (Schenk et al., 2016). Similar to the study by Schenk et al. (2016), the analysis of the P150 component included data from the parietal-occipital electrodes (PO7, PO3, POz, PO4, PO8). The maximum positive peak amplitude within the corresponding time frame of 120 to 180 ms after stimulus presentation was defined as the P150 ERP amplitude. The amplitudes of action video gamers and non-gamers were compared for both stimulus

[1] http://www.neuro-bs.com

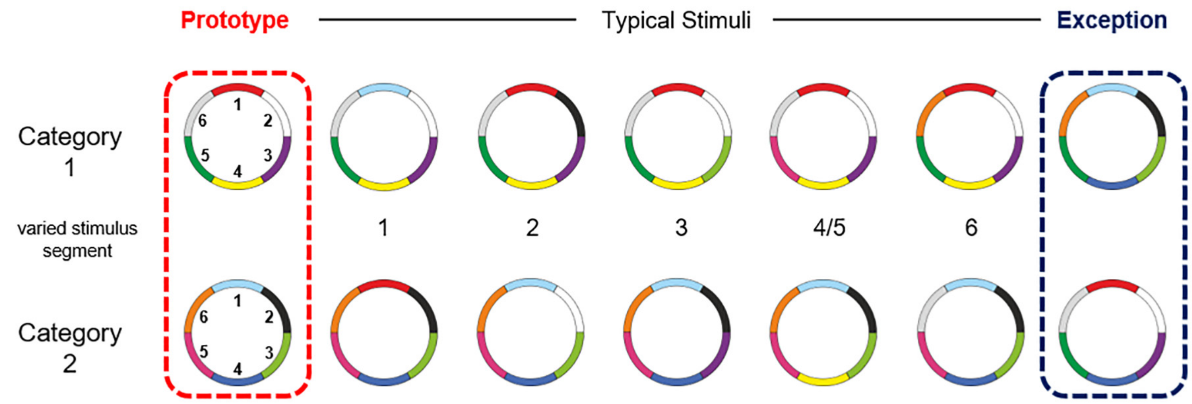

FIGURE 1 | Overview of the stimulus material. The small numbers in the middle represent the stimuli segment (clockwise) on which the stimuli varied from the prototype. The stimuli of both categories shared an average of 3.88 colors within and 2.12 colors between the categories. They shared an average of 4.57 colors with their own prototype and 1.43 with the prototype of the other category (see also Schenk et al., 2016).

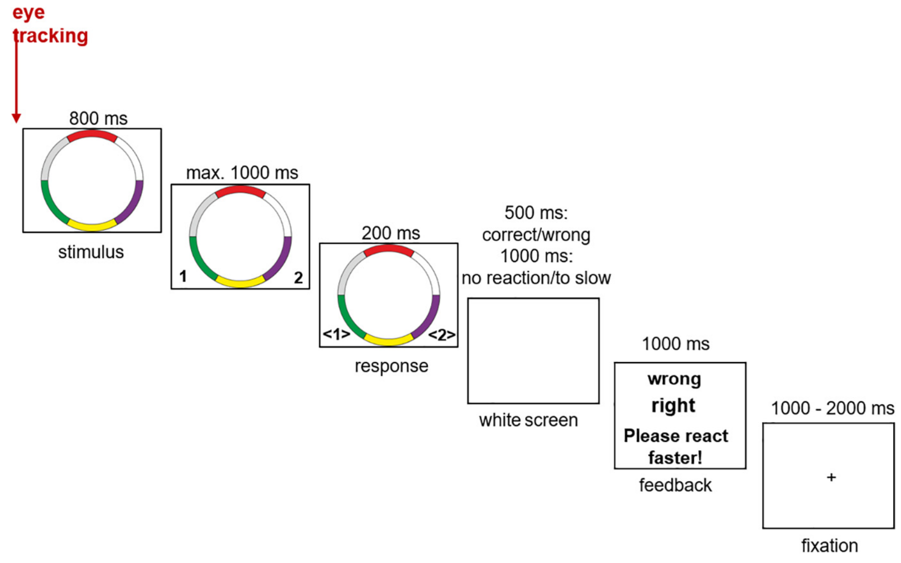

FIGURE 2 | Experimental setup of the categorization task (see also Schenk et al., 2016).

types (prototypical stimuli and exceptions). The maximum negative peak amplitude within the corresponding time frame of 150 to 190 ms after stimulus presentation was defined as the Peaks of the N170 amplitude. The analysis of the expertise related N170 was based on data from the P7, PO7, P8, and PO8 electrodes. Peak amplitudes were determined automatically in a first step by the Vision Analyzer software. Visual inspection of this procedure was performed afterward to ensure correct peak detection.

The eye-tracking data were analyzed using MATLAB R2009a (MATLAB and Statistics Toolbox Release 2009a, The MathWorks, Inc., Natick, MA, United States). Fixations were visualized on the basis of heat maps. According to the structure of the stimuli, the ring stimuli were divided into eight areas: the seven color segments of the stimuli and the center of the stimuli. The center of each stimulus was defined as a circle around this center of with a radius of 8° visual angle (191 pixel). Percentages of the fixation rates and numbers of fixation were calculated for the area of all color segments in total and for the center of the stimuli. The differences in the fixation rates within and between the two groups were compared for prototypes and exceptions. Overall, differences between a central holistic processing and a stimulus segment driven processing were investigated. Additional analyses focused on specific color segments of the stimuli that were import for the correct categorization of exceptions. Apart from fixations, eye movements were also analyzed. More specifically, saccades were detected during the 800 ms stimulus presentation period, based on individual subjects' eye position data in each trial. Changes in eye position were considered as saccades when the velocity of the change in eye position exceeded 40° visual angle per second and when the amplitude of the eye displacement was at least 1.5° visual angle. Saccade onset was determined as the point in time when the velocity exceeded the threshold of 40° visual angle per second.

For the statistical analysis of the behavioral data, prototypes and typical stimuli were combined to prototypical stimuli for the analysis. The focus of the analyses was on the percentage of correct responses as it reflects learning progress. Additionally, reaction times were analyzed within and between the groups. Two ANOVAs with repeated measures (including Greenhouse–Geisser procedure and Bonferroni correction with an alpha = 0.05) and the factor "stimulus" (prototypical stimuli; exceptions), the factor "block" (1 to 5), and the "group" factor (non-gamers; action video gamers) were applied. To resolve significant interactions two-tailed t-tests were applied. Sample size planning with G*Power (G*Power: Statistical Power Analyses; Faul et al., 2007), an $\alpha = 0.05$, a statistical power of 95% and an assumed moderate effect of $f = 0.25$ yielded optimal sample sizes of $N = 32$ ($n = 16$ per group).

For the statistical analysis of the EEG data an ANOVA with repeated measures was calculated for the P150 amplitude over all five electrodes. Additionally, Greenhouse–Geisser and additional Bonferroni corrections (alpha = 0.05) were used. The ANOVA contained the factors "stimulus" (prototypical stimuli; exceptions), "block" (1 to 5) and "group" (non-gamers; action video gamers). To resolve significant interactions two-tailed t-tests were applied. The *a priori* determination of the sample size (G * Power: Statistical Power Analyses, Faul et al., 2007) with the factor stimulus, the repeated measurement factor bock, the group factor, an $\alpha = 0.05$, a statistical power of 95% and an assumed moderate effect of $f = 0.25$, gave an minimal sample size of $N = 32$ ($n = 16$ per group).

The first analysis of the fixation eye-tracking data investigated the fixation behavior of the stimuli (central with peripheral exploration and focused on stimulus segments). Sample size planning with G*Power with an $\alpha = 0.05$, a statistical power of 95% and an assumed moderate effect of $f = 0.35$ yielded for the eye-tracking data an optimal sample size of $N = 30$ ($n = 15$ per group). A Bonferroni-corrected repeated measures ANOVA with the factors "stimulus" (prototypes; exceptions), "fixation behavior" (central; stimulus segments), "block" (1; 5), and "group" (non-gamers; action video gamers) was computed to investigate the fixation rates. In case of sphericity violation, a Greenhouse–Geisser correction was used. The second, as well as the third analysis of the fixation data focused on the fourth and fifth stimulus segments. These analyses examined whether participants focused on specific stimulus segments that are important to correctly categorize the exceptions and their category membership. Both analyses included Bonferroni corrections with an alpha value of 0.05 and Greenhouse–Geisser procedures. The second repeated measure ANOVA was computed with the factors "stimulus" (prototypes; exceptions), "block" (1; 5), and the between-subject factor "group" (non-gamers, action video gamers). The analysis examined whether the subjects of both groups had higher fixation rates in the fourth stimulus segment in order to correctly classify category 2 exceptions. Apart from the fourth segment, exceptions of category 2 look similar to prototypical stimuli of category 1. A fixation of the fourth stimulus segment is required for a correct assignment of stimuli as category 2 exceptions. In a third step, another repeated measure ANOVA with the factors "stimulus" (prototypes; exceptions), "block" (1; 5), and "group" (non-gamers; action video gamers) investigated whether subjects looked more at the fifth stimulus segment in order to categorize exceptions of category 1 correctly. Apart from the fifth stimulus segment, exceptions of category 1 look similar to prototypical stimuli of category 2. A fixation of the fifth stimulus segment is necessary to assign stimuli correctly as exceptions of category 1. To further elucidate the eye-tracking data, two additional ANOVAs were performed. One ANOVA included the amount of fixation on each segment before decision. This ANOVA included the factors "stimulus (prototypes; exceptions), "block" (1; 5), and "group" (non-gamers; action video gamers) was performed. Another ANOVA included the same factors using the numbers of eye movements as dependent variable.

Furthermore, saccades were analyzed. The first analysis referred to the mean number of saccades that were performed during the first 800 ms of stimulus presentation. For each participant the mean number of saccades per trial was calculated for prototypes and exceptions in each of the five blocks. Then a repeated measure ANOVA with the factors "stimulus" (prototypes; exceptions), "block" (1; 5), and "group" (non-gamers; action video gamers) was performed. In a second step, an ANOVA with the same factors was applied to analyze the mean latency of the first saccade.

RESULTS

Behavioral Data

The ANOVA for the percentage of correct responses yielded significant main effects for the factor "stimulus" ($F_{1,31} = 78.24$, $p = 0.0001$) and the factor "block" ($F_{4,86} = 83.99$, $p = 0.0001$). Additionally, the ANOVA showed a significant interaction of the factors "stimulus" and "block" ($F_{3,85} = 5.83$, $p = 0.001$). The following pairwise comparisons revealed for both groups more correct categorizations in the last blocks, especially for prototypical stimuli. The paired t-test showed that the interaction was based on the high number of correctly categorized prototypical stimuli compared to the low number of correctly categorized exceptions at the beginning of the experiment and the strong increase of correctly categorized exceptions in block 3 (**Figure 3** and **Table 1**). To further analyze the accuracy changes over the five blocks, we calculated the difference between percentage correct responses for exceptions and prototypical stimuli. Differences between the blocks (1 vs. 2, 2 vs. 3, 3 vs. 4, 4 vs. 5) were analyzed using paired t-tests. Results yield evidence for significant differences only between block 2 and block 3 [$t(32) = 4.17$; $p < 0.001$]. All other results showed no significant differences (all $p > 0.05$).

Regarding group differences, the ANOVA showed a significant interaction between "stimulus" and "group" ($F_{1,31} = 5.35$, $p = 0.02$), which was based on the superior categorization performance of action video gamers for exceptions (**Figure 3**). The group difference regarding the superior categorization

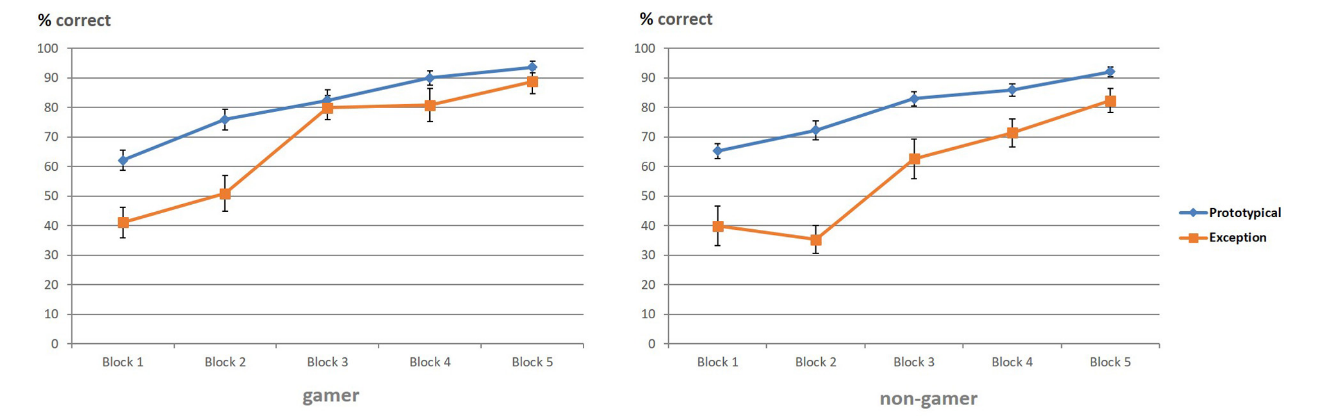

FIGURE 3 | Correct categorizations of prototypical stimuli and exceptions (in percent).

performance of action video gamers for exceptions corresponded to a strong effect size ($d = 0.83$). In view of the descriptive data, exploratory analyses were calculated to examine this "stimulus" and "group" interaction separately for each of the five blocks. According to these analyses, it seemed that the interaction effect between the factors "stimulus" and "group" was particularly enhanced in block two ($F_{1,31} = 4.19$; $p = 0.049$, $d = 0.73$) and three ($F_{1,31} = 4.72$; $p = 0.03$, $d = 0.82$; see **Table 1** and **Figure 3**) with a superior categorization performance of action video gamers for exceptions.

To illustrate this advantage of action video gamers regarding the correct identification and categorization of exceptions, especially in the early stage of the paradigm, an additional figure was created to depict descriptively the correctly categorized exceptions (in percent) of both groups at the beginning (first part) and end phase (second part) for each of the five blocks (**Figure 4**). The figure shows that action video gamers categorized exceptions earlier and better than non-gamers throughout the entire experiment and especially at the beginning of each of the five blocks.

TABLE 1 | Percentage of correct categorizations separated for stimulus types and group.

	Gamer	Non-gamer
Prototypical		
Block 1	62.13 (13.24)	65.27 (9.68)
Block 2	75.89 (13.81)	72.27 (12.53)
Block 3	82.44 (13.92)	82.91 (8.76)
Block 4	89.96 (9.37)	85.92 (8.34)
Block 5	93.68 (7.02)	92.09 (5.83)
Exception		
Block 1	41.07 (20.45)	39.92 (27.44)
Block 2	50.89 (23.89)	35.29 (19.80)
Block 3	79.91 (16.54)	62.61 (27.49)
Block 4	80.80 (22.55)	71.43 (19.40)
Block 5	88.84 (16.28)	82.35 (16.58)

Data are presented as mean ± SDM.

Additionally, an evaluative, descriptive comparison of behavioral data separated for male and female participants was performed. The descriptive comparisons of the behavioral categorization performance of male and female subjects showed that female gamers categorized better than female non-gamers and that male gamers performed better than male non-gamers. Besides, female gamers categorized better than male gamers and female non-gamers performed better than male non-gamers as well (see **Supplementary Table 2** and **Figures 1–3**). More detailed results can be found in the **Supplementary Data**.

The calculated ANOVA for the response times yielded evidence for a main effect of the factor "stimulus" ($F_{1,30} = 36.05$; $p = 0.0001$), a main effect of the factor "block" ($F_{4,120} = 29.66$; $p = 0.0001$), as well as an interaction of the factors "stimulus" and "block" ($F_{4,120} = 2.72$; $p = 0.04$). The three-way interaction did not reach significance. Reaction times separated for groups (gamers and non-gamers) are illustrated in **Figure 5**. The reaction times decreased during the experiment (block 1 to block 5) for both stimulus types. The largest difference seemed to be in block 3. However, participants categorized prototypical stimuli in total faster than exceptions (see **Figure 5** and **Supplementary Figures 4, 5**).

Eye-Tracking Data

The visualization of the eye-tracking data in heat maps showed for the start of the learning process scattered fixations over the whole stimulus (central and peripheral stimulus areas). However, the descriptive comparison also showed more focused eye movements for exceptions than for prototype stimuli. In contrast, at the end of the learning process, the eye movements were for both stimulus types more concentrated and focused on specific color segments. The descriptive group comparison showed that action video gamers exhibited less scattered and more center focused eye movements as compared to non-gamers, particularly apparent in the last block of the experiment (**Figure 6**).

The first statistical analysis on the fixation data investigated the fixation behavior in the first and the last block of the experiment (central fixation by exploring peripheral information and peripheral (focused) fixation on stimulus segments).

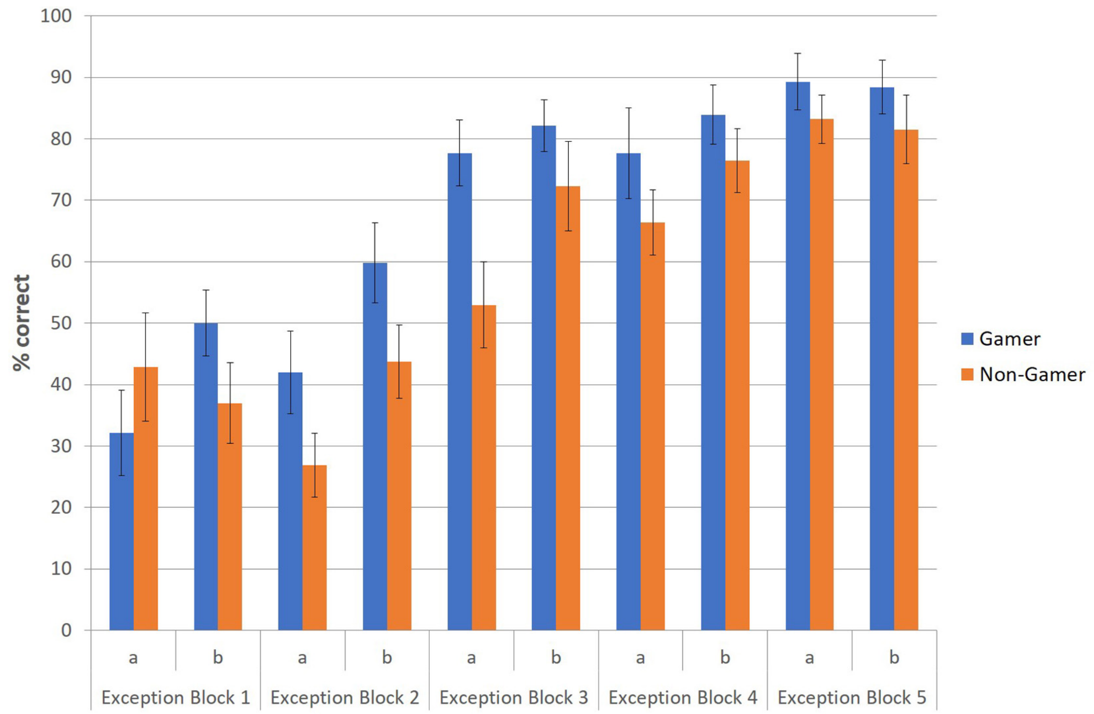

FIGURE 4 | Correctly categorized exceptions (in percent) for the first (a) and second part (b) of each block.

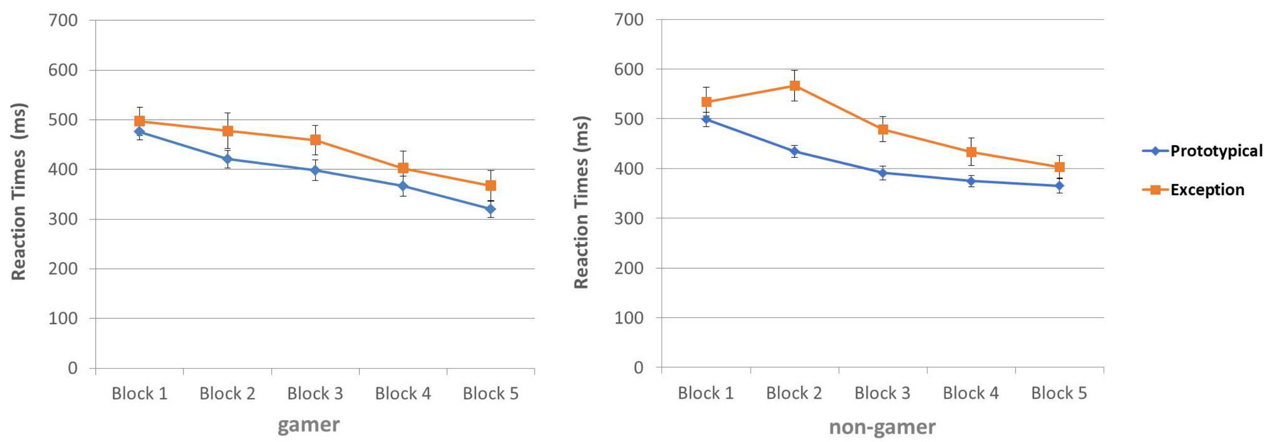

FIGURE 5 | Reaction times (ms) for categorization of prototypical stimuli and exceptions.

The analysis showed a main effect for the factor "fixation" ($F_{1,31}$ = 4.46, p = 0.04) and significant interactions of the factors "stimulus" and "fixation" ($F_{1,31}$ = 7.08, p = 0.01) and of the factors "fixation" and "block" ($F_{1,31}$ = 4.64, p = 0.03) as well as a significant interaction of the factors "stimulus," "fixation," and "group" ($F_{1,31}$ = 4.34, p = 0.04). In general, the analysis showed higher fixation rates of the stimulus center (**Table 2**).

Subsequent paired comparisons revealed in the first block in total more fixations on the stimulus segments [$t(32)$ = 2.13, p = 0.04, d = 0.37] and in the last block more fixations on the stimulus center [$t(32)$ = −2.13, p = 0.04, d = 0.37]. Furthermore, the subsequent analyses yielded only for exceptions higher fixation rates of the stimulus center [exceptions: $t(32)$ = 2.63, p = 0.01, d = 0.46; prototypes: $t(32)$ = 0.83, p = 0.42]. In comparison to exceptions, the analysis showed for prototypes more fixations on the six stimulus segments [$t(32)$ = 2.47, p = 0.01, d = 0.43]. Further subsequent analyses to resolve the interaction of the factors "stimulus," "fixation," and "group" revealed within the stimulus types that only action video gamers showed higher fixation rates on the center of exceptions than on the six stimulus segments of exceptions [$t(15)$ = 2.74, p = 0.02, d = 0.69; see **Table 2** and **Figure 7**].

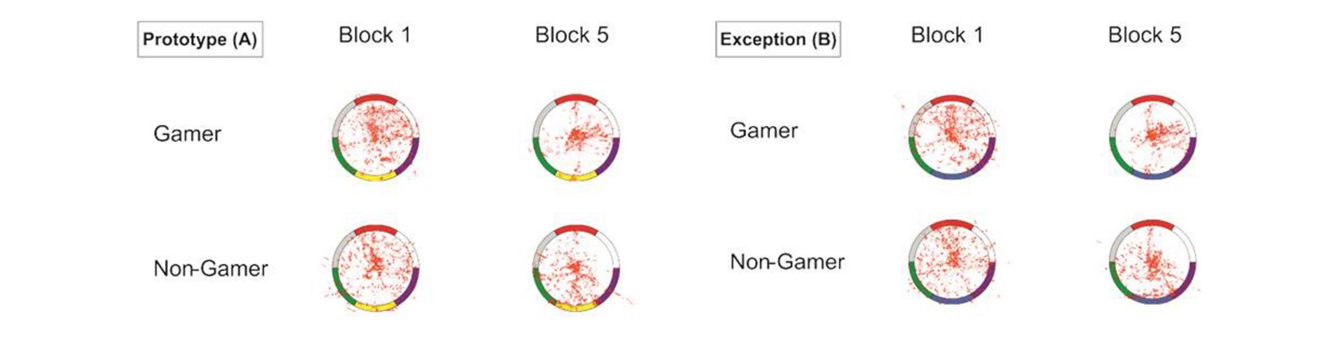

FIGURE 6 | Heat map graphs of the eye-tracking data for both stimulus types (A = prototypes, B = exceptions).

TABLE 2 | Percentage of fixations for each group and both stimuli.

	Stimulus type	Central	Stimulus segments	*t*-score	*p*
Gamer	Prototypes	54.10 (5.43)	45.89 (5.43)	0.76	0.46
	Exceptions	71.68 (7.92)	28.33 (7.92)	2.74	0.02*
Non-gamer	Prototypes	52.04 (5.16)	47.96 (5.16)	0.40	0.70
	Exceptions	54.17 (5.08)	45.83 (5.07)	0.82	0.42

*t-scores and p-values refer to the statistical comparisons of central and stimulus segment-based fixations within the stimulus types. Data are presented as mean ± SEM; *p ≤ 0.05.*

The second statistical analysis of the fixation data, which focused on the fourth stimulus segment of the stimuli of the first category, did not yield significant results. However, the third analysis, which investigated the fixation rates on the fifth stimulus segment for stimuli from category 2, showed a significant interaction of the factors "stimulus" and "block" ($F_{1,31} = 7.38$, $p = 0.01$). Subsequent paired comparisons revealed for the last block with a small effect size significant more fixations on the fifth stimulus segment of exceptions [$t(32) = -2.55$; $p = 0.01$, $d = 0.44$].

A further analysis on the fixation data of the 4th/5th segment was performed by combining the data from categories 1 and 2. The analysis focused on the idea that fixation on these segments should be observed also in the non-exception trials reflecting some performance control. Results of this analysis yielded neither significant main effects nor a significant interaction (all $p > 0.05$).

Concerning saccadic eye movements, the ANOVA on the mean number of saccades per trial yielded a main effect of block ($F_{4,124} = 9.07$; $p = 0.002$). The number of saccades decreased from the beginning to the end of the experiment (see **Table 3**) and some participants did not perform saccades at all during the first 800 ms of stimulus presentation toward the end of the experiment, which is in line with the pattern more fixations in the stimulus center at the end of the experiment that was described above. None of the other main effects and interactions for the number of saccades per trial reached significance (all $p > 0.30$). For the subsequent analysis on the mean latency of the first saccade those participants were excluded who did not perform saccades in at least three trials per block and condition. The sample for this analysis thus consisted of 10 gamers and 14 non-gamers. Again, a significant effect of block ($F_{4,88} = 8.28$; $p < 0.001$) was the only significant effect (for the remaining main effects and interactions all $p > 0.28$). The block main effect indicated an increase in saccade latencies during the course of the experiment (see **Table 4**), which is in line with the reduced number of saccades that were performed during stimulus processing. Both analyses on saccadic eye movements were repeated considering prototypes and typical stimuli combined in one condition and then compared with exceptions. The pattern of findings for these analyses was comparable with the pattern reported for prototypes vs. exceptions.

A further ANOVA including the fixation on the segments before decision showed a significant main effect for the factor "block" ($F_{4,124} = 13.09$, $p < 0.001$). Fixation rates decreased over the five blocks.

EEG Data

The results of the P150 amplitude analysis showed a significant group effect with a strong effect size ($F_{1,31} = 5.73$, $p = 0.02$, $d = 0.86$). Action video gamers generally exhibited higher P150 amplitudes than non-gamers for both stimulus types (see **Table 5** and **Figure 8**). The descriptive comparisons of the P150 amplitudes showed that male as well as female gamers had higher P150 amplitudes than male and female non-gamers (see **Table 5**).

In addition, the analysis yielded for the N170 amplitude a significant between-subject effect ($F_{1.00,31.00} = 7.70$, $p \leq 0.01$). The amplitude is more negative for non-gamers than for action video gamers (**Table 6** and **Figure 8**). Over all participants the analysis yielded a main effect for the factor electrode ($F_{1.92,59.64} = 4.63$, $p = 0.05$). The PO7 and the PO8 amplitudes are more negative than the others (see **Table 6** and **Figure 8**). Separated analyses of the both groups showed different profiles. Only for the non-gamers there was a significant effect for the factor electrode ($F_{1.91,30.48} = 3.70$, $p = 0.05$). For action video gamers the analysis yielded no significant main effects or interactions. Furthermore, the analysis of the N170 latency revealed an interaction between the factors electrode and group ($F_{1.73,53.64} = 4.89$, $p \leq 0.05$),

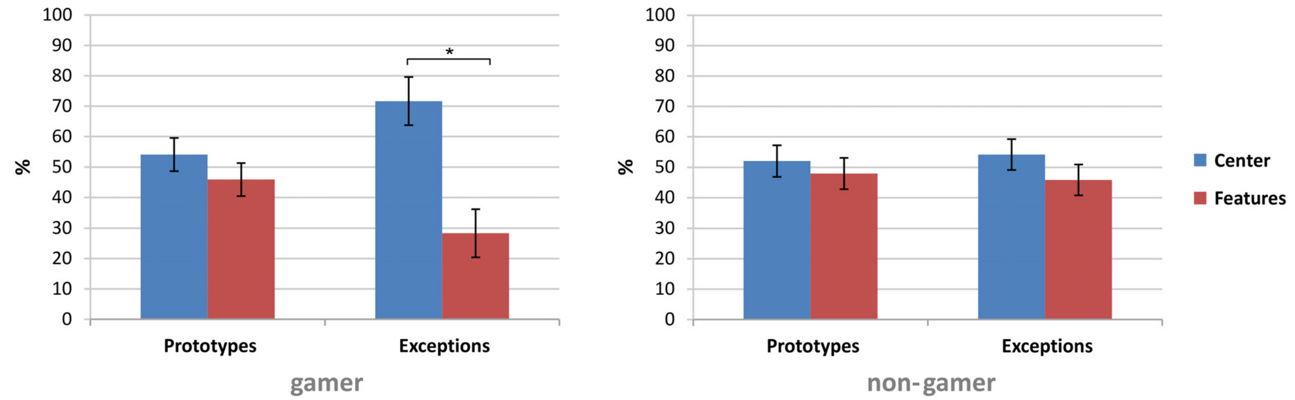

FIGURE 7 | Group comparison of the fixation rates on the six stimulus segments and the stimulus center of prototypes and exceptions. All data are presented in percent as mean ± SEM; *$p \leq 0.05$.

TABLE 3 | Mean number of saccades per trial for prototypical and exception stimuli in blocks 1 to 5 in gamers and non-gamers (SD in brackets).

	Gamer	Non-gamer
Prototypical		
Block 1	2.93 (1.79)	3.18 (3.35)
Block 2	1.98 (0.94)	1.68 (0.91)
Block 3	1.41 (1.17)	1.75 (1.16)
Block 4	1.36 (1.08)	1.66 (0.99)
Block 5	1.17 (1.09)	2.11 (1.79)
Exception		
Block 1	2.74 (1.23)	3.04 (2.69)
Block 2	1.96 (1.06)	1.87 (1.00)
Block 3	1.39 (1.13)	1.95 (1.27)
Block 4	1.39 (1.11)	1.50 (0.81)
Block 5	1.18 (1.18)	1.79 (1.02)

Data are presented as mean ± SDM.

TABLE 4 | Mean latencies of the first saccade per trial (in ms, SD in brackets) for prototypical and exception stimuli in blocks 1 to 5 in gamers and non-gamers.

	Gamer	Non-gamer
Prototypical		
Block 1	244.38 (59.40)	277.61 (56.22)
Block 2	285.44 (43.64)	289.21 (79.27)
Block 3	335.28 (99.08)	325.87 (97.99)
Block 4	302.99 (92.75)	321.42 (84.58)
Block 5	339.08 (69.48)	325.55 (101.58)
Exception		
Block 1	261.91 (48.43)	284.99 (63.62)
Block 2	267.85 (41.46)	275.81 (91.55)
Block 3	349.73 (94.41)	306.47 (71.37)
Block 4	325.54 (82.34)	316.31 (84.40)
Block 5	311.62 (65.29)	327.67 (76.00)

Note that these data are based on a subsample of participants who performed saccades in at least three trials per condition and block. Data are presented as mean ± SDM.

TABLE 5 | Analysis results of the P150 amplitudes (μV).

	Gamer	Non-gamer
Prototypical		
All	**2.58 (1.20)**	**0.81 (2.63)**
Men	2.71 (1.18)	0.86 (1.83)
Woman	1.63 (1.22)	0.80 (2.83)
Exception		
All	**3.29 (1.80)**	**1.39 (2.96)**
Men	3.42 (1.89)	1.91 (1.62)
Woman	2.43 (0.18)	1.28 (3.21)

Data are presented as mean ± SDM.

such as the factors stimulus and electrode ($F_{1.97,60.92} = 3.28$, $p = 0.05$). Action video gamers had descriptively higher latencies at the right side ($F_{1.00,31.00} = 1.28$, $p = 0.27$; see **Table 6**) and non-gamers showed almost significant higher latencies at the left side ($F_{1.00,31.00} = 3.88$, $p = 0.058$). For exceptions non-gamers showed a significant higher PO7 latency ($F_{1.00,31.00} = 4.49$, $p = 0.05$), meanwhile action video gamers had higher latencies at the P8 position for prototypical stimuli ($F_{1.00,31.00} = 3.72$, $p = 0.06$). Besides, the P7 and PO7 latencies were descriptively shorter for prototypical stimuli and the P8 and PO8 latencies were descriptively shorter for exceptions (all $p \geq 0.10$; see **Table 6**).

DISCUSSION

The behavioral results are in line with the findings of Cook and Smith (2006), showing that both groups categorized prototypical stimuli in prior blocks and with shorter reaction times than exceptions. At the beginning of the experiment prototypical stimuli were better categorized than exceptions, but in the third block the number of correctly categorized exceptions increased (Lech et al., 2016; Schenk et al., 2016). In line with this, the subsequent analyses of accuracy changes over the five blocks yield evidence for significant differences only between the second and third block. Furthermore, participants categorized prototypical stimuli in total faster than exceptions, but highest differences in the reaction times for the two stimulus types could be detected in

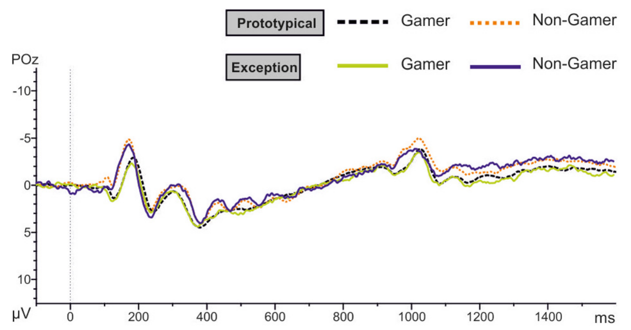

FIGURE 8 | EEG results at POz position for both stimulus types.

TABLE 6 | Means and standard deviations of the N 170 amplitudes (µV) for electrode position P7 and P8.

	Gamer		Non-gamer	
	P7	**P8**	**P7**	**P8**
Prototypical	−0.61 (0.78)	−1.12 (1.85)	−2.06 (1.98)	−3.10 (3.2)
Exception	−0.98 (0.96)	−0.76 (1.84)	−2.25 (2.33)	−3.22 (3.68)

Data are presented as mean ± SDM.

the third block. These results may be due to the different learning strategies required for the stimulus types or the need to explicitly remember exceptions. However, the use of special or different learning strategies cannot be clearly demonstrated.

The analyses and illustrations of the behavioral learning data showed a significant group-stimulus interaction, which was based on the superior categorization performance of action video gamers for exceptions, especially in the second and third block. Regarding the categorization performance of exceptions, action video gamers additionally showed a better categorization performance at the beginning of each block throughout the experiment. Nevertheless, the advantage of action video gamers is balanced toward the end of the experiment. It seemed that non-gamers need more trials to correctly categorize the exceptions.

Based on the stimulus-type-dependent learning curves, differences in the eye-tracking data with respect to the stimulus type and between the beginning and the end phase of the learning process might have been expected. Especially in terms of the two stimulus segments that are critical for categorizing exceptions, higher fixation rates during the categorization of exceptions were expected. The visualization of the eye-tracking data showed in the first block in total more fixations on the stimulus segments and in the last block more fixations on the stimulus center. However, the statistical analyses showed for all eye-tracking measures except one (center vs. periphery fixations) no differences between action video gamers and non-gamers. The analyses mainly yielded only for exceptions higher fixation rates of the stimulus center. For both groups fixation rates decreased over the five blocks. Furthermore, the number of saccades decreased from the beginning to the end of the experiment, which is in line with the pattern more fixations in the stimulus center at the end of the experiment. In addition, an increase in saccade latencies during the course of the experiment was observed. As expected in the case of exceptions, one of the two segments that are decisive for correct categorization shows higher fixation rates at the end of the experiment. These findings indicate for both groups a learning process regarding the stimulus material. It is possible that in an early learning phase, both groups tried to learn the stimuli based on their different color features and showed more fixations on the stimulus segments, while in the last block they showed more fixations on the stimulus center. The participants had learned the stimuli and did not need to explore them entirely anymore.

In general, only action video gamers showed higher fixation rates on the stimulus center for exceptions. In comparison to non-gamers, action video gamers showed different, more central fixations possibly indicating covert peripheral processing. This might also be explained by the special design of the stimuli used in this study. It can be hypothesized that this advantage of video game players might vanish if critical stimuli were presented in the center. On the other side it might be the case, that action video gamers show even in an experiment with such stimuli better performance as they might be faster in capturing visual information *per se*. The critical factor for such an advantage might be the processing of especially complexity of the stimuli. Stimuli with low information content or complexity might lead to a ceiling effect in performance independently whether the participants are action video gamers or not. Additionally, regarding fixation rates, it may be possible that the stimulus presentation times were too short to ensure a clear and detailed analysis of the stimuli. Furthermore, there was no clear instruction to fixate critical stimulus segments. As no group effect or interaction was observed for the eye tracking data, central fixation with possible peripheral exploration and processing of the information might reflect best the advantage of video game player in the current experiment with no changes over time. Nevertheless, the eye-tracking data yielded no clear information about the strategy used by the participants during categorization in this experiment. Unfortunately, this explanation is statistically not supported by the results.

Moreover, the analyses of EEG Data showed that groups differed with respect to differential expressions of the attention related P150 ERP component (early perceptual analysis). Action video gamers generally exhibited higher P150 amplitudes than non-gamers for both stimulus types. The higher P150 amplitudes of action video gamers may be an indicator for an early and more enhanced perceptual analysis of the stimulus material This early perceptual analysis maybe due to their video game experience, but, above all, is more useful for the categorization of exceptions, particular at the beginning of the learning paradigm. Therefore, it could facilitate a faster learning of exceptions with no changes over blocks.

We have shown in a recent study (Schenk et al., 2016) that it might be speculated whether the P150 amplitude is a critical EEG component which reflects the effort of an attention driven perceptual analysis used for categorization in general, especially in the task used in both studies. The study of Schenk et al. (2016)

used the same categorization paradigm and compared the categorization performances as well as the P150 amplitudes of elderly and young subjects to investigate age-dependent differences. In contrast to young subjects, elderly subject showed a worse categorization performance in combination with a higher P150 amplitudes. Taken the results of both studies together, it seems that the P150 can be found with better and worse categorization performance. One possible interpretation of this is that action video gamers, as well as elderly subjects, used an enhanced early perceptual analysis, which requires a higher level of attention effort. It seems likely that elderly subjects need this enhanced attention driven early perceptual analysis to compensate their cognitive decline (e.g., in memory functions) in order to be able to learn the categories at all. Overall, it seems to be more difficult for elderly subjects to learn the explicitly remembered exceptions. It might be speculated whether the performance of elderly subjects might be even worse if the compensating P150 effect and its underlying process might have not been available. In contrast, the increased P150 amplitudes of action video players are more likely explained due to a training effect. Action video players have to perceive and analyze the environment within their games, including the smallest features, very quickly. This necessary early perceptual analysis requires high attention efforts in order to be able to react quickly. Action video gamers are trained in the detection of relevant stimulus information and may thereby use a more enhanced perceptual analysis, which is in this case especially important for the learning of exceptions. A further interpretation might be that for action video gamer the high P150 amplitude reflects their state during categorization based on their experience. In contrast, elderly subjects have to make an effort to achieve this state as a compensatory mechanism. Missing experience with action video gaming and cognitive decline might therefore not lead to the use of these processes that are reflected by the P150. In general, it has to be pointed out, that these are interpretations based on the results of these two studies.

Meanwhile, the significant group difference in the N170 amplitude might reflect group specific differences in perceptual process. It has been shown, that N170 amplitudes differs in the case of visual expertise (Rossion et al., 2004). Present results showed that non-gamers showed higher N170 amplitudes. This result suggests that the N170 is not exclusive to faces. It may further be speculated whether the higher N170 amplitude might reflect increased processing demands in the non-gamers as suggested by findings from Rossion et al. (1999) for faces. In contrast, lower N170 amplitudes in action video gamers could be due to a lower demanding for action video gamers in the current task.

Taken these findings together multi fold differences between action video gamers and non-gamers have been found which might support the idea of advantages for action video gamers in categorization learning, particular for exceptions and at an early learning stage. Similar to the study of West et al. (2015) the findings of the current study may be attributed to a more efficient direction in attention and an increased perceptual system of action video gamers that helped them to resolve the learning tasks. While we did find differences between the fixations and ERPs of action video game players and non-video game players, these differences did not always change as a function of block or exemplar type, making it difficult to link them to categorization specifically. The fixation group differences (central vs. peripheral) did interact with stimulus type, but the ERP differences were only manifested as main effects of group. Therefore, these results have to be considered independently and reflect each an individual factor that seems to be relevant for categorization. West et al. (2015) showed in their study that in contrast to non-gamers, it seemed that action video gamers showed an enhanced counting and remembering of specific sequences, features and target locations. This enhanced counting and remembering of specific features and locations could have given the action video players in the present study advantages in particular when learning the exceptions. It is possible that action video gamers can generate a more explicit knowledge of the exceptions through this different type of stimulus exploration and processing and can therefore remember them better.

However, it should be noted that the results of the current study only provide a first indication of potential group differences between the categorization performances of action video gamers and non-gamers. Different types of video games may lead in different impact (e.g., Green and Bavelier, 2003; Krishnan et al., 2013). A differentiated consideration of gaming varieties is necessary in order to be able to make concrete statements about the effects.

Another limiting factor of the current study is the heterogeneous sample of participants with an unequal gender distribution. Exploratory analyses suggest that women irrespective whether they were action video gamers or non-gamers outperform men in categorization (**Supplementary Figures 1–3**). This is interesting as other studies have shown that video games can lead to a reduction of gender differences in similar tasks (Subrahmanyam and Greenfield, 1994; Feng et al., 2007; Stoet, 2011). Based on the small sample size, this effect has to be seen very cautious. Separate statistical analyses with respect to gender are not meaningful. Further gender-balanced training studies with an intervention and control group employing a within-subjects design with pre- and post-tests are needed to pinpoint the exact effects of action video game experience on categorization learning and to exclude other personal factors.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the Faculty of Psychology, Ruhr University Bochum, Germany.

The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SS conceptualized and designed the study, carried out the data analyses and interpreted data, drafted the initial manuscript and reviewed and revised the manuscript. CB analyzed the eye tracking data and wrote parts of the manuscript and reviewed it for important intellectual content. RL supervised data collection and critically reviewed the manuscript for important intellectual content. RH carried out additional data analyses of the eye-tracking data and reviewed the method section of the manuscript. BS conceptualized and designed the study, supervised data collection, interpreted data and reviewed the manuscript for important intellectual content. All authors approved the final manuscript as submitted and agreed to be accountable for all aspects of the work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2020.00933/full#supplementary-material

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Past Gaming Experience and Cognition as Selective Predictors of Novel Game Learning Across Different Gaming Genres

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Past experience with video games and cognitive abilities have been hypothesized to independently facilitate a greater ability to learn new video games and other complex tasks. The present study was conducted to examine this "learning to learn" hypothesis. We examined the predictive effects of gaming habits (e.g., self-identification as a "gamer," hours spent gaming per week, weekly gaming frequency, relative preference for strategy over action games) and cognitive abilities (short-term memory, working memory, and processing speed) on learning of two novel video games in 107 participants (aged 18–77 years). One video game was from the action genre, and the other was from the strategy genre. Hours spent gaming per week and working memory were found to specifically predict learning of the novel strategy video game, after controlling for the effects of age, gender, and action game learning. In contrast, self-identification as a "gamer" was the only specific significant predictor of action game learning, after controlling for the effects of age, gender, and strategy game learning. Age of the participant negatively impacted learning of both games; however, the pattern of the predictive relationships on both action and strategy game learning was not moderated by age. Importantly, a preference for the action versus the strategy game genre had no differential effects on learning of the two novel games, nor were there any gender differences in identification as a gamer or genre preference. Findings from this study suggest that while past gaming experience and cognition do appear to influence the learning of novel video games, these effects are selective to the game genre studied and are not as broad as the "learning to learn" model suggests.

Keywords: video games, genres, learning, life span, working memory, gaming habits

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INTRODUCTION

Video games are not only an incredibly prevalent medium of entertainment (Lenhart et al., 2008; Rideout et al., 2010); they have become a much-researched topic of investigation within the cognitive sciences. A large body of work investigating the cognitive profiles of video game players has established an advantage in perceptual and spatial attentional skills for gamers who play for 3 h or more per week, compared to novices who play video games for, at most, 1 h per week (for a meta-analysis, see Bediou et al., 2018). In response to these findings, numerous experimental studies have been conducted to investigate the possibility of video game training directly enhancing cognition in not only younger adults aged 18–30 years but also older adults, aged 60 years and above, who have impaired cognitive abilities (Powers et al., 2013; Simons et al., 2016). While many such intervention studies have demonstrated positive cognitive outcomes (e.g., Green and Bavelier, 2006; Basak et al., 2008, 2020; Green et al., 2010; Toril et al., 2014), others have failed to identify training-related gains to cognition (e.g., Boot et al., 2013; van Ravenzwaaij et al., 2014; Minear et al., 2016). Given these mixed findings, the efficacy of video game interventions remains highly contentious (Bisoglio et al., 2014; Simons et al., 2016). One factor that may explain these mixed findings of video game intervention studies is *game genre*.

While terms vary, games within the cognitive training literature are most commonly divided into the following *game genres*: “action games,” “strategy games,” and “casual games” (see Simons et al., 2016, for a review). These genres have been argued to be an unreliable categorization of video games, particularly in cases where a game demonstrates features that can be attributed to multiple different genres (Dale and Green, 2017). However, studies that explicitly compared action games and strategy games to other games have shown differential benefits to cognition in younger adults (Cohen et al., 2008; Glass et al., 2013; Oei and Patterson, 2013, 2014; Wu and Spence, 2013). Training on the action game genre, such as first-person shooter (FPS) games and racing video games, selectively improved measures of attention, when compared to training on non-action games (Cohen et al., 2008; Wu and Spence, 2013; Oei and Patterson, 2014). In contrast, training on the strategy game genre, such puzzle games and real-time strategy (RTS) games, selectively improved working memory (including verbal and spatial and executive functions, when compared to other non-strategy and action games (Glass et al., 2013; Oei and Patterson, 2013, 2014). These results on strategy games from younger adults are extended to older adults, where training on RTS games has shown improvements in working memory, executive functions, and reasoning abilities (Basak et al., 2008; Whitlock et al., 2012), with faster learning of the RTS game being associated with greater improvements in executive functions and working memory (Basak et al., 2008) and with larger fronto-parietal and cerebellar gray matter volumes (Basak et al., 2011). In addition to these differential effects on cognition from action versus strategy game genres, studies have also shown partially different cognitive profiles that underlie performance on action versus strategy games (Baniqued et al., 2013; Ray et al., 2017). Working memory, reasoning, and processing speed were more correlated to games with strong reasoning and memory components—common attributes of the strategy game genre. Games with attention and speed components—common attributes of the action game genre—were related to measures of perception and reasoning (Baniqued et al., 2013; Ray et al., 2017). Together, these results from training and cognitive profiling indicate that the coarse genre distinction of action versus strategy does have some reliability and validity.

The genre distinction is supported by a neuroimaging study, where tract-based spatial statistics (TBSS) analysis of diffusion tensor imaging (DTI) was conducted in novice video gamers of a broad age range (18–80 years). Different regions of white-matter connectivity predicted selective learning of action versus strategy genres. Increased connectivity between limbic brain regions (fornix–stria terminalis), that are argued to underlie emotional arousal (Ravaja et al., 2004, 2006, 2008), predicted specifically action video game learning, whereas increased connectivity between subcortical regions that subserve memory (left cingulum–hippocampus) specifically predicted strategy video game learning. The casual games used in this study were Sushi-Go-Around, which combined attributes of the strategy game genre, and Tank Attack 3D, a shooter game that combined attributes of action game genre. Sushi-Go-Around was also investigated and classified in Baniqued et al. (2013). In the current study, we therefore limit our investigation to these two games, given the reliability and validity of these games under their respective genres. We assessed complex skill learning in these two novel games in an adult life span sample of participants who had not played this game before, and related the learning measures to past gaming experience and cognition. Given the past findings that showed that games with attention and speed components, such as FPS and shooter games, are related to perception, and that strategy games are related to memory (Baniqued et al., 2013) and brain structures underlying memory processing (Ray et al., 2017), we hypothesize that there will be a greater positive relationship between strategy novel-game game learning and cognition, specially working memory, compared to the relationship between action game learning and cognition.

Alternatively, we may observe just a general positive relationship between complex skill learning and cognition but no differential relationships across the two games, especially when accounting for gaming experience. The “learning to learn” model (Bavelier et al., 2012; Green and Bavelier, 2012) posits that enhanced cognitive ability observed in habitual video game players is not due to specifically bolstered attentional or memory capacity but, rather, an acquired ability to learn novel tasks for which they have no prior experience. Bavelier and colleagues specifically argue that, due to the wide variety of cognitive demands presented by different types of video games and the propensity of habitual video game players to periodically acquire and play new games, habitual game players have developed strategies and propensities which allow them to learn the intricacies of a novel, never-before-played video game—and by extension, other tasks that they have no prior exposure to—more quickly than non-players.

From this perspective, we hypothesize that individuals who either play video games more frequently, or identify themselves as gamers, or play for longer duration would demonstrate an advantage in novel game learning, irrespective of the gaming genre. To date, this hypothesis has not been tested with respect to novel game learning. However, one study observed no difference in learning rates on a serial reaction time task between habitual action video game players and non-gamers (Morin-Moncet et al., 2016), which runs counter to the primary prediction of the “learning to learn” model. Moreover, there is paucity of studies reporting any correlation between duration or frequency of game play and cognition. To date, only one study has reported scaled benefits to motor control and visual perception related to self-reported hours of weekly game play (Rupp et al., 2019).

In the current study, not only will we evaluate the relationships between novel game learning across the two genres and cognition; we will also determine if these relationships are mitigated by game experience, such as gaming frequency or lengths of time spent on gaming or self-identification as a gamer. We hypothesize that gaming frequency and gaming duration will be significantly correlated with learning of both new games, based on the "learning to learn" hypothesis. However, it is not known whether there are any specific, differential effects of past game experiences on the two different games under investigation. If these game experience variables predict similarly the learning of the two games, we will find support for the "learning to learn" model, whereas differential predictors of these two different genres of games would suggest that the influence of past experience on novel game learning is more nuanced than the "learning to learn" model suggests.

Additionally, we will also evaluate at post-learning participant's preference ratings of the two games played. It is possible that the speed with which we learn a game may influence our preference for that game compared to the other, and this preference may influence cognition–learning relationships. However, if no relationships between game preference and game learning are found, then the specific effects of cognition and game experience on learning of the two games can be considered to be independent of individual differences in game preference.

An important aspect of the current study is the use of a life span sample. Most studies on video games experience and cognition are restricted to younger adults and therefore cannot be generalized to other age groups. Given the prevalence of video games as a cognitive intervention tool in older adults (for meta-analyses, see Lampit et al., 2014; Toril et al., 2014; Basak et al., 2020), it is important that we understand these relationships from an adult life span perspective. However, not all types of cognitive interventions have similar beneficial effects on cognition, especially on *far* cognitive abilities that were not trained. In a recent meta-analysis, effects of cognitive training from randomized control trials on healthy older adults and older adults with mild cognitive impairments (MCIs) were evaluated (Basak et al., 2020). In particular, cognitive training targeting a single cognitive component was compared to those training multiple cognitive components. Single cognitive component training studies were further separated into following modules: speed, executive functions (including switching, inhibition, and working memory updating), reasoning, and memory (including memory training strategies). Only executive functions (including working memory) training and memory training had significant effects on far cognitive abilities, measured by tasks that are unrelated to the training task(s). Therefore, it is possible that certain genres of video games, depending on what cognitive components they rely upon, may be more effective as cognitive intervention tools, particularly in middle and late adulthood. The current study, by engaging a life span approach that incorporates not only young adults but also older adults as participants, is poised to investigate if speed and working memory are correlated differently to action and strategy game learning and whether these effects are moderated by age. This research is significant because it has the potential to inform on what game genres may be the best for cognitive interventions, tailored to a participant's cognition, past gaming experience, age, and game preferences.

MATERIALS AND METHODS

Participants

One hundred and seven adults (40 females; M_{Age} = 34.79, SD_{Age} = 20.59; aged 18–77) participated in this study. Fifty-three participants were recruited from the University of Texas at Dallas and received class credit for their participation. The remaining 54 participants were recruited from Dallas and its neighboring communities and were paid $10/h for their participation. Inclusion criteria were high school education (or more), normal or corrected-to-normal vision (visual acuity $>$20/30), and no reported history of major medical or psychological illnesses (e.g., visual neglect, epilepsy, heart attacks, etc.). Participants aged 55 and older were required to score 26 or above in the Mini-Mental State Examination (MMSE 2nd Edition; Folstein et al., 2010), an indicator of normal cognitive health.

Ethical Approval and Informed Consent

The study was approved by the Institutional Review Board of the University of Texas at Dallas and performed in accordance with the ethical standards for research outlined by that review board. Written and informed consent was collected from all participants included in this study prior to any testing procedures.

Procedures

In this 2 h study, after informed consent, participants underwent cognitive assessments of processing speed (a measure of attention), short-term memory, and working memory. Then the participants played two novel online video games for which they had no reported prior experience. These games were played in succession for 40 min each (80 min total). The order of the games played was counterbalanced between the participants. Finally, participants answered a survey of their past gaming experience and their preferences on the two games played.

Cognitive Measures

Cognitive tests administered included the following: forward digit span (*FSpan*), a measure of short-term memory that requires temporary storage of digits for a very short period of time (*WAIS-R: Wechsler Adult Intelligence Scale—Revised*; Wechsler, 1981); backward digit span (*BSpan*), a measure of working memory that requires, in addition to storage, manipulation of the digits in mental workspace (*WAIS-R*; Wechsler, 1981); and the Symbol–Digit Substitution Test (*SDST,* taken from the *MMSE 2nd Edition*), a measure of processing speed (Folstein et al., 2010).

Gaming Genres and Calculation of Learning Composites

The two video games played were Tank Attack 3D, an action game, and Sushi-Go-Round, a strategy game, on miniclip.com, a website which hosts free casual games spanning multiple genres (Baniqued et al., 2013). Games from minilip.com were utilized due to their ease of access and short individual play duration, which allowed for multiple iterations of the game to be played in a relatively short time period and facilitated the assessment of game learning quickly. Additionally, both games feature adaptive difficulty, introducing new and more challenging mechanics in response to high performance by the player, which allowed us to assess the degree to which our participants learned these mechanics by proxy of progression through each game. Lastly, both of these selected games conform to the "action" and "strategy" genres as defined by the video game cognition literature, thereby avoiding issues of interpretation presented by more complex, longer-playing video games that involve multiple genre features (Dale and Green, 2017).

Tank Attack 3D (**Figure 1**) was selected as an exemplar action game due to its strong perceptual and attentional demands, coupled with relatively minimal resource management and decision-making requirements (Baniqued et al., 2013; Ray et al., 2017). In Tank Attack 3D, players are required to operate a tank through a war area to destroy enemy radars, tanks, and bases. To complete the mission successfully, players were required to arrive at their home base with remaining energy before the timer ran out. In addition to the time awareness required for successful play, players had to react to fast-moving stimuli and keep track of multiple items, such as the number of radars destroyed and life energy left. Additionally, Tank Attack 3D periodically introduces new types of enemies in response to player victories, forcing the player to adapt to those new challenges to succeed in later missions.

Sushi-Go-Round (**Figure 1**) was selected as an exemplar strategy game due to its strong emphasis on resource management, coordination between multiple information units and tasks, rapid reasoning, and decision making (Baniqued et al., 2013; Ray et al., 2017). In Sushi-Go-Round, players are required to serve a variety of sushi preparations to a continuous stream of customers while simultaneously monitoring customer happiness, order times, remaining ingredients, and monetary incomes and expenses. To complete a level successfully, players were required to accumulate a certain monetary value by serving customers the requested dishes, while avoiding making the customers wait too long, serving the customer an incorrect dish, or making errors in dish preparation. Additionally, Sushi-Go-Round periodically introduces new and more complex recipes to the menu in response to player success, forcing players to continuously learn new recipes to succeed in later levels.

Participants were asked to play each game continuously for 40 min, and the play order was counterbalanced across participants. A round of either game lasted for about 7 min. The games also become adaptively more difficult, indexed by the game level, based on the participant's performance. In cases where a round was in progress after 40 min had elapsed, participants were asked to finish that round and then cease play.

A *learning composite (LC)* measure was calculated for each game for each participant based on two outcome measures: *highest level* reached in each game at the end of 40 min and the *learning rate*. *Learning rate* was calculated as the slope of a logarithmic function fitted to each participant's scores (higher scores indicate higher success in game play). A steeper slope implies faster learning and greater improvement (Basak et al., 2011; Ray et al., 2017). *Highest level reached* reflected the difficulty tier reached in each game and was reported as "day" for Sushi-Go-Round and "mission" for Tank Attack 3D. These two measures (*learning rate* and *highest level reached)* were first standardized (z-scored) and then averaged to create the *LC*. We utilized a composite measure to assess learning rates as a method of insulating against fatigue effects: the score output of both Sushi-Go Round and Tank Attack 3D fluctuates with the participant's performance and can drop over time if the participant becomes fatigued or less engaged with the task. *Highest level*, conversely, can never fall as a result of poor performance in these games and, as discussed above, is a proxy of the participant's learning of the mechanics of each game. Constructing these measures allowed us to examine two different metrics of learning on each game, while lessening the overall measure's susceptibility to fatigue effects, and is consistent with our approach in previous published research which assessed learning rates on these two games or similar games (Boot et al., 2010; Basak et al., 2011; Ray et al., 2017).

Past Gaming Habits and Preferences Survey

Participants completed a survey of gaming habits and preferences adapted from that used by Basak et al. (2008, 2011) and Boot et al. (2008) to assess the level of video game skill (i.e., to identify expert or novice players). This adapted questionnaire addressed the participants' typical video game habits on a weekly basis, as is the standard methodology used in the game cognition field to differentiate between non-players and players of various skill levels (Green and Bavelier, 2006; Feng et al., 2007; Basak et al., 2008, 2011; Boot et al., 2008; McDermott et al., 2014).

Unless otherwise noted, responses were recorded on a five-point Likert scale for the questions in the survey. Individuals rated how frequently they played different genres and formats of video games from "never" to "often"; ratings were collapsed across five common game formats (personal computer game, game arcade, home gaming console, internet gaming website, phone/tablet game) to determine an individual's gaming *Frequency*. Experience with specific action game subgenres (FPS, racing, and simulation); specific strategy game subgenres [RTS, role-playing games (RPGs), simulation, and puzzle]; and casual games was assessed on the same scale. *Identification* as a gamer was rated on a five-point Likert scale of "do not identify at all" to "strongly identifies."

Gaming duration was measured via a numeric report of estimated weekly hours spent gaming over the past month. These variables (*Frequency, Duration, Identification*) constitute an individual's game habits for the purpose of this study.

In addition to these questions, participants also rated their level of enjoyment of playing the two games used in this study (1 = did not enjoy, 5 = highly enjoyable). The enjoyment rating for Tank Attack 3D was subtracted from that of Sushi-Go-Round to yield the game *Preference* score; a positive score indicates greater preference for Sushi-Go-Round, whereas negative score indicates greater preference for Tank Attack 3D.

Justification of Statistical Power

We have sufficient power to not only examine correlations between two variables but also conduct multiple regressions required to evaluate the cognition–learning, experience–learning, and cognition–experience–learning relationships. All estimations for power analyses were conducted using G*power3.1 (Faul et al., 2009). Our sample size of 107 participants provides us with a power greater than 0.95 to detect an effect size of 0.5 in a regression analysis with only one predictor, and a power greater than 0.92 to detect the same effect size in a multiple regression analysis with three predictors (e.g., three cognitive variables as predictors of game learning). We also have a power greater than 0.8 to detect an effect size of 0.5 in a multiple regression analysis with all seven regressors of interest in this study, that is, three cognitive variables (*FSpan, BSpan, SDST*), three game habit variables (*Identification, Duration, Frequency*), and one game preference variable.

RESULTS

Descriptive Statistics of Cognitive and Game Habit Variables

Table 1 reports means and standard deviations of responses to the game habit variables (*Frequency, Duration, Identification)* as well as means and standard deviations of the cognitive assessments administered (*FSpan, BSpan, SDST*) and of game *Preference*. Notably, the primary *Preference* measure (relative preference of Sushi-Go-Round over Tank Attack, *S-A*) indicated that participants preferred Tank Attack 3D (action game) over Sushi-Go-Round (strategy game), mean *S-A* = −0.29, SD = 1.72. A paired-samples t-test comparing reported preference for each of these games found this difference to be significant, $t(106) = 2.26$, $p = 0.03$.

Relationships Between Cognition, Game Habits, Game Preference, and Novel Game Learning

We ran a series of bivariate correlations, using Pearson's method, between the variables of game habits, cognition, and novel game learning, as well as *Preference*, to establish baseline relationships between these measures. The results of these correlations are presented in **Figure 2**. The game habit variables (*Frequency, Duration,* and *Identification*) were significantly inter-correlated: *Frequency–Duration,* $r(106) = 0.7$, $p < 0.01$; *Frequency–Identification,* $r(106) = 0.68$, $p < 0.01$; *Duration–Identification,* $r(106) = 0.74$, $p < 0.01$. Similarly, both *Action LC* and *Strategy LC* were significantly correlated, $r(106) = 0.78$, $p < 0.01$. These bivariate correlations suggest that the multiple measures of the two constructs, *game habit* and *novel game learning*, were strongly inter-correlated and were reliable measures of these constructs. For cognition, *FSpan* and *BSpan* were significantly correlated, $r(106) = 0.47$, $p < 0.01$, but neither was significantly correlated with *SDST*, [*FSpan* $r(106) = -0.06$, $p = 0.6$; *BSpan* $r(106) = 0.13$, $p = 0.21$].

Regarding the habit–learning relationship, all measures of game experience (*Frequency*, *Duration*, and *Identification*) were significantly and positively correlated with both Action LC [*Frequency,* $r(106) = 0.67$, $p < 0.01$; *Duration,* $r(106) = 0.59$, $p < 0.01$; *Identification,* $r(106) = 0.62$, $p < 0.01$] and Strategy LC [*Frequency,* $r(106) = 0.53$, $p < 0.01$; *Duration,* $r(106) = 0.5$, $p < 0.01$; *Identification,* $r(106) = 0.46$, $p < 0.01$]. Regarding habit–cognition relationships, *Duration* was significantly correlated with *FSpan*, $r(108) = 0.23$, $p = 0.03$, as was *Identification*, $r(106) = 0.21$, $p = 0.04$. *Identification* was additionally significantly correlated with b *BSpan*, $r(106) = 0.22$, $p = 0.03$. These results suggest that greater gaming experience was related to better learning of novel games, better working memory, and to a lesser degree, better short-term memory.

Preference was significantly and positively related to both *Duration*, $r(106) = 0.21$, $p = 0.03$, and *Identification*, $r(106) = 0.25$, $p = 0.01$, but not with *Frequency*, $r(106) = 0.17$, $p = 0.08$, indicating that participants who reported a higher preference for the action game than the strategy game tended to also report, on average, more hours of gameplay per week and more strongly identified as "gamers." *Preference* was not related to either of the two memory span measures [*FSpan*, $r(106) = 0.08$, $p = 0.48$; *BSpan*, $r(106) = 0.08$, $p = 0.43$], nor to either LC [*Action LC*, $r(106) = 0.1$, $p = 0.29$; *Strategy LC*, $r(106) = -0.11$, $p = 0.26$]. *SDST* was, however, significantly but negatively correlated with preference of the action game over the strategy game, $r(106) = -0.27$, $p = 0.01$. This result suggests that individual differences in greater preference for the strategy game over the action game was related to better performance on SDST (a measure of processing speed), although preference for one type of game over another was not impacted by individual differences in memory spans, either *FSpan* or *BSpan*. The results from the effects of *Preference* for a specific game on learning of the two games are reported in detail in section "Additional Analyses: Effect of Game Preference on Novel Game Learning."

Age and Gender as Predictors of Novel Game Learning

In order to investigate the potential influence of demographic variables on novel game learning, we first analyzed the relationships of participants' age and gender with the other variables (game habits, preference, cognition, and learning).

Bivariate correlations using Pearson's method indicated that age was inversely correlated with *Frequency*, $r(106) = -0.48$, $p < 0.01$, *Duration*, $r(106) = -0.3$, $p < 0.01$, and *Identification*, $r(106) = -0.32$, $p < 0.01$, as well as LCs of both action, $r(106) = 0.75$, $p < 0.01$, and strategy, $r(106) = -0.73$, $p < 0.01$, games. Age was not significantly correlated with *Preference*, $r(106) = 0.09$, $p = 0.36$. For cognition, age was inversely correlated with working memory capacity (*BSpan*), $r(106) = -0.2$, $p = 0.06$, and processing speed (*SDST*), $r(106) = -0.65$, $p < 0.01$, but not with STM (*FSpan*), $r(106) = -0.14$, $p = 0.19$ (**Figure 1A**).

A

	Frequency	Duration	Ident.	Preference (S>A)	Forward Span	Backward Span	SDST	Action LC	Strategy LC
Age	-0.48**	-0.3**	-0.32**	0.09	-0.14	-0.2**	-0.65**	-0.75**	-0.73**

B

	Frequency	Duration	Ident.	Preference (S>A)	Forward Span	Backward Span	SDST
Action LC	0.49**	0.51**	0.58**	0.25	0.06	0.18	0.03
Strat. LC	0.28*	0.41**	0.33*	-0.08	0.21	0.23	0.16

C

	FPS	RTS	Puzzle	RPG	Racing	Simulation	Sports	Casual
Action LC	0.42**	0.29**	0.05	0.51**	0.07	0.15	0.07	0.17
Strat. LC	0.11	0.27**	0.05	0.32**	-0.13	0.11	-0.20*	0.25**

Corr. range: -1 … 1

* = p < .05, ** = p < .01

FIGURE 1 | Results of correlation analyses performed. Panel **(A)** depicts Pearson's correlations between age and our variables of interest. Panel **(B)** depicts partial correlations between Action and Strategy LCs (learning composites) and our cognitive and game habit variables of interest, controlling for age and gender. Panel **(C)** depicts partial correlation between Action and Strategy LCs and participant reports of experience with eight specific genres of games, controlling for age and gender. Ident. = identification as a "gamer."

TABLE 1 | Means and standard deviations of behavioral and cognitive measures (left), and reported frequency of experience with specific game genres (right).

Primary measure	Mean (SD)	Genre experience	Mean (SD)
Frequency	2.14 (0.78)	FPS game	1.48 (0.75)
Duration (h/week)	2.01 (1.53)	RTS game	1.58 (0.8)
Identification	2.31 (1.33)	Puzzle game	1.81 (0.81)
Preference ($S > A$)	−0.29 (1.72)	RPG	1.82 (1.18)
FSpan	6.87 (1.31)	Racing game	1.73 (0.95)
BSpan	5.3 (1.17)	Simulation game	1.59 (0.85)
SDST	22.98 (5.12)	Sports game	1.55 (1.11)
		Casual game	1.94 (1)

FSpan, forward digit span; BSpan, backward digit span; SDST, Symbol–Digit Substitution Test; FPS, first-person shooter; RTS, real-time strategy; RPG, role-playing game.

Considering the asymmetry of the age distribution of our sample, we next fitted linear models to each of the age-to-habit, age-to-cognition, and age-to-learning relationships to establish if these relationships are linear and, therefore, can be subjected to linear regressions in subsequent analyses. Regarding *habit* variables, the relationship between age and *Frequency*, $F(1/105) = 31.61$, $p < 0.01$, $R^2 = 0.23$, age and *Duration*, $F(1/105) = 13.8$, $p < 0.01$, $R^2 = 0.11$, and age and *Identification*, $F(1/105) = 14.14$, $p < 0.01$, $R^2 = 0.12$, was significantly linear. Age and *Preference* demonstrated no such relationship, linear or nonlinear, $F(1/105) = 0.87$, $p = 0.35$, $R^2 = 0.01$. Regarding *Cognition*, age and *BSpan*, $F(1/105) = 7.03$, $p = 0.01$, $R^2 = 0.06$, and age and *SDST*, $F(1/105) = 117.67$, $p < 0.01$, $R^2 = 0.52$, demonstrated significant linearity (**Figures 3A,C**), but age and *FSpan* displayed no significant relationship (**Figure 3A**), $F(1/105) = 0.71$, $p = 0.4$, $R^2 = 0.01$. Age also demonstrated a linear relationship with both the Action LC, $F(1/105) = 138.17$, $p < 0.01$, $R^2 = 0.57$, and the Strategy LC, $F(1/105) = 124.11$, $p < 0.01$, $R^2 = 0.54$ (**Figure 3B**).

Additionally, we ran a series of independent sample T-tests comparing male and female participants on habits, preference, learning, and cognitive variables. No significant gender differences were observed in these comparisons (**Table 2**).

Gaming Habits and Cognition as Predictors of Novel Game Learning

The primary intent of this study is to examine the relationship between past gaming habits, cognitive abilities, game preference, and the learning of novel games, across life span, irrespective of age and gender differences. Although these variables are correlated (see section "Relationships Between Cognition, Game

	Frequency	Duration	Ident.	Preference (S>A)	Forward Span	Backward Span	SDST	Action LC	Strategy LC
Frequency		0.70**	0.68**	0.17	0.03	0.04	0.22*	0.67**	0.53**
Duration	0.70**		0.74**	0.21*	0.23*	0.17	0.07	0.59**	0.50**
Ident.	0.68**	0.74**		0.25*	0.21*	0.22*	0.15	0.62**	0.46**
Preference (S>T)	0.17	0.21*	0.25**		0.08	0.08	-0.27**	0.10	-0.11
Forward Span	0.03	0.23*	0.21*	0.08		0.47**	-0.05	0.14	0.23*
Backward Span	0.04	0.17	0.22*	0.08	0.47**		0.13	0.29**	0.31**
SDST	0.22	0.07	0.15	-0.27	-0.05	0.13		0.44**	0.53**
Action LC	0.67**	0.59**	0.62**	0.10	0.14	0.29**	0.44**		0.78**
Strategy LC	0.53**	0.50**	0.46**	-0.11	0.23*	0.31**	0.53**	0.78**	

Corr. range: -1 to 1

* = $p < .05$, ** = $p < .01$

FIGURE 2 | Results of Pearson's correlations between our variables of interest.

Habits, Game Preference, and Novel Game Learning"), it not clear to what extent these relationships are driven by individual differences in age. Therefore, we conducted correlations between these variables, after controlling for age and gender. Action LC was still significantly correlated with *Frequency*, $r(104) = 0.49$, $p < 0.01$, *Duration*, $r(104) = 0.52$, $p < 0.01$, and *Identification*, $r(104) = 0.58$, $p < 0.01$. Likewise, Strategy LC was correlated with *Frequency*, $r(106) = 0.28$, $p = 0.04$, *Duration*, $r(104) = 0.41$, $p < 0.01$, and *Identification*, $r(104) = 0.33$, $p < 0.02$ (**Figure 1B**). *Preference* was now marginally correlated with Action LC, $r(104) = 0.25$, $p = 0.07$, but not with Strategy LC, $r(104) = -0.08$, $p = 0.59$, after controlling for age and gender. None of the cognitive variables examined were found to be correlated with either Action LC [*FSpan*: $r(104) = 0.09$, $p = 0.61$; *BSpan*: $r(104) = 0.18$, $p = 0.29$; *SDST*: $r(104) = 0.03$, $p = 0.87$] or Strategy LC [*FSpan*: $r(104) = 0.21$, $p = 0.22$; *BSpan*: $r(104) = 0.23$, $p = 0.16$; *SDST*: $r(104) = 0.15$, $p = 0.35$], after controlling for age and gender.

To determine if the relationships between novel game learning and game habits, preference, and cognition are linear, we fit linear models to these relationships. The linear relationships between Action LC and *Frequency*, $F(1/105) = 70.09$, $p < 0.01$, $R^2 = 0.4$, *Duration*, $F(1/105) = 63.92$, $p < 0.01$, $R^2 = 0.38$, *Identification*, $F(1/105) = 63.59$, $p < 0.01$. $R^2 = 0.37$, *BSpan*, $F(1/105) = 11$, $p < 0.01$, $R^2 = 0.09$, and *SDST*, $F(1/105) = 47.7$, $p < 0.01$, $R^2 = 0.31$, were significant. The linear relationships between Action LC and *Preference*, $F(1/105)$, $p = 0.33$, $R^2 = 0.01$, and between Action LC and *FSpan*, $F(1/105) = 2.33$, $p = 0.12$, $R^2 = 0.02$, were not significant. The relationships between the Sushi LC and variables of game habit and cognition had similar patterns [*Frequency:* $F(1/105) = 41.71$, $p < 0.01$, $R^2 = 0.28$; *Duration:* $F(1/105) = 40.91$, $p < 0.01$, $R^2 = 0.28$; *Identification:* $F(1/105) = 30.24$, $p < 0.01$, $R^2 = 0.22$; *BSpan:* $F(1/105) = 10.8$, $p < 0.01$, $R^2 = 0.09$; *SDST:* $F(1/105) = 62.36$, $p < 0.01$, $R^2 = 0.37$; *Preference:* $F(1/105) = 1.32$, $p = 0.25$, $R^2 = 0.01$; *FSpan:* $F(1/105) = 3.18$, $p = 0.08$, $R^2 = 0.03$].

These results above demonstrate that measures of novel game learning in both genres are related individually to measures of game experience, over and beyond the effects of age and gender. However, they do not reflect the potentially interrelated effects of our variables of interest on novel game learning. To investigate this possibility, we next performed a series of multiple regressions to examine the combined effect of the collected gaming experience and cognition on the game LCs. Two sets of stepwise multiple regressions were conducted, one set using Action LC and another set using Strategy LC as the dependent variable. In both stepwise multiple regressions, age and gender were entered as control variables in the first step. In the second, game experience variables (*Frequency, Duration, Identification*), and cognitive variables (*FSpan, BSpan, SDST*) were entered, which resulted in a handful of significant predictors. The results of these analyses are presented in **Table 3**. The final regression model for Action LC, $R^2 = 0.67$, $F(4,102) = 41.9$, $p < 0.01$, included *Identification*, $\beta = 0.15$, $t(102) = 2.78$, $p < 0.01$, and *Duration*, $\beta = 0.11$, $t(102) = 2.46$, $p = 0.02$, as significant predictors. The final regression model for Strategy LC, $R^2 = 0.57$ $F(4,102) = 27.67$, $p < 0.01$, included *Duration*, $\beta = 0.21$, $t(102) = 4.79$,

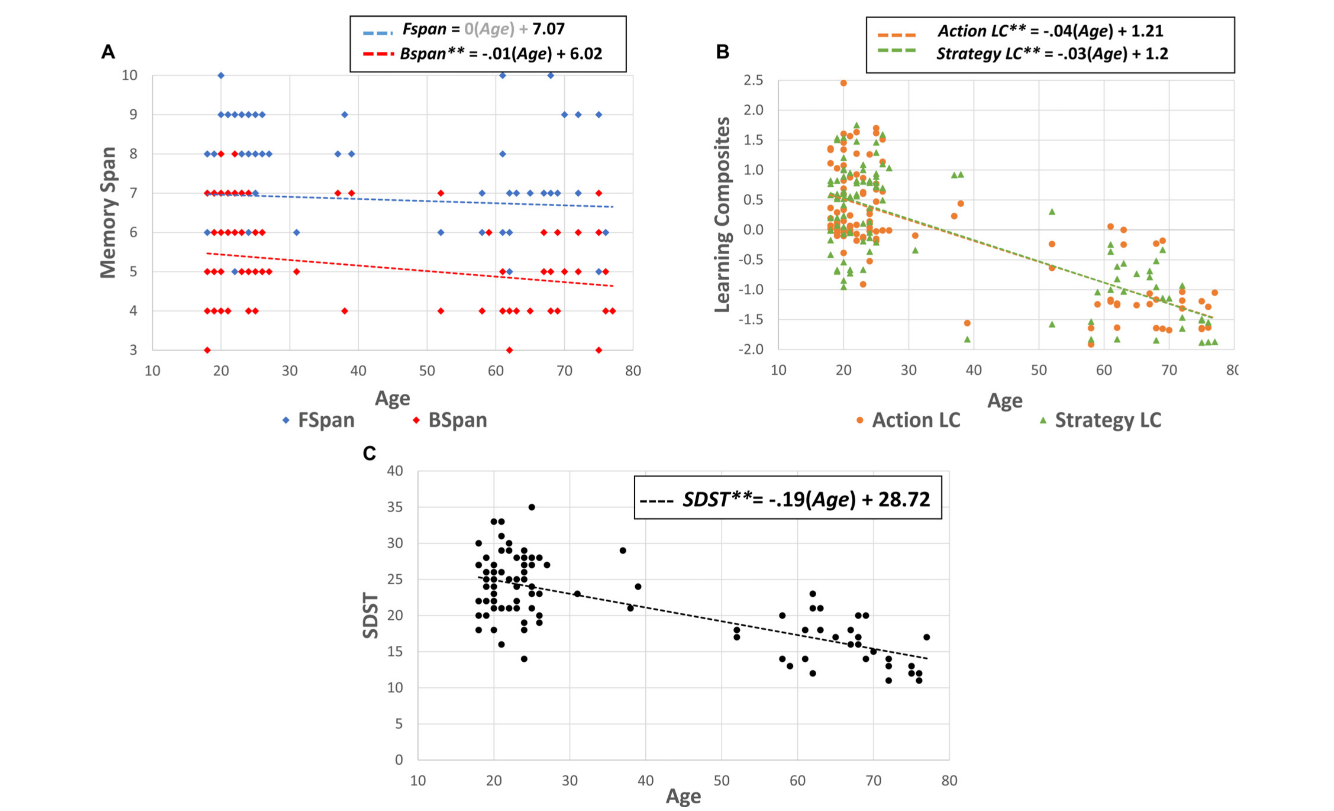

FIGURE 3 | Scatterplots of age–cognition and age–learning relationships, with linear trendiness plotted. Panel **(A)** depicts the relationship between age and the forward (*FSpan*) and backward (*BSpan*) memory span measures. Panel **(B)** depicts the relationship between age and the Action LC and Strategy LC. Panel **(C)** depicts the relationship between age and the Symbol–Digit Substitution Test (SDST).

TABLE 2 | Results of *T*-tests comparing male and female participants on variables of game habits cognition and learning.

Measure	Mean (SD)$_M$	Mean (SD)$_F$	*t (df)*	*P*
Frequency	2.1 (0.82)	2.2 (0.72)	0.62 (105)	0.54
Duration (h/week)	2.02 (1.49)	2.17 (1.61)	0.51 (105)	0.61
Identification	2.24 (1.34)	2.41 (1.32)	0.67 (105)	0.51
Preference (*S* > *A*)	−0.27 (1.95)	−0.32 (1.29)	−0.14 (105)	0.89
FSpan	6.89 (1.4)	6.83 (1.18)	−0.23 (105)	0.82
BSpan	5.21 (1.13)	5.46 (1.25)	0.98 (105)	0.33
SDST	23.56 (5.2)	22.06 (4.9)	−1.39 (105)	0.17
Action LC	−0.07 (0.95)	0.14 (0.93)	1.09 (105)	0.28
Strategy LC	−0.04 (0.96)	0.07 (0.98)	0.6 (105)	0.55

LC, learning composite.

$p < 0.01$, and *BSpan*, $\beta = 0.15$ $t(102) = 2.58$, $p = 0.01$, as significant predictors.

How Specific Are These Effects?

The above multiple regressions indicate that gaming duration is a common predictor of both action and strategy learning, but this result can be driven by the inter-correlation between the Action and Strategy LCs. A correlation analysis indeed demonstrated that Action LC and Strategy LC were significantly related, $r(106) = 0.78$, $p < 0.01$. To account for this inter-correlation, two sets of stepwise multiple regression analyses were conducted, such that the effects of gaming experience and cognition on either game learning could be determined, over and beyond the effects of the other game learning.

As in previous regressions, the first step included age and gender, and the second step included the other game LC (that is, Strategy LC when Action LC was the dependent variable, and Action LC when Strategy LC was the dependent variable). For the third step, only the significant predictors of earlier regression analyses (see **Table 3**) for a specific game learning were used to determine their specificity on that game learning. For example,

TABLE 3 | Results of stepwise regression across 3 steps.

	Action LC Models					Strategy LC Models			
Model	***R^2***	***ΔR^2***	***F***	***p***	**Model**	***R^2***	***ΔR^2***	***F***	***p***
1) Age + Gender	0.57	–	69.3	**<0.01**	1) Age + Gender	0.53	–	58.82	**<0.01**
2) + Identification	0.73	0.15	90.89	**<0.01**	2) + Duration	0.62	0.09	56.66	**<0.01**
3) + Duration	0.75	0.02	74.6	**<0.01**	3) + BSpan	0.64	0.02	45.45	**<0.01**

	Regression Model from Step 3				Regression Model from Step 3		
Factors	***β***	***t***	***p***	**Factors**	***β***	***t***	***p***
Age	−0.03	−10.9	**<0.01**	Age	−0.03	−9.13	**<0.01**
Gender	−0.12	−1.25	0.2	Gender	0.02	0.15	0.89
Identification	0.19	3.47	**<0.01**	Duration	0.19	4.8	**<0.01**
Duration	0.13	2.79	**0.01**	BSpan	0.12	2.25	**0.03**

Details of final regression model from step 3 are provided.
Bold values indicate $p < 0.05$.

TABLE 4 | Results from follow-up regression models, after controlling for opposite game learning.

	Action LC Models					Strategy LC Models			
Model	***R^2***	***ΔR^2***	***F***	***p***	**Model**	***R^2***	***ΔR^2***	***F***	***p***
1) Age + Gender	0.57	–	69.3	**<0.01**	1) Age + Gender	0.53	–	58.82	**<0.01**
2) + Strategy LC	0.68	0.11	73.36	**<0.01**	2) + Action LC	0.65	0.12	64.06	**<0.01**
3) + Add. Predictors	0.78	0.10	69.55	**<0.01**	3) + Add. Predictors	0.68	0.03	42.3	**<0.01**

	Regression Model from Step 3				Regression Model from Step 3		
Factors	***β***	***t***	***p***	**Factors**	***β***	***t***	***p***
Age	−0.02	−5.95	**<0.01**	Age	−0.02	−4.23	**<0.01**
Gender	−0.12	−1.35	0.18	Gender	0.06	0.56	0.58
Strategy LC	0.28	3.65	**<0.01**	Tank LC	0.37	3.36	**<0.01**
Identification	0.18	3.45	**<0.01**	Duration	0.10	2.22	**<0.03**
Duration	0.08	1.78	*0.08*	BSpan	0.09	1.77	*0.08*

Additional predictors in Step 3 were significant predictors from the previous step-wise regressions described in ***Table 3****.*
Bold values indicate $p < 0.05$; Italicized values indicate $p < 0.10$.

for Action LC, *Identification* and *Duration* were entered in the third step. For Strategy LC, *BSpan* and *Duration* were entered in the third step. The results of these analyses are reported in **Table 4**.

Identification remained a significant predictor of *Action LC* even after accounting for Strategy LC, $\beta = 0.16$, $t(101) = 3.16$, $p < 0.01$, but *Duration* was no more a significant predictor, $\beta = 0.05$, $t(101) = 1.13$, $p = 0.26$. However, *Duration* remained a significant predictor of Strategy LC even after accounting for Action LC, $\beta = 0.14$, $t(101) = 2.83$, $p < 0.01$, with *BSpan* still being a marginally significant predictor of Strategy LC, $\beta = 0.11$, $t(101) = 1.94$, $p = 0.056$.

Are These Predictors Stable Across the Life Span?

So far, our analyses have focused on the effects of game habits, preference, and cognition on novel game learning, irrespective of age. However, it is plausible that the pattern of these relationships varies across the adult life span. We therefore performed moderator analyses using multiple regressions to account for the effects of age on these relationships. Gender was introduced in the first step of these multiple regressions. Age and the significant predictors demonstrated previously (*Identification* and *Duration* for the Action LC, *Duration* and *BSpan* for the Strategy LC) were entered in the second step. The third step included the moderation terms that accounted for the interaction between age and the two variables, which were entered in the second step. The results of these analyses are reported in **Table 5**.

While age was demonstrated to be a significant predictor of both Action LC, $\beta = -0.03$, $t(100) = -6.61$, $p < 0.01$, and Strategy LC, $\beta = -0.03$, $t(100) = -0.4.18$, $p = 0.01$, none of the interaction terms with *Age* demonstrated significance in either analyses, and neither of the regression models in the third step demonstrably improved model fit compared to the previous step, indicating that age is not a meaningful moderator of the previously observed relationships.

TABLE 5 | Results of moderator analyses.

	Action LC Models					Strategy LC Models			
Model	R^2	ΔR^2	*F*	*p*	**Model**	R^2	ΔR^2	*F*	*p*
1) Gender	0.01	–	1.2	0.28	1) Gender	0.01	–	0.09	0.77
2) + Age & Add. Preds.	0.75	0.74	74.59	**<0.01**	2) + Age & Add. Preds.	0.64	0.63	45.45	**<0.01**
3) + Moderators	0.76	0.01	51.34	**<0.01**	3) + Moderators	0.65	0.01	30.36	**<0.01**

	Regression Model from Step 3				Regression Model from Step 3		
Factors	*β*	*t*	*p*	**Factors**	*β*	*t*	*p*
Gender	−0.11	−1.12	0.27	Gender	0.02	0.18	0.85
Age	−0.03	−9.17	**<0.01**	Age	−0.02	−6.34	**<0.01**
Identification	0.19	3.48	**<0.01**	Duration	0.21	4.82	**<0.01**
Duration	0.15	2.98	**<0.01**	BSpan	0.13	2.48	**0.02**
Age * Identification	−0.14	−1.89	*0.09*	Age * Duration	0.09	1.07	0.29
Age * Duration	0.16	1.74	*0.06*	Age * BSpan	0.04	0.69	0.49

Bold values indicate $p < 0.05$; Italicized values indicate $p < 0.10$.

Game Experience With Specific Genres

In addition to the general game experience/habits data collected, we also gathered information from each participant regarding their frequency of play with eight specific genres of video games. We examined the potential relationship between experience on a specific game genre and novel game learning through correlation analyses that compared self-rated frequency of playing of these genres with Action and Strategy LCs. These correlations were controlled for individual differences in age and gender. The results are displayed in **Figure 1C**.

Action LC was found to be positively correlated with frequent experience with FPS games, $r(103) = 0.42$, $p < 0.01$, RTS games, $r(103) = 0.29$, $p < 0.01$, and RPGs, $r(103) = 0.51$, $p < 0.01$. Strategy LC was positively correlated with frequent experience with RPG, $r(103) = 0.32$, $p = 0.01$, and casual games, $r(103) = 0.25$, $p = 0.01$ Additionally, Strategy LC was inversely correlated with frequent experience with sports video games, $r(103) = -0.2$, $p = 0.04$.

Additional Analyses: Effect of Game Preference on Novel Game Learning

To further examine the impact of game preference on novel game learning, we next divided our participants into subgroups based on self-reported preference for the two games utilized in this task. Subjects were divided into three groups based on their reported enjoyment of Tank Attack 3D and Sushi-Go-Round. The *Prefer Tank* group ($n = 34$, 10 females, $M_{Age} = 29.79$, $SD_{Age} = 18.14$) reported higher enjoyment of Tank Attack 3D compared to Sushi-go-Round. The *Prefer Sushi* ($n = 46$, 17 females, $M_{Age} = 25.89$, $SD_{Age} = 11.53$) group reported higher enjoyment of Sushi-go-Round than Tank Attack 3D. The *No Preference* ($n = 27$, 13 females, $M_{Age} = 55.79$, $SD_{Age} = 20.96$) group reported identical levels of enjoyment of both games.

We first assessed how these preference groups differed in regard to the game LCs. A one-way ANOVA demonstrated that preference group had a significant effect on *Tank LC*, $F(2,104) = 29.86$, $p < 0.01$. Post hoc comparisons using the Sidak method demonstrated that *Tank LC* was significantly higher for the *Prefer Tank* group compared to the *No Preference* group ($p < 0.01$) but did not differ significantly from the *Prefer Sushi* group ($p = 0.36$). A second one-way ANOVA demonstrated that preference group had a significant effect on *Sushi LC* as well, $F(2,104) = 20.71$, $p < 0.01$. Post hoc comparisons using the Sidak method demonstrated that *Sushi LC* was significantly higher for the *Prefer Sushi* group compared to the *No Preference* group ($p < 0.01$) but did not differ significantly from the *Prefer Tank* group ($p = 0.26$). These results indicate that individuals with a preference for either game demonstrated greater LCs on both the action and strategy games utilized. Therefore, greater preference for a specific game was not related to better learning of that game.

Considering the apparent disparity in age between the three preference groups as reported above, we next compared participant age across these three groups. A one-way ANOVA indeed demonstrated a significant difference in age between the three groups, $F(2,104) = 31.06$, $p < 0.01$. Post hoc comparisons using the Sidak method demonstrated that the *No Preference* group was significantly older than both the *Prefer Tank* group ($p < 0.01$) and the *Prefer Sushi* group ($p < 0.01$), but there was no significant age difference between the *Prefer Tank and Prefer Sushi* groups ($p = 0.65$). These results suggest that the differences in relative learning rates between the preference groups and the no-preference group are possibly driven by participant age.

DISCUSSION

The purpose of this study was to examine the relationship between gaming experience, cognition, and the learning of novel games, particularly any specific patterns of relationships for the two different video game genres, action and strategy, which have been most predominant as cognitive training tools in past research (Oei and Patterson, 2014; Simons et al., 2016; Ray et al., 2017). Our results demonstrated a strong correlation between learning of both genres of video games and the gaming experience (*Frequency, Duration, Identification*), such that longer hours spent gaming per week (*Duration*), greater gameplay frequency, and greater extant of self-identification as a "gamer" (*Identification*) were related to faster learning of both action and strategy video games. These results seem to support the "learning to learn" framework, which predicts general enhancement of novel game learning as a result of previous game experience (Bavelier et al., 2012; Green and Bavelier, 2012). However, after controlling for the learning of the other game, *Duration* demonstrated a significant relationship only with the strategy game learning, not with action game learning. This result suggests that the observed positive relationship between *Duration* and action game learning may be spurious, contrary to the "learning to learn" model's prediction of broad transfer to novel task learning. Both the present study as well as past research which has utilized these specific games (Baniqued et al., 2013; Ray et al., 2017) have demonstrated that Tank Attack 3D and Sushi-Go-Round have distinct patterns of cognitive correlates, which may have factored into the differential effects of game habits on the learning of these two games that we observed. It is conceivable that past game experience allowed our more experienced participants to better adapt to the working memory demands of the strategy game used in the study, without affecting their ability to learn the relatively attentionally demanding action game. This theory is supported by the observed contribution of *BSpan*, a measure of working memory capacity, to learning of the strategy game but not the action game. Overall, the relationship between game habits and the learning of novel games does not appear to be as straightforward as the "learning to learn" model suggests. Specifically, the learned capacity to learn new, complex tasks appears to relate differently to novel tasks that vary regarding the types of cognitive demands. In terms of video game cognition research, our results demonstrate that this claim needs to be examined with regard to the specific cognitive demands of the video game being learned.

Self-identification as a gamer (*Identification*) significantly predicted learning of the action game but not the strategy game. This relationship was stable across our wide age range and persisted even after corrected for potential gender effects. There is a well-documented positive relationship between identification as a gamer and both frequency and duration of video game play (Stone, 2019), which data from the present study reflect (**Figure 2**), but *Identification* importantly differs from these other measures, as it solely reflects self-perception rather than any more quantifiable habit. This effect may be explained as a matter of preference, as the action game was significantly preferred over the strategy game in our sample, and the degree of preference of the action game over the strategy game was strongly correlated with *Identification* (**Figure 2**). Importantly, we did not identify any gender differences in either *identification* as a gamer or genre *preference* in our sample, contrary to past research (Stone, 2019), which precludes gender as a factor explaining the relationship between gamer *identification* and *learning* of the action game.

The wide age range of our sample (18–77 years) afforded us a unique opportunity to examine the interaction between the participants' age and their measures of learning, habit, preference, and cognition. Understanding these age-related interactions is of particular importance considering the prevalence of video game–based interventions targeting older adults (for meta-analysis, see Lampit et al., 2014; Basak et al., 2020). In the current study, age was, as expected, negatively correlated with gaming habit variables (Osmanovic and Pecchioni, 2016), as well as with measures of working memory (Bopp and Verhaeghen, 2005) and processing speed (Cerella, 1990). These age–cognition results are in line with past meta-analysis where age-related declines are significant for processing speed (Cerella, 1990) and working memory capacity (including *BSpan*), but not with short-term memory capacity indexed by *FSpan* (Bopp and Verhaeghen, 2005). Our results suggest that age-related declines are observed in processing resources and coordination between multiple items but not in maintenance of items in a temporary memory buffer. In addition to these standard neuropsychological measures of cognition, age was found to be negatively correlated with the learning of both games; this result is similar to prior studies on age-related differences in game learning (e.g., Ray et al., 2017).

It is important to note that although individual differences in age predicted cognitive and learning outcomes as well as game habits, the patterns of the predictive effects of cognition and game habits on novel game learning did not vary with age. Our results suggest that the differential, interrelated patterns of game habits, cognition, and novel game learning for action and strategy games are stable across the life span. Considering the prevalence of video game intervention as a method of cognitive intervention in older adults (Lampit et al., 2014; Toril et al., 2014; Basak et al., 2020), and the stability of these effects across the life span, these results can potentially inform expectations of intervention effects in that population. Therefore, expected gains on cognition from action versus strategy video game training, and their dose response effects (frequency, duration), may be stable across adulthood. For example, assuming these results generalize, the specific ability to learn tasks with high working memory demands may result from extended strategy game training in not only younger but also older adults. Importantly, a preference for the action versus the strategy game genre had no differential effects on learning of the two novel games, suggesting that the game-based benefits to cognition may supersede individual's game preferences. Such generalization is far from guaranteed, however, and independent replication of these results is warranted, with particular attention paid to the cognitive profiles of the video games examined.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

This study was approved by the Institutional Review Board of the University of Texas at Dallas. All participants were provided with detailed study information, and responded with written consent, before participating in this study.

AUTHOR CONTRIBUTIONS

CB designed and supervised the research. ES, AH, and BB collected the data. ES and BB analyzed the data. ES and CB wrote the manuscript. All authors approved the final version of the manuscript for submission.

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BRIEF RESEARCH REPORT
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Physiological and Cognitive Functions Following a Discrete Session of Competitive Esports Gaming

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Competitive organized electronic video gaming, termed "esports," has become an international industry. The physiological and cognitive health results of prolonged esport practice and competition have not been adequately studied. The current study examined physiological and cognitive changes after a session of esport gameplay for two types of games, first-person shooter and multiplayer online battle arena games. Increases in systolic blood pressure, increases in speed, and decreases in accuracy and inhibitory processes were found for esport gamers overall. For peak heart rate change, first-person shooter games elicited a larger change than did multiplayer online battle arena games. These results have implications for the management of esport player cognitive and physical health as well as for the optimization of performance in competitive esport tournaments.

Keywords: esports, competitive gaming, executive functions, cognition, health

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INTRODUCTION

The term "electronic sports" or "esports" refers to organized electronic and video game competitions that have recently exploded in popularity and are now a global multimillion-dollar industry (Willingham, 2018). Many colleges and universities already have esport varsity teams, and some even offer scholarships akin to traditional sports scholarships (Morrison, 2018). Although requiring less contact and physical activity than most sports, esports do share some commonalities with tradition athletic sports. For example, tournaments involve players either as individuals or teams facing opponents in games that are divided into rounds and matches. Players often train for hours each day, are coached professionally, and can receive sponsorships from companies (Jacobs, 2015). Many times, these players play for hours in practice and competition without any mental or physical break.

Esport games encompass a wide breadth of genres that are thought to require a unique skill set to play competitively (Norman, 2011). For example, *League of Legends* is a multiplayer online battle arena (MOBA) game. Teams are formed and tasked with the mission of destroying the opposing team's base (core) while also defeating the opposing team members. In this game, characters are developed, requiring teamwork and strategy (Alloza et al., 2018). In contrast, *Overwatch* is a first-person shooter (FPS) game. FPS games put the player in the first-person perspective of their character and task them with various missions, such as defending or attacking an objective or protecting a fort. FPS games are different from MOBA games in that they are usually more fast-paced (Alloza et al., 2018). FPS games are meant to simulate the player's visual field during gameplay occurring in real time. Therefore, faster decision making, strategizing, and reaction times are likely required to provide the best outcome. MOBA games, in contrast, place the player in the middle of the screen along with the surrounding map, allowing the player to be able to interact and anticipate moves from the opposing team, which may require a larger degree of strategizing. However, given that there are differences even between games within each genre, these assumptions are likely not universal truths, and little research informs the issue.

Few studies have examined the physical and physiological effects of esports. Tournament conditions may be similar to traditional sport competitions in that they both produce stress for the player. However, the type of stress is likely quite different; esports do not involve the level of physical exertion required for many other sports but may elicit a psychological state of stress or tension that results in autonomic nervous system alteration. Esports also seem to involve some degree of physical injury. One study listed the common complaints of esport players to include joint pain, headaches, sleep problems, and vision problems (Benchebra et al., 2019), and in another study of collegiate esport players, digital eye strain was the most common reported ailment (DiFrancisco-Donoghue et al., 2019).

Executive functions, the cognitive functions that govern our behavior, decision-making abilities, organization, planning and goal setting, time management, and self-regulation, are likely utilized during gameplay. An esport player simultaneously performs complex actions while analyzing various amounts of stimuli in order to create a fluent and coordinated action, while trying to minimize the amount of erroneous choices that may be detrimental to their desired goals. Some studies have found that people who play video games may exhibit faster response times but reduced accuracy on some executive functioning measures (Kowal et al., 2018). Similarly, a study of FPS and MOBA game types found that gamers who played FPS presented faster reaction times but a lower control over inhibition than did gamers who favored MOBAs (Deleuze et al., 2017).

The primary purpose of this study was to examine potential changes in executive function and physiological markers following a discrete session of competitive gaming. We anticipated physiological changes associated with increased sympathetic nervous system stress. We were also interested in potential changes in executive functioning that may result from prolonged esport gameplay.

METHODS

Design

This study was a prospective observational cohort study, which allowed investigation of the temporal sequences between exposure and outcome and investigation of the effects of one exposure on multiple outcomes. The outcome measures including both cognitive and physiological measures were examined before and after a session of esport gaming across two types of esport games (FPS and MOBA).

Setting

Data were collected at the CyBears Arena at New York Institute of Technology (NYIT), Old Westbury, United States. The room consists of gaming computers, monitors, headsets, specialized gaming keyboards, and mouses, set up around the perimeter of the room. The data were only collected from tournament settings, including competing against another school for a prize or playing using ranked settings online against strangers to gain or lose ranking. Playing ranked online utilizes the same format and rules as is in competition against other schools.

All members of the NYIT CyBears reported to the room during competition times to have their data collected before and after a discrete gaming session. The opposing team was not physically present.

Sample

This study was approved by the NYIT Internal Review Board, and all subjects signed written consent after the study was explained to them and they were given time to ask questions. Subjects were recruited from the student population at NYIT, Old Westbury, NY, United States. Esport players in the age group of 18–30 were recruited through Discord, the communication application used by members of the CyBears esport team. Inclusion criteria included women or men age 18 to 30 years who were members of the NYIT esport team. Exclusion criteria included any player that did not participate in competition for the esport team or who had any current injury that would affect typical gameplay.

Data Collection

Data were collected immediately before and after a gaming session. Prior to a match, measurements included blood pressure (BP), heart rate (HR), respiratory rate (RR), visual acuity, and a measure of psychomotor speed [finger-tapping test (FTT)]. In addition, participants were administered a series of online executive function tests. Subjects were then fitted into a Hexoskin® shirt, which monitored their HR throughout gameplay.

At the completion of the match (approximately 2.5 h depending on the natural length of type of game played), the subjects repeated the online cognitive function tests. This was done to ensure that members did not break eye contact from the screen immediately after gameplay, followed by measurement of visual acuity. After that, participants had their vital signs and FTTs completed one additional time.

Outcome Measurements

Visual Acuity

Visual acuity was measured using a standard eye chart (Snellen chart). First, subjects stood 6 m away from the chart and were asked to occlude one eye while viewing the chart with the other eye. Subjects then read the letters on each line, starting from the top of the chart and reading left to right, and continued until they failed to correctly identify a letter on a line (Marsden et al., 2014). Because digitally strained eyes begin to recover when the eyes are not looking at a screen, the eye exam was given as soon as the subjects finished practicing.

Blood Pressure

Blood pressure was taken manually after sitting quietly following 5 min for initial measure. For the post-gameplay measure, BP was taken upon completion of cognitive measures along with HR and RR.

Mental Flexibility

The Trail Making Test (TMT) is a neuropsychological instrument that evaluates speeded visual search (Corrigan and Hinkeldey, 1987). A computerized version of the TMT, whereby subjected used a mouse to connect numbered and lettered circles in chronological and alphabetical orders, was administered through Inquisit Lab, produced by Millisecond. The test itself took no longer than 3 min and was completed prior to and after the subjects' gaming sessions.

Inhibition

Color-word stroop with keyboard

The Stroop Color and Word Test is a measure of speeded inhibitory control and set switching (Stroop, 1935; Scarpina and Tagini, 2017). We utilized a computerized version of the Color-Word Stroop by Inquisit Lab, developed by Millisecond. The software measures the time to reaction in milliseconds as well as accuracy of responses. The test took 3–5 min to complete. This measure was administered before and after gaming sessions.

Psychomotor Speed

The FTT is a quantitative tool used as a measure of psychomotor speed in many standard neuropsychological evaluations (Halstead, 1947). It measures the motor speed of the index finger on both the dominant and non-dominant hands as a proxy evaluation of cortical motor area and efferent motor pathway integrity and motor functioning. Upon administering the test, the subject's hand is placed on a wooden board with a pushable lever and counter while the administrator is tracking the taps. The test was completed within 5–10 min. This measure was done prior to and after the esport session was completed.

Physiological Variables

Hexoskin

During gameplay, subjects wore a Hexoskin Smart Shirt® (5800 Denis St. Montreal, Quebec H2S-3L5), which is a garment with electrodes that can measure and calculate a number of physiological variables, including HR, HR changes, RR, steps taken, and sleep. Hexoskin's validity in measuring these variables has been established (Cherif et al., 2018). The Hexoskin is worn on bare skin, with conductance gel applied to the electrodes to obtain accurate measurements. The shirt was worn for the entire gaming session. Following each session, the Hexoskin was connected to a computer, and the data were uploaded to the associated program for analysis.

Statistical Analysis

IBM SPSS Statistics Version 25 was used to complete the statistical analysis. For each outcome variable, a repeated-measures general linear model was run with two levels. The within-subjects factor was the outcome variable, and a between-subjects factor of "type of game" was also used. Normality of distribution of data was ensured for each of the outcome variables. Significance level of $p = 0.05$ was used to determine statistical significance.

RESULTS

Demographics

Data from all 17 subjects were utilized for the analysis. Subjects were all of male gender, average age was 20 years (SD = 1.82 years), and all but one participant were right-handed. Demographic information is listed in **Table 1**. Subjects' gaming sessions lasted on average 151 min (SD = 49 min).

Physiological Outcome Measures

For physiological variables, we found that systolic BP significantly increased after game play session for the FPS game (t = -2.94, p = 0.019). For the MOBA game, systolic BP was decreased but not significantly (t = 1.44, NS). Respiration rate during gameplay increased at trend levels for the whole group (F = 4.24, p = 0.057). HR was not significantly different after gameplay session for either game type (F = 0.30, NS). **Table 2** shows these results. However, the change from resting HR to peak HR during gameplay was significantly different for game types; for FPS game, HR increased significantly more during play than for the MOBA game (t = 2.22, p = 0.043). **Figure 1** shows these results.

Neuropsychological Outcome Measures

Psychomotor speed as measured by the FTT was significantly faster after gameplay for the dominant hand (F = 11.68, p = 0.004) but was not significantly changed from pregaming to postgaming for the non-dominant hand (F = 0.00, p = 0.95). For executive functions, numerical sequencing speed (TMT A) was not significantly changed after gameplay (F = 0.19, p = 0.67).

TABLE 1 | Demographic information and performance on outcome variables broken down by type of game players.

	FPS game players (*Overwatch*) *N* = 9	MOBA game players (*League of Legends*) *N* = 8	Total group *N* = 17
Age	19.4 (1.3)	20.8 (2.1)	20.1 (1.8)
Gender (% male)	100	100	100
Handedness (% right-handed)	88	100	94

FPS, first-person shooter; MOBA, multiplayer online battle arena.

TABLE 2 | Pregaming and postgaming comparison of physiological outcome variables with *F* statistic and *p*-values.

Outcome measure	Pregaming Mean (SD)	Postgaming Mean (SD)	Pre–post comparison (*F*)	Significance (*p*)	Interaction with game type (*F*)	Interaction with game type (*p*)
Systolic blood pressure	122 (10)	125 (12)	0.62	0.44	7.3	0.016*
Systolic blood pressure (*Overwatch*)	121 (10)	130 (8)	$t = -2.94$	0.019*		
Systolic blood pressure (*League of Legends*)	124 (10)	119 (13)	$t = 1.44$	0.12		
Heart rate	78 (8)	84 (14)	2.68	0.12	0.30	0.59
Respiration rate	15 (4)	17 (3)	4.24	0.057**	0.50	0.49
Vision	24 (6)	23 (5)	1.98	0.18	0.21	0.66

**Significant at the p = 0.05 level. **Non-significant but at the trend level.*

However, while performance on a measure of mental flexibility (TMT B) was significantly faster ($F = 8.32$, $p = 0.011$), the number of errors made increased, but only at a trend level of significance ($F = 3.35$, $p = 0.087$). On the Tower of London test, a measure of problem-solving ability, while accuracy was not significantly changed after gameplay ($F = 0.12$, $p = 0.73$), speed was significantly increased ($F = 7.79$, $p = 0.014$). Finally, on the Stroop test, a measure of impulsivity and response inhibition, while reaction time decreased and subjects were faster after gameplay ($F = 5.89$, $p = 0.028$), they made a significantly higher number of errors and were less accurate ($F = 4.95$, $p = 0.042$). **Table 3** shows differences between pregaming and postgaming time points as well as interaction analyses when participants were grouped by type of game.

DISCUSSION

Esports have rapidly become an ever-expanding industry with a large competitive arena. Many colleges and universities have incorporated formal esport teams into their offered varsity sports and scholarships. This has brought the health and well-being of esport athletes into the spotlight and the safety of long periods of competitive gaming into question. Yet to be made are recommendations for time-period parameters requiring rest of body or mental processes. This is important both from the perspective of the esport athletes' health and to optimize playing ability in competitive tournaments.

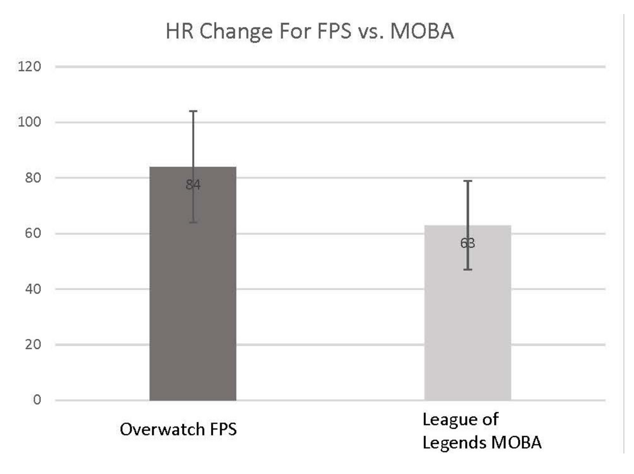

FIGURE 1 | Maximum heart rate change observed for FPS vs. MOBA game type.

In this study, we investigated the effects of esport gaming over a period of approximately 2.5 h for two types of games, FPS and MOBA. For physiological outcomes, our findings suggest that esport activity can increase sympathetic nervous system activation. Our findings that FPS gaming resulted in a larger change in low to peak HR and systolic BP increase when compared with the MOBA game suggests that FPS games elicit more of a sympathetic nervous system response. Other researchers have also found more aggressive or violent video games to elicit a cardiovascular stress response and a systolic BP increase (Siervo et al., 2013; Porter and Goolkasian, 2019). Still, others have found that gamers' HR and electrodermal activity correlated with gamers' subjective game-playing experience (Drachen et al., 2010). This may be a reflection of our FPS game, *Overwatch*, being more subjectively fast-paced than *League of Legends*. Our physiological findings may lead one to argue that esports can elicit an "aerobic" response, but this would in all likelihood be in error, akin to comparing an anxiety attack to health-promoting exercise. The main difference is that esports are likely eliciting physiological changes due to catecholamines, or stress hormones produced by the adrenal glands, given the low level of physical exertion. True aerobic exercise elicits these changes owing to physical exertion and oxygen demands of working muscles.

The cognitive effects of gaming have been lesser studied. One meta-analysis examined the effects of action video games, or games involving simulated physical challenges such as fighting or shooting games, on cognition and found that the cognitive areas of top-down attention and spatial processing were improved (Bediou et al., 2018). Another systematic review examining the neural bases of video-gaming found that video game players show enhanced attention functions for some types of attention, some visuospatial functions, and cognitive control, or the ability to manage tasks or information simultaneously (Palaus et al., 2017). We examined the short-term executive function effects of esport gaming over a session of gaming. Executive functions are the cognitive abilities that humans possess that allow them to manage behaviors, regulate emotional responses, and problem solve.

TABLE 3 | Pregaming and postgaming comparisons of neuropsychological outcome variables with *F* statistic and *p*-values.

Outcome measure	Pregaming Mean (SD)	Postgaming Mean (SD)	Pre–post comparison (*F*)	Significance (*p*)	Interaction with game type (*F*)	Interaction with game type (*p*)
Finger tapping (non-dominant hand)	47 (15)	46 (7)	0.00	0.95	0.68	0.42
Finger tapping (dominant hand)	48 (7)	52 (7)	11.68	0.004*	0.10	0.76
Trail Making Test Part A (speed in seconds)	25 (5)	24 (4)	0.19	0.67	1.37	0.26
Trail Making Test Part B (speed in seconds)	36 (12)	31 (10)	8.32	0.011*	0.84	0.36
Trail Making Test (total errors)	2 (1)	3 (2)	3.35	0.087**	0.05	0.82
Tower of London number correct	30 (6)	30 (5)	0.12	0.73	1.14	0.30
Tower of London (time)	8 (2)	7 (2)	7.79	0.014*	2.32	0.15
Stroop accuracy	0.95 (0.05)	0.91 (0.06)	4.95	0.042*	2.84	0.11
Stroop speed	0.8 (0.1)	0.7 (0.1)	5.89	0.028*	0.05	0.83

**Significant at the p = 0.05 level. **Non-significant but at the trend level.*

A number of interesting findings were revealed. In general, we found for two of our three neuropsychological measures that contained both speed and accuracy components that although esport players exhibited faster response times after having competed, they were generally less accurate and exhibited more impulsive response styles. This was true for our measures of mental flexibility and impulsivity. However, for our measure of problem solving, although time was also improved, no decrement in performance was apparent. One could hypothesize that while gaming increases the need for problem solving and speed, there is little real repercussion for impulsivity, and therefore, behavior follows suit. Similarly to our findings, other researchers have also found that inhibitory control was decreased for players of FPS games (Deleuze et al., 2017).

Our findings may also be relevant to informing those interested in maximizing gaming performance in competitive esports. A functional MRI (fMRI) study showed that activation in areas of the brain implicated in executive control was associated with better gaming performance (Wang et al., 2018). Our findings of reduced executive functioning accuracy after hours-long gameplay may indicate the need for breaks in gaming in order to mitigate what might be a type of cognitive fatigue. Given that esport players of FPS games can elicit upward of 500 moves per minute, a loss in accuracy could be detrimental to gaming performance.

Limitations of the current study include a small sample size, as more participants would increase power for this study. Also, although we examined outcomes measures pregaming and postgaming, we cannot explain from our data how long the significant changes persist after gaming sessions. Some work has already examined the long-term effects of gaming, but more is needed (see Krarup and Krarup, 2020). Additionally, the length of time of esport engagement was not a tightly controlled variable, as we instructed esport players to complete matches for 3 h but did not specifically control the variable. This was in part done to not add stress of having to stop gaming while competing in a match, which conceivably could induce stress. Finally, we did not directly examine how executive function changes over esport gaming sessions might affect gaming performance. Future work may benefit from exploring the direct relationship between executive function and game performance.

In conclusion, this study demonstrates differences in executive function and physiological variables before and after a discrete session of esport gaming and across two types of esport games. Although 2.5 h of continuous gameplay demonstrated greater speed, it resulted in less accuracy and more impulsivity. Further research is needed in a larger cohort of competitive gamers to establish optimal duration of play before a decline in performance or risks to health occurs.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the NYIT Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SA, TH, and KY worked to design the research study and to run participants, organize the data, and complete sections of the manuscript. AS and PD advised design regarding neuropsychological measures. JD-D and HZ advised design regarding physiological measures. AS, JD-D, and PD completed the statistical analysis.

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Arline Allera contributed toward the successful completion of this study in the role of research coordinator. Saad Quadri, Dan Hong, and Viraj Modi all contributed to the study in the form of data collection.

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The Relationship Between Cognition and Sensorimotor Behavior in an F1 Driving Simulation: An Explorative Study

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Sensorimotor control simultaneously engages multiple cognitive processes, like decision making, intention, processing, and the integration of multisensory signals. The reciprocal relationship of cognition and sensorimotor learning is well documented. However, little is known if the status of cognitive skills relates to immediate sensorimotor performance of performing a novel skill. Thus, we aim to explore whether cognitive skills in general and executive functions (EFs) in particular may relate to novel sensorimotor performance and adaptive skills. Therefore, 23 male participants engaged in a novel driving simulation for 2 days. On the first day, they accustomed to the F1 simulation until meeting a preset threshold (adaption). On the second day, they aimed to drive as fast as possible (performance). In addition, we measured EFs and global cognition. We found meaningful relationships between response inhibition (Stroop Color and Word Test), the driving performance (r = 0.48, p = 0.013), and the adaptive ability (r = 0.34, p = 0.012). All other tests of executive functioning and global cognition remained non-significant. Our results illustrate an association of driving performance and adaptive abilities and the EF selective attention/inhibition in a novel F1 simulation. Given the novelty of the task, the ability to adjust sensorimotor behavior to keep the car on the track seems to be the primary necessary skill to navigate the lap and achieve fast times.

Keywords: driving, cognition, esports, gaming, executive functions

INTRODUCTION

The importance of cognitive control processes becomes apparent especially when we engage in complex situation where multiple afferent signals from sensory inputs must be integrated and coordinate in an abundance of degrees of freedom (i.e., hand and feet or the whole body). In this article, we attempt to investigate how executive functions (EFs) may be related to immediate sensorimotor learning ability to a specific novel and complex sensorimotor skill (i.e., racing in an e-game).

The idea, that sensorimotor performance and aspects of cognition are interrelated, has gained wide acceptance nowadays (Seidler and Carson, 2017). Particularly of interest in this regard are EFs.

EF comprises a family of cognitive processes associated with planning, organizing, and executing goal-directed behavior (Müller and Kerns, 2015). EFs help to regulate our behavior by governing afferent sensory information, aligning attention, and selecting a motor response (Diamond, 2013). Given the involvement of EF in motor planning, execution, and supervision, it does not surprise that components of EF (working memory, timing measures of inhibition, and set switching) correlate with sensorimotor performance (manual dexterity, ball skills, and balance) (Rigoli et al., 2012). While motor performance generally is operationalized using fine-motor coordination tasks like manual dexterity or balance performance, the relationship between EF and sensorimotor performance can be extended to multitasking skills like e-gaming. It is well documented that experienced e-gamer (mostly action game player) demonstrated increased performance in global cognition compared to non-players (see Hubert-Wallander et al., 2011 for a review). For example, Steenbergen et al. (2015) found that experienced action-game players outperformed non-players on a stop–change paradigm that provides a well-established diagnostic measure of action cascading. In addition, action-game players perform better at tests of EF, like task switching (Green and Bavelier, 2006), and tests of global cognition, like multiple object tracking (Cain et al., 2012) and dual-task performance (Strobach et al., 2012), among others.

Driving a car, also a virtual car, is a complex and "executive" task (Anguera et al., 2013). That is, car driving requires the coordination and a combination of multiple components (i.e., braking, accelerating, navigation, etc.) into a coherent global action. Based on our understanding of EF, which aligns with the framework by Miyake et al. (2000), a recent review by Walshe et al. (2017) stated that, out of the three core components of EF, working memory, inhibition, and set shifting, the latter was reported only in very few studies and none found a relationship with driving performance in a driving simulation. In contrast, inhibition, particularly in combination with working memory, responsible for governing multitasking, seems to be related to driving performance (Walshe et al., 2017). For example, Ross et al. (2015) showed that poor performance on inhibitory tasks and poor working memory together contributed to unsteady driving performance. Similarly, poorer inhibitory control on the Go/No–Go task positively correlated with risky behavior in a driving simulation (Hatfield et al., 2017). Similar, Mackenzie and Harris (2017) found that participants, who performed better at attentional functioning tests, exhibit more ecological eye movement and safer driving, like lane maintenance. However, a study by Van Leeuwen et al. (2017) showed that there are no major differences in a non-domain specific choice reaction time task and tracking task between racing and non-racing drivers. Not surprisingly, racing drivers drove faster laps than their controls. Naturally, this is due to years of sensorimotor learning. The authors showed that this was mainly because of more sensorimotor control in lane control and anticipatory gaze behavior. A recent investigation by Wood et al. (2016) showed that working memory capacity, measured with an automated version of the operation span task, correlates with hazard perception performance and self-reported driving behavior. The authors point out the relationship between controlled visual attention in motor-cognitive interference tasks and driving behavior, particularly in a more ecological environment like a driving simulation.

All above-mentioned studies showed that (driving) performance is not only based merely on superior sensorimotor behavior and intelligence but also on cognitive domain-specific sets, learned and adapted over years and years of specific practice (Lappi, 2015). However, little is known if different levels of cognitive skills, measured by tests of EF and global cognition, may relate to novel sensorimotor performance. Given the importance of EF in learning paradigms and the overall important role in driving performance, a relationship between cognition and sensorimotor behavior may impact study designs of any investigation regarding sensorimotor learning, at least in simulated driving studies. Therefore, the aim of the current study was to explore the relationship between EFs, global cognition, and sensorimotor behavior in a novel F1 driving simulation. We would hypothesize first that there is a relationship between fast driving, i.e., performance, and EF, based on the review by Walshe et al. (2017). Second, we would assume that global cognition does not relate to performance because of the inconsistent results throughout the literature. Given the novel nature of the sensorimotor task, we stratified participants in a short adaption session. Similar to performance, we would assume, third, that adaptive skills would relate to EF and, fourth, that there is no relationship between adaption and global cognition.

MATERIALS AND METHODS

Participants

We performed a statistical power analysis for sample size estimation. The targeted effect size (ES) in this study was medium to large, based on several investigations (Ross et al., 2015; Hatfield et al., 2017), using Cohen's criteria (Cohen, 1988). With an alpha of 0.05 and a power of 0.80, the projected sample size needed for this ES is approximately N = 23–67 for a bivariate normal correlation model (GPower 3.1.9.2). In total, 23 male participants (M_{age} = 25.6, SD = 2.2) participated voluntarily in this study. They were recruited by word-of-mouth advertising. Exclusion criteria were any neurological or musculoskeletal pathology, uncorrected visual impairment, and a professional occupation in e-gaming (competitive player who is paid to play video games). Our participants were engaged in e-gaming ($M_{hours/week}$ = 1.1, SD = 0.9) but had no previous experienced in a driving simulation. On average, participants received their driving license 8 years ago (M_{years} = 8, SD = 2). The participants where naive to the study hypothesis. All participants provided written informed consent prior to enrollment. The local ethics committee of the University of Oldenburg gave their approval (EK/2020/049), and we complied with the relevant ethical standards of the latest Declaration of Helsinki (WMA, October 2013).

Apparatus

The driving evaluation was conducted with an F1 simulator (The Codemasters Software Company Limited). The simulation was run on a PC, using Windows 10 (i7-8700 CPU @ 3.20 GHz, NVIDIA GeForce GTX 1070 graphics card). The visual system consisted of a 27-in screen (BenQ XL2720T), with a resolution of 1,920 × 1,080 pixels, a refresh rate of 120 Hz and a latency of 1 ms. Auditory feedback was provided through external speakers set to ~60 dB for all participants. To pilot the simulation, we used a steering wheel (ClubSport wheel Formula Carbon, Fanatec®, Landshut, Germany), throttle, and brake pedals (CSL Elite Pedale LC, Fanatec®, Landshut, Germany). The steering wheel was mounted on wheel-base pedals (ClubSport Wheel Base V2.5, Fanatec®, Landshut, Germany) providing force feedback. The driving aids *traction control* and *ABS* were fully enabled, while gear shifting was set to manual. All other driving aids were disabled. Participants were tested under the same conditions: track, Austria; car, Ferrari; perspective, third person; session, practice (without opponents).

Measures of Executive Functions

Our understanding of EF aligns with the framework by Miyake et al. (2000), emphasizing (a) shifting between tasks or mental sets, (b) updating and monitoring of working memory representations, and (c) inhibition of dominant or prepotent responses. While there is evidence that these target EF are moderately correlated, they contribute differentially to performance on complex executive tasks. Given the indication of non-meaningful influence of set-shifting abilities for driving performances (Ross et al., 2015; Hatfield et al., 2017; Walshe et al., 2017), we choose not to include data about those abilities. In addition, tests comprising global cognitive functions were used in the present study. All computerized tests of EF where based on the psyToolkit (Stoet, 2017) but translated to German. We recorded the computerized tests using a Macbook Pro (Apple Inc.) with a 13.3″ screen, running macOS Sierra Version 10.12.6.

Response Inhibition

Stroop Color and Word Test

To assess the ability to inhibit cognitive interferences and selective attention, we administered a computerized Stroop Color and Word Test (Penner et al., 2012). Forty color–word sets were shown in a random order on a computer screen, and participants had to recognize the color of the word by pressing a corresponding key on the keyboard. We presented 20 congruent word–color sets, where the color (i.e., red) and the word (i.e., red) of the presented stimuli were identical and 20 incongruent word–color sets, where the word (i.e., red) did not match the color (i.e., green). The ability to selectively attend and control response output was calculated as the time ratio (i.e., Stroop Score) of color–word interference and congruent tasks (incongruent/congruent).

Simon Task

Another test to assess selective attention and conflict resolution is the Simon Task (Hommel, 2011). In contrast to the Stroop Color and Word Test, participants are faced with a potential spatial conflict. The words "left" or "right" are presented either left or right of a central cross. Participants were asked to press "A" on the left side of the keyboard when they recognized the word "left" and press "L" on the right side of the keyboard when they recognized the word "right." The ability to identify and control response output was calculated as the time ratio (i.e., Simon Score) of conflicting and non-conflicting spatial presentations (conflict/non-conflict).

Visuospatial Memory

We used a computerized version of the Corsi Block Test to access visuospatial short-term working memory (Kessels et al., 2000). The task represents the participant's ability to remember series of spatial locations presented in sequences of different lengths. Participants were asked to memorize and reproduce the sequence of two to nine squares displayed on a computer screen. At the beginning of the Corsi Block Test, a sequence of two squares appears for a short time of 250 ms. Immediately after the sequence, participants were asked to repeat the sequence correctly. If the reproduction was correct for two trials, the sequence was increased by one square. If participants failed to reproduce the correct sequence for two trials, or if they reached the maximum of nine squares, the test was over.

Mental Rotation

In this task, 10 versions of triplets with random geometric forms were presented simultaneously. The triplets were presented in triangular, where the top form represented the original and the bottom forms were either rotated or mirrored (Hirschfeld et al., 2013). The task was to mentally rotate the top geometric form and decide which geometric form (A or B) was rotated and which was a mirrored image of the form on the top. Participants were instructed to press the A key (left image) or L key (right image) on a keyboard to indicate the rotated image.

Working Memory Span

To test working memory, we used the Digit Memory Test. This test consists of two parts: A, Digit Span Forward and B, Digit Span Backward. The assessor read out a random sequence of numbers (one per second) aloud, beginning with three digits and ending with nine digits. Participants were asked to either recall the sequence in normal (Part A) or reverse order (Part B). Each correctly repeated sequence counted as 1 point. The total

TABLE 1 | Descriptive values.

	M	SD	95% CI
Time (sensorimotor performance in s)	75.28	2.22	71.44, 80.45
Adaption in s	728.2	373.70	360, 1629
Trials to adaption (*n*)	22.7	7.8	13.2, 39.4
Driving experience (years)	8.0	2.3	5, 11
Time engaging in e-gaming (h/w)	1.46	0.92	0.96, 2.20
Stroop Score (incongruent/congruent)	1.14	0.11	0.95, 1.35
Simon Score (incongruent/congruent)	0.94	0.13	0.64, 1.20
Corsi Span Task (span)	6.13	1.10	4, 8
Mental rotation (% correct responses)	82.26	7.22	73, 93
Mental rotation (time per trial in s)	4.14	1.20	2.42, 6.45
Digit Memory Test (score)	94.96	11.14	75.8, 122.8

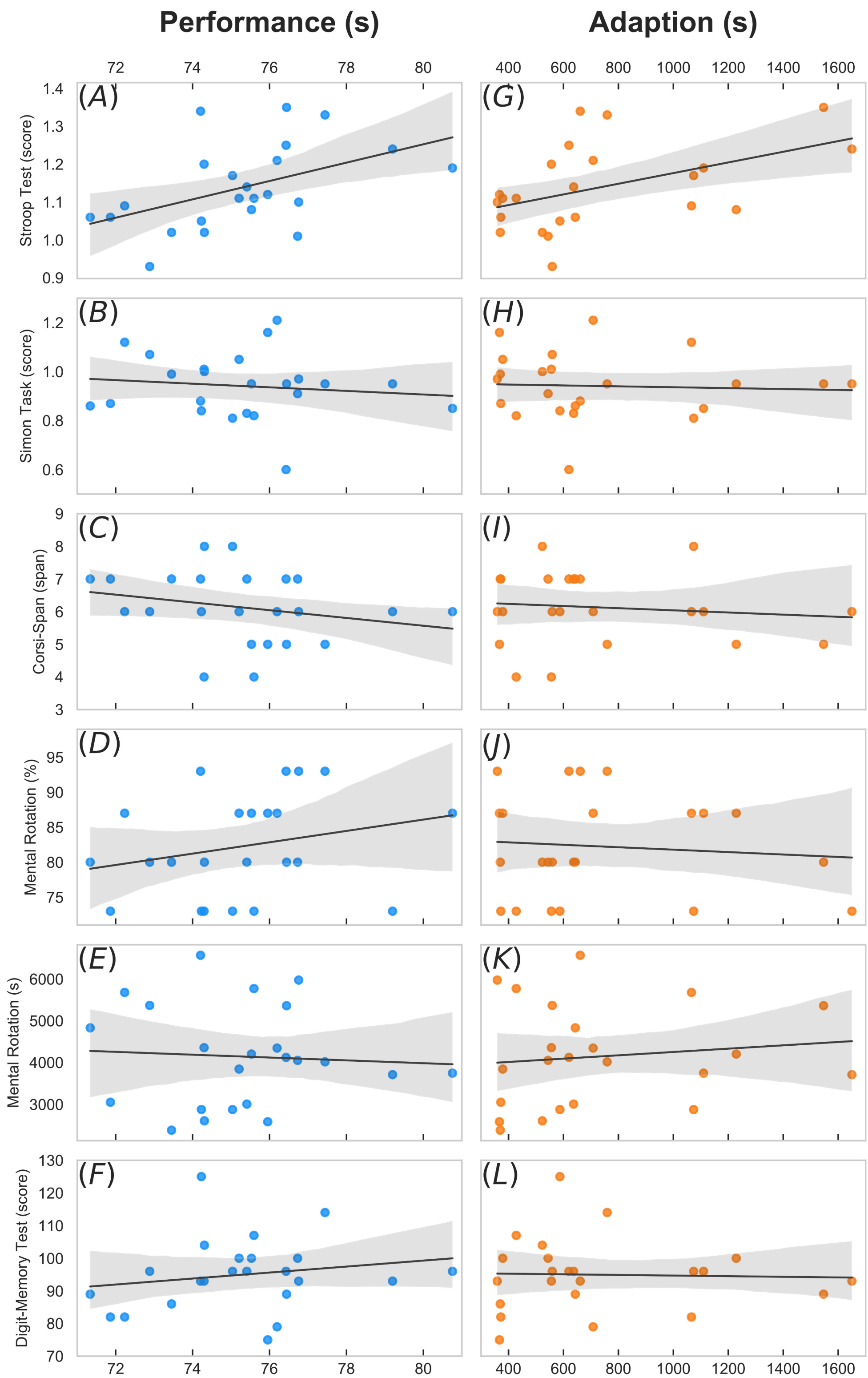

FIGURE 1 | Results of correlation analyses performed. Scatter plots depicts Pearson's correlations between **(A–F)** performance, **(G–L)** adaption and our variables of interest (executive functions and measures of global cognition). The straight line represents the linear regression model fit and the gray shade its 95% CI.

number of correct responses (backward and forward) were added and converted into a standard score, indexing working memory capacity (Turner, 2005).

Procedure and Measures of Driving Performance

The testing was conducted over two consecutive days. An assistant who was trained in administering the computerized EF test battery ran the data collection. On day 1, participants received a paper handout explaining the experiment, and they had to sign an informed consent. Then, participants performed the EFs tests. After completing the tests of executive functioning and a 10-min break, participants took a seat in front of the desktop computer with the driving simulation. The assessor shortly explained the necessary functions of the driving simulation, such as throttle, breaks, steering, and shifting. Participants were instructed to drive the fastest possible lap time while keeping their vehicle on the road, i.e., they were not allowed to cut corners. If participants took a shortcut, like leaving the track, the simulation marked this as invalid lap and the assessor restarted the lap. All sessions begun with a flying start, just before the final curve heading on the home straight. However, the session on the first day did not serve the purpose of driving the overall fastest personal time but to merely parallelize participants skills and test their adaptive skills, given that this was a novel task for all participants. We ended the session if participants undercut the 1:20 min twice or after 30 min. The time until participants reached 1:20 min was recorded and operationalized adaptive skills (*Adaption*). The threshold of 1:20 min was chosen because it requires a minimum of control over the simulation and lane maintenance. During pilot testing, we felt that after 30 min of engaging in the simulation, we experienced some signs of mental fatigue and choose this threshold. On the second day, participants were instructed to drive the fastest possible lap time. After they undercut 1:20 min again, the time of 10 valid laps were recorded, averaged, and subjected for further analysis. The mean lap time served as *Driving Performance*.

Statistical Analysis

We conducted an explorative cross-sectional study, examining the relationship between EFs and sensorimotor behavior in a driving simulation. First, we checked for normal distribution by determining the significance of skewness. Therefore, we calculate skewness z-scores by dividing them by their associated standard error. A z-score of ≥ 1.96 determines a significant skewness. We ran either Pearson's rho Bayesian correlation analysis, or in case of violating the assumption of normality or ordinal scaled data, the non-parametric alternative Kendall's rho instead. Further, we calculated BF_{+0}, the Bayes factor that quantifies evidence for the one-sided alternative hypothesis that the population correlation is higher than 0, with a stretched beta prior width of 1. In addition, we report 95% credible intervals of the posterior density of the correlation (Wetzels and Wagenmakers, 2012). Alpha was set at 5%. All data were analyzed using the freeware JASP (Version 0.9.2).

RESULTS

Given that we recruited 23 participants, which is on the lower bound of the required number of participants due to the power analysis, we would discuss non-significant results extensively and only with caution.

The only variable showing significant skewness was "Adaption;" therefore, we used Kendall's rho for further analysis for this variable. After the inspection of the Bayes Factor robustness check, we are confident that choosing a prior width of 1 was appropriate, given that the results would not change using different prior width.

Furthermore, we checked if driving experience (duration of having a driver's license in years) has an effect on our variables of interest. However, we found that driving experience has neither effect on "Performance" (r = 0.15, p = 0.490) nor on "Adaption" (r = -0.27, p = 0.090).

Descriptive results are shown in **Table 1**. All correlation results are visually presented in **Figures 1A–L** and in **Table 2**. Across all participants, the ability to selectively pay attention and inhibit response output measured by the Stroop Color and Word Test was positively related to driving performance (r = 0.48, p = 0.013; 1−β = 0.78, **Figure 1A**) and the ability to adapt quickly to a novel driving simulation task (r = 0.34, p = 0.012; 1−β = 0.49, **Figure 1G**). We found moderate evidence (Bayes Factor) for a relationship. The other measures of EF and global cognition remained without meaningful relationships.

Given different places on the track of lane violations, there was a heterogenous amount of trials to threshold (adaption). However, the number of trials until the threshold was reached was no mediating factor and had, thus, no relation to adaption time or performance.

TABLE 2 | Correlation outcomes.

	r	*r*−95% CI	*p*	BF_{+0}
Sensorimotor performance (s)				
Stroop Score (incongruent/congruent)	0.48	0.10, 0.72	0.013	6.47
Simon Score (incongruent/congruent)	−0.12	0.01, 0.38	0.771	0.18
Corsi Span Task (span)	−0.23	0.02, 0.43	0.168	0.07
Mental rotation (% correct responses)	0.25	0.02, 0.58	0.262	0.83
Mental rotation (time per trial in s)	−0.06	0.01, 0.41	0.289	0.21
Digit Memory Test (score)	0.18	0.01, 0.54	0.184	0.57
Adaption (s)				
Stroop Score (incongruent/congruent)	0.34	0.09, 0.72	0.012	6.30
Simon Score (incongruent/congruent)	−0.09	0.01, 0.27	0.592	0.18
Corsi Span Task (span)	−0.08	0.01, 0.28	0.695	0.18
Mental rotation (% correct responses)	−0.01	0.01, 0.32	0.658	0.28
Mental rotation (time)	0.12	0.01, 0.39	0.287	0.58
Digit Memory Test (score)	−0.08	0.01, 0.32	0.557	0.28

df = 21; BF_{+0}, Bayes factor that quantifies evidence for the one-sided alternative hypothesis that the population correlation is higher than 0.

DISCUSSION

Previous studies have demonstrated a relationship between EFs and sensorimotor performance in driving (Walshe et al., 2017). Here, we explored the relationship between EF and sensorimotor performance in a novel driving simulation task. All our hypotheses were supported. While global cognition and working memory reveal no relationship with neither driving performance nor adaptive ability, measures of EF such as selective attention and inhibitory behavior are meaningfully related to both driving performance and the time to adapt to a novel task.

The findings are in line with previous research, particularly the results of Ross et al. (2015), stating that the inhibition of inappropriate or non-ecological reactions are important for drivers to maintain a less variable traffic line. These inappropriate reactions might be unnecessary steering maneuvers happening when scanning for the next braking point and/or scanning the environment. This might result in a reduced time to adapt a novel task and to an increased driving performance (faster lap times). In other words, people with improved inhibition abilities would faster release the foot from the accelerator and might show faster braking times. Walshe et al. (2017) summarized that drivers with particularly high speed violation rates as well as drivers with low inhibition controls for speed could be associated with poorer inhibition skills. The authors assume that the poor inhibition control may contribute to the inability to ignore irrelevant information and therefore disturb speed control and general control on the track. The other domains of EF do not seem to be that important to driving behavior, although the authors of the above-mentioned review question the non-association of set shifting and driving, mostly due to the poor examination rate of set shifting in the literature (Walshe et al., 2017). In line with Van Leeuwen et al. (2017), we found no relationship between global cognition and performance. While they compared racing and non-racing drivers, the choice reaction time task and tracking task had no distinctive effect between the performance levels. The authors explain this with task-specific differences in sensorimotor skills between experts and novices while there are no major differences in general cognitive abilities. Yet, this is not directly comparable to our study, given that our participants were roughly at the same sensorimotor level. However, the small differences in response inhibition in our study, most likely leading to safer and more controlled driving, resulted in better performance.

In contrast to Wood et al. (2016), we did not find a relationship of performance and safe driving (lane maintenance) and working memory. Similar to set shifting, this EF seemed to be not important to our task. This does not exclude that, with a more complex task, we would see correlations between working memory and performance and adaption. Although the latent variables of EF do correlate with each other (Miyake et al., 2000), the correlation coefficient between updating/working memory and inhibition is moderate, meaning that task specificity may be responsible for the non-significant result in working memory and performance/adaption.

Interestingly, we found an effect for the Stroop Color and Word Test but not the Simon Task, although they are logically similar. Both produce two sources of interference in information processing; however, in recent years, it was debated whether the conflicts resulting from the two tasks are resolved by the same or different mechanisms (Scerrati et al., 2017). The authors assume that, in contrast to the Simon Task, stimuli in the Stroop Color and Word Test are unrelated to the response, and processing might be already occurring at the stimulus identification stage, rather than at the response level. In addition, the perceptual account claims that the interference of the Stroop Color Task, resulting from a semantic conflict (i.e., ink color vs. meaning of the word), and the interference in the Simon Task, stemming from a non-semantic conflict (i.e., different locations for stimulus and response) causes distinct conflicting effects (Li et al., 2014; Scerrati et al., 2017). Therefore, it is possible that, although both tasks are investigating response inhibition, the nature of the specific sensorimotor task (i.e., e-gaming) determines relevant effects rather for the Stroop Color and Word Test than for the Simon Task.

The current study has some limitations that warrant discussion. First, we included exclusively male participants. More studies are needed in order to verify the reliability and repeatability of our findings in samples with both sexes. Second, some might argue that we did not administer the full range of EF tests, like set shifting. However, prior research reported no significant influence of set-shifting abilities for driving performances (Fazeli et al., 2013; Hatfield et al., 2017; Walshe et al., 2017). For this purpose, we decide not to include any task for measuring set-shifting abilities. Third, we included 23 participants, which is at the lower bound of our estimated sample size, meaning that we might had some false negatives and missed certain existing relationships. Therefore, we tried to avoid extensive discussions on non-significant results.

CONCLUSION

In summary, our results illustrate an association of driving performance and adaptive abilities and the EF selective attention/inhibition in a novel F1 simulation. Given the novelty of the task, the ability to adjust sensorimotor behavior to keep the car on the track seems to be the primary necessary skill to navigate the lap and achieve personal fastest times. We would expect that other components of EF such as set shifting and working memory would be more important in a learning paradigm when participants must remember the optimal acceleration and braking landmarks and may deal with opponents. Indeed, there is some evidence that the ability to maintain attention is related to skill learning in driving contexts (Drews et al., 2008). Furthermore, since there is lack of secondary tasks presented, which we would face in a common real-world driving situation like listing to music, talking, and being aware of the environment and other drivers/opponents, our driving situation was more "clinical." In addition, participants did not have to interact with opponents, as they drove in a training session without any other vehicle on the lap. Apart from a minor rule (i.e., do not take a short cut→invalid lap), no sanctions were applied for misbehavior, bad driving, crossing the lane, etc. Thus, additional EFs, i.e., long-term memory and particularly set shifting, might play a vital role in other experimental setups. Previous research into action gaming indicated benefits of playing such games for memory (Li et al., 2015). Whether this assumption can be transferred to a driving simulation needs to be tested in future studies.

The results support the relationship of EF, sensorimotor performance, and learning. Our findings add further information on more ecologically valid research regarding sensorimotor learning. Given the importance of EF in learning paradigms and the important role in driving performance, we would suggest that studies that investigate sensorimotor learning may have to stratify their participants due to EF performance rather than randomize them.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/ **Supplementary Material**.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Kommission für Forschungsfolgenabschätzung und Ethik (EK/2020/049). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

NE analyzed the data, wrote the manuscript, and contributed to the conception and design of the study. IR, DG, and JS contributed to the study design, assisted with the data analysis and interpretation, and critically reviewed the manuscript. All authors read and approved the final version of the manuscript.

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SUPPLEMENTARY MATERIAL

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Cognitive and Motor Learning in Internally-Guided Motor Skills

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Several canonical experimental paradigms (e.g., serial reaction time task, discrete sequence production task, $m \times n$ task) have been proposed to study the typical behavioral phenomenon and the nature of learning in sequential keypress tasks. A characteristic feature of most paradigms is that they are representative of *externally-specified* sequencing—motor tasks where the environment or task paradigm extrinsically provides the sequence of stimuli, i.e., the responses are stimulus-driven. Previous studies utilizing such canonical paradigms have largely overlooked the learning behaviors in a more realistic class of motor tasks that involve *internally-guided* sequencing—where the sequence of motor actions is self-generated or internally-specified. In this work, we use the grid-navigation task as an instance of internally-guided sequencing to investigate the nature of learning in such paradigms. The participants performed Grid-Sailing Task (GST), which required navigating (by executing sequential keypresses) a 5 × 5 grid from start to goal (SG) position while using a particular key-mapping (KM) among the three cursor-movement directions and the three keyboard buttons. The participants performed two behavioral experiments—Single-SG and Mixed-SG condition. The Single-SG condition required performing GST on a single SG position repeatedly, whereas the Mixed-SG condition involved performing GST using the same KM on two novel SG positions presented in a random, inter-mixed manner. In the Single-SG condition, we show that motor learning contributes to the sequence-specific learning in GST with the repeated execution of the same trajectories. In the Mixed-SG condition, since the participants utilize the previously learned KM, we anticipate a transfer of learning from the Single-SG condition. The acquisition and transfer of a KM-specific internal model facilitates efficient trajectory planning on novel SG conditions. The acquisition of such a KM-specific internal model amounts to trajectory-independent cognitive learning in GST. We show that cognitive learning contributes to the learning in GST by showing transfer-related performance improvements in the Mixed-SG condition. In sum, we show the role of cognitive and motor learning processes in internally-guided sequencing and further make a case for using GST-like grid-navigation paradigms in investigating internally guided skill learning.

Keywords: motor sequence learning, skill learning, internally-guided sequencing, grid-navigation tasks, cognitive learning

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INTRODUCTION

Our everyday experiences are an excellent demonstration of the surprisingly adaptive and fluid learning behavior that is orchestrated by the human brain. Such a learning behavior is a hallmark of human cognitive ability and spans a broad spectrum of tasks. Ranging from complex tasks such as cycling and driving to seemingly simpler ones such as typing and grasping movements, all tasks involve the acquisition of skillful behavior. Skill learning is a natural behavioral phenomenon concerned with the acquisition of the ability to perform tasks proficiently. *Motor skill learning* refers to learning a specific subclass of skills that involve sequential motor movements such that they are executed accurately and quickly with practice (Newell, 1991; Clegg et al., 1998; Haibach et al., 2017; Schmidt et al., 2019). Much of the early interest in motor sequencing focused on investigating the typical behavioral phenomenon in sequence learning tasks (Lashley, 1951; Hebb, 1961; Fitts and Posner, 1967). This has led to the formulation of many serial order canonical experimental tasks such as the $m \times n$ task (Hikosaka et al., 1995; Bapi et al., 2000, 2006) and discrete sequence production (DSP) task (Verwey, 2001; Abrahamse et al., 2013; Verwey et al., 2015) in the explicit domain and serial reaction time (SRT) task (Nissen and Bullemer, 1987; Willingham, 1999; Robertson, 2007) in the implicit domain. While explicit learning involves conscious awareness of what is being learned, implicit learning occurs without conscious awareness of learning. Subsequent research has extensively used these paradigms to understand the brain processes involved in sequence learning, memory, attention, etc.

In SRT and DSP tasks, the participants repeatedly respond to a fixed set of visual stimuli organized in successive trials. Each trial involves presenting a sequence of visual cues that prompt corresponding keypress responses on a visuospatially-compatible button-box. In the $m \times n$ task, each trial consists of n consecutive visual stimuli (called a hyperset). Each visual stimulus consists of m illuminated squares on a 3×3 grid presented on a screen. The participants learn to press m corresponding keys (called a set) successively in the correct order on a keypad in response to the visual stimulus. The visual stimuli that guide the sequencing behavior in such paradigms are predetermined and fixed by experimental design. The sequence of motor actions to be performed is not contingent on the participant's choice or plan. Therefore, these canonical tasks belong to a class of discrete sequence learning tasks that involve *externally-specified* (visual) sequences. The sequence of motor actions in such tasks is conditioned on fixed, externally-specified visual cues/stimuli.

While such simple canonical paradigms are useful for investigating skill learning in controlled experimental settings, they fail to account for a larger class of real-life motor tasks. Unlike SRT, DSP, or $m \times n$ task, many real-life motor skills are internally-guided, i.e., the sequence of the motor actions is triggered by self-choice or some internal model of the environment. Such tasks constitute a class of *internally-guided* motor tasks. The sequence of actions is self-initiated or generated internally by the participant and is not extrinsically prescribed or predetermined by the environment. Unlike externally-specified sequencing, the sequential action in such tasks is not elicited as a chain of stimulus-response pairs. While the visual cues might help the agent make sense of the environment in such tasks, it does not specify the sequence of motor movements to be executed. The central point of difference between externally-specified and internally-guided sequencing is that the latter involves volitional planning of motor action sequences. A template tracing task on paper is an example of an externally-specified task. It employs external cues and visual feedback with a greater role of visuomotor associations for imitating the given template. On the other hand, drawing is an internally-guided task that relies on internal cues for guiding the pencil strokes to self-determined positions on paper. Such behavior is characterized by greater demands on brain processes related to memory and planning as compared to the tracing task. Other examples of such motor skills are composing music on a keyboard, creating a dance choreography, or solving a Rubik's cube. Such tasks involve planning as well as execution of a self-generated sequence of motor actions. The performance in internally-guided sequencing tasks depends on the dexterity of executing the motor actions and the ability to program the sequence of future actions.

Previous studies have investigated the motor behavior in externally-guided and internally-guided tasks and determined the neural underpinnings of the underlying processes. The externally-guided movements predominantly involve brain areas related to sensory guidance and optimization of movements, perception, and salience, whereas internally-guided movements involve brain areas related to muscle/movement selection, mental imagery, and planning complex behaviors (Gowen and Miall, 2007; Drucker et al., 2019). Other investigations have confirmed the role of cerebellar and premotor circuits in externally-guided tasks and basal ganglia, pre-supplementary motor cortex and dorsolateral prefrontal cortex in internally-guided tasks (Jueptner et al., 1996; Jueptner, 1998; van Donkelaar et al., 1999).

In externally-specified sequencing, bindings between the presented stimuli and the corresponding responses emerge with simple association rules between stimuli and response (S-R): selecting an action in response to a given stimulus binds the codes of the action-relevant stimulus attributes and the corresponding action codes (Logan, 1988). Due to repeated execution of sequences, the activity of the system controlling stimulus-based actions results in stimulus-response or sensorimotor learning (Herwig and Waszak, 2009). Therefore, the sequencing in the externally-specified domain is exhibited as a chain of stimulus-response-effect (S-R-E). On the other hand, the internally-guided or voluntary actions typically involve a goal-directed motivation to achieve an internally pre-specified outcome. The studies have shown that such self-determined action goals play a role in the acquisition and planning of internally-guided actions (Hommel et al., 2001; Hommel, 2003). The activity of the system guiding intention-based actions results in action-effect or ideomotor learning due to the formation of associations between movements and their ensuing sensory effects (Herwig and Waszak, 2009). According to the ideomotor framework of action control (Greenwald, 1970; Prinz, 1997), internally-guided actions primarily refer to anticipated action effects or, in other words, response-stimulus (R-S) bindings. In internally-guided actions, the participants might only attend to response-effect (R-E) contingencies (Herwig and Waszak, 2009). None of the previous studies have explored the nature of learning processes in such a class of discrete, self-guided sequential movement tasks. Motivated by this apparent gap, our present study investigates the role of different learning components in internally-guided sequencing.

Sequence learning in simple grid-navigation tasks is an example of an internally-guided sequencing task. The tasks involve navigating (typically, using a cursor) on the grid from the *start* position to the *goal* position. Each unique trajectory from the start to the goal position constitutes a novel sequence of keypresses. The optimality of trajectory is conditioned on the task specifications such as the reward scheme, possible agent movements, and time constraints. Participants are free to choose among many possible optimal trajectories for a trial to be successful. The repeated execution of these trajectories results in learning a self-generated, voluntary sequence of keypresses. The behaviors in grid-navigation tasks give us rich insights into the learning processes involved in internally-guided sequencing. We propose a novel usage of the simple grid-navigation task—*Grid-sailing task* (GST; Fermin et al., 2010, 2016) as a canonical paradigm to investigate the learning processes involved in internally-guided sequencing. The GST requires navigating a 5 × 5 grid from start to goal (SG) position using a given key-mapping (KM). The KM associates possible movement directions of the cursor with the corresponding keyboard buttons. The participants are instructed to reach the goal in an optimal number of steps as quickly as possible. **Table 1** provides a concise summary of different sequencing tasks—SRT, DSP, $m \times n$, and GST—based on the experimental paradigm and the nature of learning involved.

Specifically, we considered the involvement of two learning components—motor and cognitive. The cognitive component involves learning the sequential order of movements, whereas the motor component concerns the acquisition of fine-tuned movement dynamics and sensorimotor integration (Doya, 2000; Ghilardi et al., 2009; Penhune and Steele, 2012). Using GST as our canonical paradigm, we employ two behavioral experiments to identify the underlying learning processes in the internally-guided sequencing. In Experiment-1 (Single-SG condition), participants perform GST on a single SG-condition. We show evidence for motor learning due to the repeated execution of sequences. In Experiment-2, the participants use the learned KM from Experiment-1 to perform grid-navigation on the Mixed-SG condition, which consists of randomized trial order of two previously unseen SG conditions. A successful transfer of a KM-specific internal model would enable efficient trajectory planning on the novel SG conditions and, thus, would point out the role of the cognitive learning in Experiment-2. We further make a case for using GST-like grid-navigation tasks for investigating the typical behavioral phenomena in internally guided sequencing.

EXPERIMENT-1: SINGLE-SG CONDITION

We hypothesize that sequence-specific motor learning contributes to the learning in GST. As the participants repeatedly execute the same trajectory, the motor movements are optimized to facilitate accurate and fast sequential keypresses. This can be empirically tested by examining the effect of trials on the mean execution in Experiment-1 (also referred to as the Single-SG condition). The Single-SG condition also involved a rotation trial to test whether the learning in GST occurs due to the acquisition of a motor program or general motor improvements. The general motor improvements can result from factors such as task familiarity or adaptation. The rotation

TABLE 1 | Task comparison between externally-specified (SRT, DSP, $m \times n$) and internally-guided sequencing tasks.

	Serial reaction time task (SRT)	Discrete sequence production task (DSP)	$m \times n$ task	Grid-sailing task (GST)
Features of experimental paradigm				
Number of effectors	1/2	2	1	1
Number of choices/fingers used	4	4/6/8	3	3
Stimuli	Visual: spatially-compatible and key-specific	Visual: spatially-compatible and key-specific	Visual: consists of *m* illuminated squares on a grid	Visual cues for start, goal and agent positions
Sequence length	10	3–8	10–12	5–7
Number of trials	800	500–1,000	10–20 successful trials	20
Behavioral measures	Response time	Response time	Choice time, movement time	Reward, number of moves, execution time, reaction time
Nature of sequences and learning				
Sequence specification	Explicitly specified	Explicitly specified	Explicitly specified—discovery by trial and error	Internally planned
Kind of sequences learnt	Typically first-order and second-order	Typically first-order and second-order	Hierarchical sequence	Higher-order trajectory of grid-cell states
Nature of learning	Implicit	Explicit	Explicit	Explicit

was introduced such that the sequence of keypresses required to navigate the cursor from the start position to the goal position remained the same as in the normal trials. Consequently, the execution time on the rotation trials is expected to remain unaffected if the performance improvements in GST occur only due to general motor improvements.

Materials and Methods

Participants

Forty-two healthy participants volunteered for the study. The participant pool consisted of 29 women and 13 men between ages 17 and 27 (mean age: 21) years. All participants were non-musicians with normal or corrected-to-normal vision. The study was approved by the Institute Review Board, IIIT-Hyderabad, India. The participants gave informed written consent before the study. Additionally, permission for participation was obtained from the College Principal for participants below 18 years of age. The participants initially performed Experiment-1 (Single-SG condition with visuomotor rotation trial) followed by Experiment-2 (Mixed-SG Condition).

Apparatus

The participants were seated on a chair facing a high-resolution 24-in computer screen placed ~2 ft away. A conventional desk keyboard was used to record responses. The participants used the right index, middle, and ring fingers to press the number-pad buttons "4," "5," and "6," respectively. All the other keys on the number-pad were removed to prevent meddling in response selection. The experiment program for stimulus presentation and data recording was written using Python3 and PyGame (Python Game Development[1]).

Procedure

The participants were verbally instructed about the task procedure before the session started. A 5 × 5 grid with a red fixation cross at the center was displayed at the beginning of each trial. On pressing the "space" button, after a random delay of 500–1,000 ms, the trial started with the start position marked as a green tile and the goal position marked as a blue tile. The cursor, shown as a black triangle, was initially placed in the starting position. The participants were given 6 s to solve each trial, and this duration was not explicitly conveyed to them. During the trial response period, participants executed sequential keypresses to navigate the cursor from the starting position to the goal position. The possible cursor-movement directions were defined by the KM (see **Figure 1A**). In the beginning, the task required participants to explore the KM directions and its association with the corresponding keys by trial and error.

The participants were explicitly instructed to achieve a maximum score (of 100 points) while executing each trial as quickly as possible. If an optimal path is traversed, a maximum of 100 points is awarded for that trial. A minimum steps trajectory from start to the goal is considered an optimal trajectory. If the participant took a non-optimal path, a penalty of −5 points incurred for every excess move. In case the participant tried to perform an invalid move, such as moving out of the grid, the cursor position remained the same with an incremented move count. If the participant failed to reach the goal in the given time duration, 0 points were awarded for that trial. At the end of each trial, the performance feedback was displayed for 2 s, following which the fixation screen signaled the beginning of the next trial. On the center of the feedback screen, the performance feedback was presented as two numbers. The display showed the number of moves in the traversed trajectory and the reward score for that trial. A trial outline is shown in **Figure 1C**. The participants were given a rest block after every 20 trials to minimize the effects of muscle fatigue on the performance. The participants were also advised to maximally re-use the explored trajectories in order to execute the task quickly and accurately.

Two different KMs were used in the experiment to avoid any unwanted performance effects or bias due to a particular KM. Moreover, each KM was associated with a unique set of SG pairs (see **Figure 1A**). The participants were randomly assigned one of the two possible KMs. The participants used the same assigned KM throughout the experiment for both, Single-SG and Mixed-SG conditions. Twenty-four participants used KM1, whereas 18 participants used KM2 for the experiment.

In Experiment-1, the participants repeatedly performed GST on a single SG condition. The participants were presented with the same SG condition for trials 1–41. The rotation trial (trial 42) was introduced after the completion of 41 successful trials. The rotation trial was followed by the re-introduction of the learned single SG condition for the next five trials (trials 43–47). The post-rotation trials (trials 43–47) were used only for a comparative analysis between the rotation and normal condition. The rotation trial involved a 90° clockwise rotation of the grid. The start and goal positions also changed accordingly with the grid rotation. The rotated cursor changed its color from black to red to indicate the transformed KM associations (see **Figure 1B**). Therefore, the sequence of keypresses required to reach the goal position effectively remained the same. In the case of error trials in the rotation condition, the participants were repeatedly presented with the rotation trial. The participants were already instructed about the rotation trial beforehand. The participants took about 15 min to complete Experiment-1.

Behavioral Measures

The number of moves in the traversed trajectory, reward obtained, reaction time and execution time were the performance measures recorded for each trial of the experiment. Reaction time is defined as the time interval between the onset of stimuli and the first keypress. Execution time is the total time taken for sequential keypresses in a particular trial. Execution time is computed as the difference between the keypress time of the last and the first response. For analysis purposes, the trials were classified into three categories (1) Successful trials—if the goal position is reached with a non-zero reward, (2) Optimally successful trials—if the goal position is reached in an optimal number of moves and thereby scoring a maximum reward, and (3) Error trials—if the goal position is not reached in the given time duration.

[1]Retrieved from https://www.pygame.org

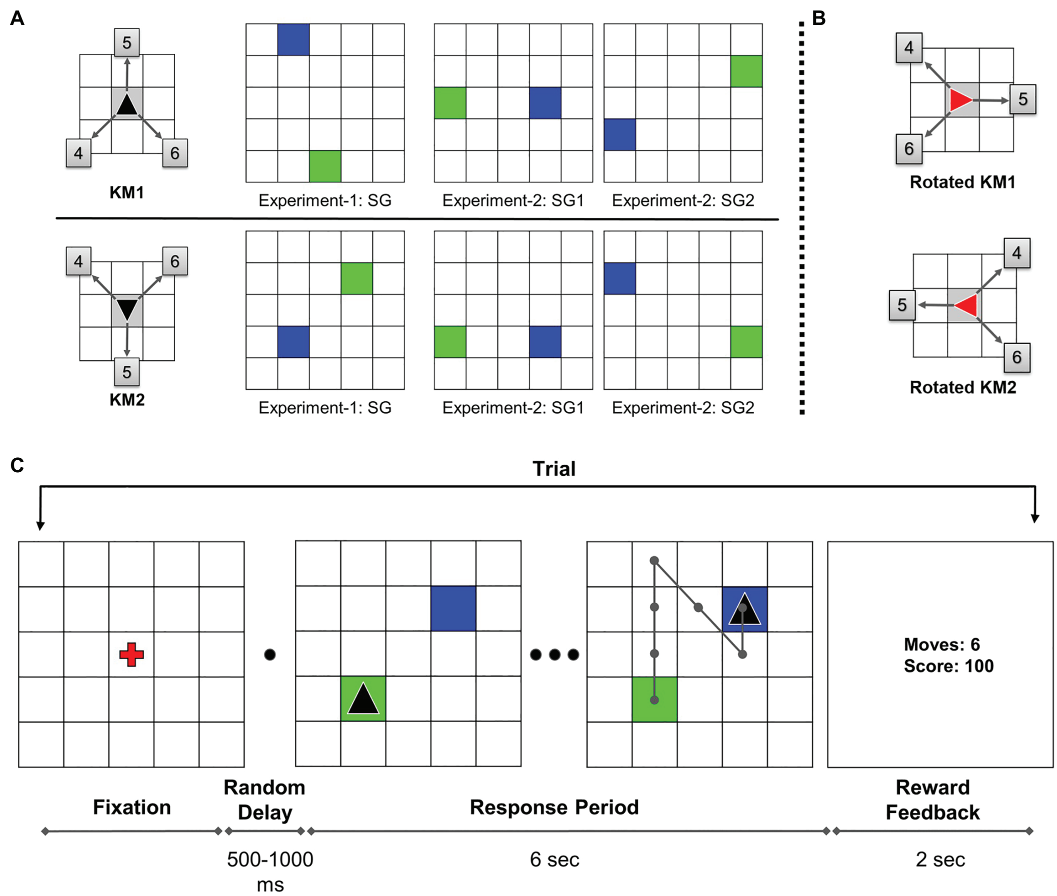

FIGURE 1 | (A) Key-mapping (KM) and start-goal (SG) position sets used in the experiment. Each participant was randomly assigned either KM1 or KM2. The boxed numbers on KM figure show corresponding numeric keys associated with the movements. In SG figures, green and blue tiles represent start and goal positions, respectively. **(B)** The 90° clockwise rotated KMs used in the rotation trials in Experiment-1. **(C)** Task diagram: sequence of trial events (adapted from Fermin et al., 2010). In this illustration, the participant is assigned key-map KM1. An example optimal trajectory is shown on the grid.

Results

The following behavioral measures were included for the analysis: reward score, reaction time, execution time, number of moves, and error rate. The error rate is a computed measure that denotes the average number of error trials attempted to complete one successful trial. The successful and error trials were both included in the analysis to show the emergence of learning and skillful behavior in the task. However, only successful trials were considered for other analysis purposes. A within-subjects repeated-measures ANOVA was used to test for the effect of practice (trials) on different behavioral measures. A series of Wilcoxon signed-rank tests was performed on various measures to compare the performance on rotation and normal trials. Repeated-measures ANOVA was used to probe any KM-specific effects on the performance. The statistical analysis was performed using Python (scipy and statsmodels packages) and JASP software (JASP Team, 2020).

The learning in the task is evident from the performance improvements in various behavioral measures. With practice, we see an increasing and decreasing trend in reward and execution time, respectively, which suggests that within a few (10–15) trials, the participants progressively learned to perform the task while optimizing for speed (execution time) and accuracy of navigation (reward; see **Figure 2A**). We took reward, moves, execution time, and reaction time as dependent measures of learning for successful trials. To evaluate the learning behavior, we plotted the mean values of behavioral measures in successful trials (see **Figures 2B,C**). The mean reward increases to a maximum of 100 points as the number of moves reduces over the practice to reach the optimal/minimum number of steps. A non-parametric Friedman test of differences among repeated measures (within-subjects) rendered a significant effect of trials on average reward obtained $[\chi^2(40) = 73.97, p < 0.001]$ and the average number of moves required to reach the goal $[\chi^2(40) = 73.97, p < 0.001]$.

The learning is also evident by comparing the mean execution time of the first successful trial (M = 3,110 ms, SD = 1,062) with the last successful trial (M = 1,271 ms, SD = 380 ms). The mean reaction time decreased from

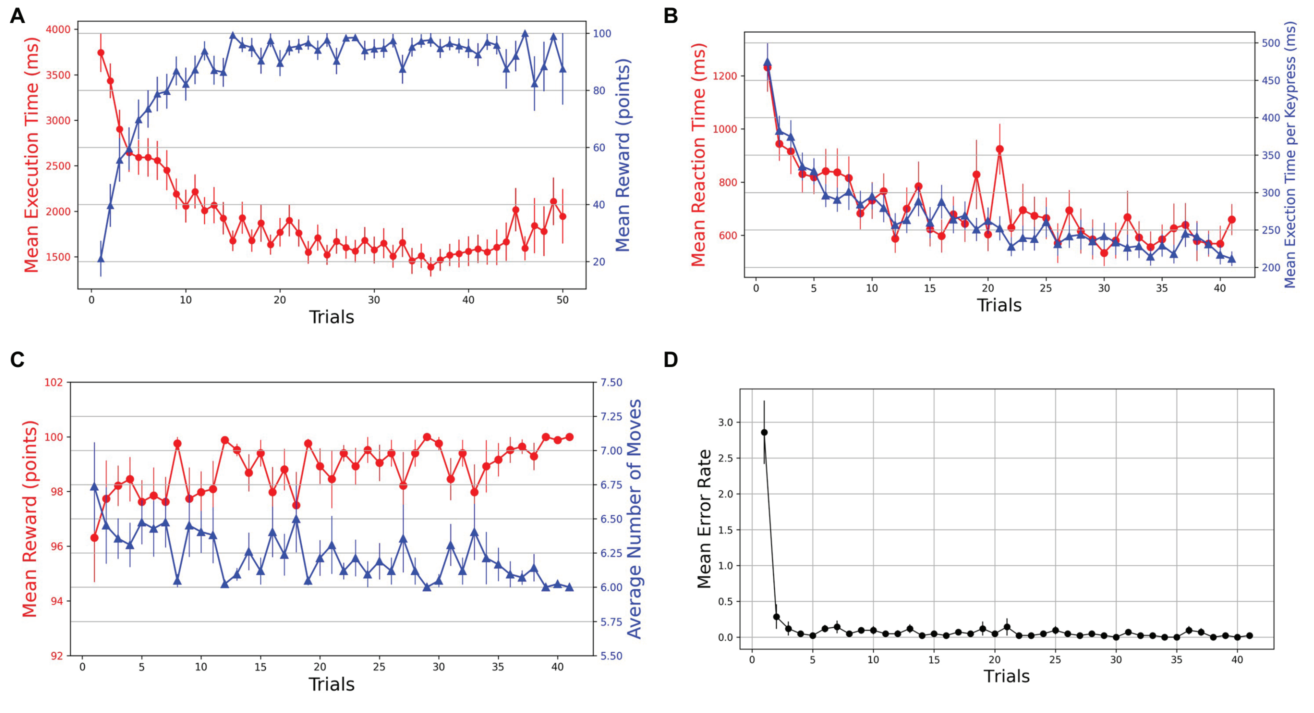

FIGURE 2 | Trial-by-trial course of performance improvement in Single-SG condition (rotation trial excluded). The bars on the plot data-points denote standard error in measurement. **(A)** Evolution of learning behavior in the task. Mean execution time and mean reward across trials—averaged over both successful and error trials. **(B)** Mean reaction time and normalized execution time in successful trials. **(C)** Mean reward and average number of moves in successful trials. **(D)** Mean error rates in successful trials.

1,232 ms (SD = 592) to 659 ms (SD = 380). The Friedman test indicated significant improvements in execution time $[\chi^2(40) = 485.90, p < 0.001]$ as well as reaction time $[\chi^2(40) = 300.55, p < 0.001]$. However, this decrease in execution time could have been a function of the number of moves in the trajectory. Therefore, we computed normalized execution times or execution time per keypress to account for the unequal lengths of trajectories in successful trials. The Friedman test indicated significant improvements in normalized execution time $[\chi^2(40) = 499.93, p < 0.001]$. The acquisition of learned sequences was examined by computing the error rates and plotting them against trials. A steep decrease in error rates is observed over the first few trials (see **Figure 2D**). Additionally, sequence-specific motor learning was examined by controlling the number of keypresses and the trajectories followed. For each participant, the most frequently used optimal trajectory was determined. The trials that employed the most-frequented optimal trajectory were extracted. A decrease in mean execution time from 2,473 ms (SD = 1,051) to 857 ms (SD = 157) in extracted trials suggests sequence-specific learning. To evaluate the performance improvements across these trials, we performed a Friedman test, which indicated a significant effect of trials $[\chi^2(38) = 78.72, p < 0.001]$ on execution time.

In order to examine whether the learning observed in the GST was particular to KM, we performed 2 (KM: 1 and 2) × 41 (Trials: 1–41) mixed repeated-measures analysis of variance (ANOVA) on normalized execution time. The KM was used as a between-subject factor, and trials were a within-subject factor. A Greenhouse-Geisser correction was applied when the ANOVA assumptions were violated. The ANOVA results suggested a significant main effect of trials $[F(11.16, 446.25) = 19.148, p < 0.001, \eta_p^2 = 0.324]$ on the normalized execution times. Similarly, a significant main effect of KM $[F(1,40) = 7.517, p = 0.009, \eta_p^2 = 0.158]$ indicated that the normalized execution times are different for the two KM. However, the Trial × KM interaction was not found to be significant $[F(11.16, 446.25) = 1.347, p = 0.194, \eta_p^2 = 0.033]$, suggesting that the variation in normalized execution time across the trials is not dependent on KM.

On the visuomotor rotation trial (trial 42), we observed a spike in the execution time (see **Figure 3A**). The execution time comes down with the re-introduction of the learned SG condition after the rotation trial. To assess whether the mean execution time for the visuomotor rotation trial is significantly higher than the normal condition, we took the average execution time of the preceding and the succeeding optimally successful trials and compared it with the rotation trial (trial 42). The mean execution time increased from 1,473 ms (SD = 496) in the normal trials to 2,906 ms (SD = 919) in the rotation trial. A Wilcoxon signed-rank test was used as the normality assumptions were violated. It suggested that the mean execution time for the rotation trials is significantly higher than the normal trials $(df = 29, Z = 0, p < 0.001)$. Similarly, the mean

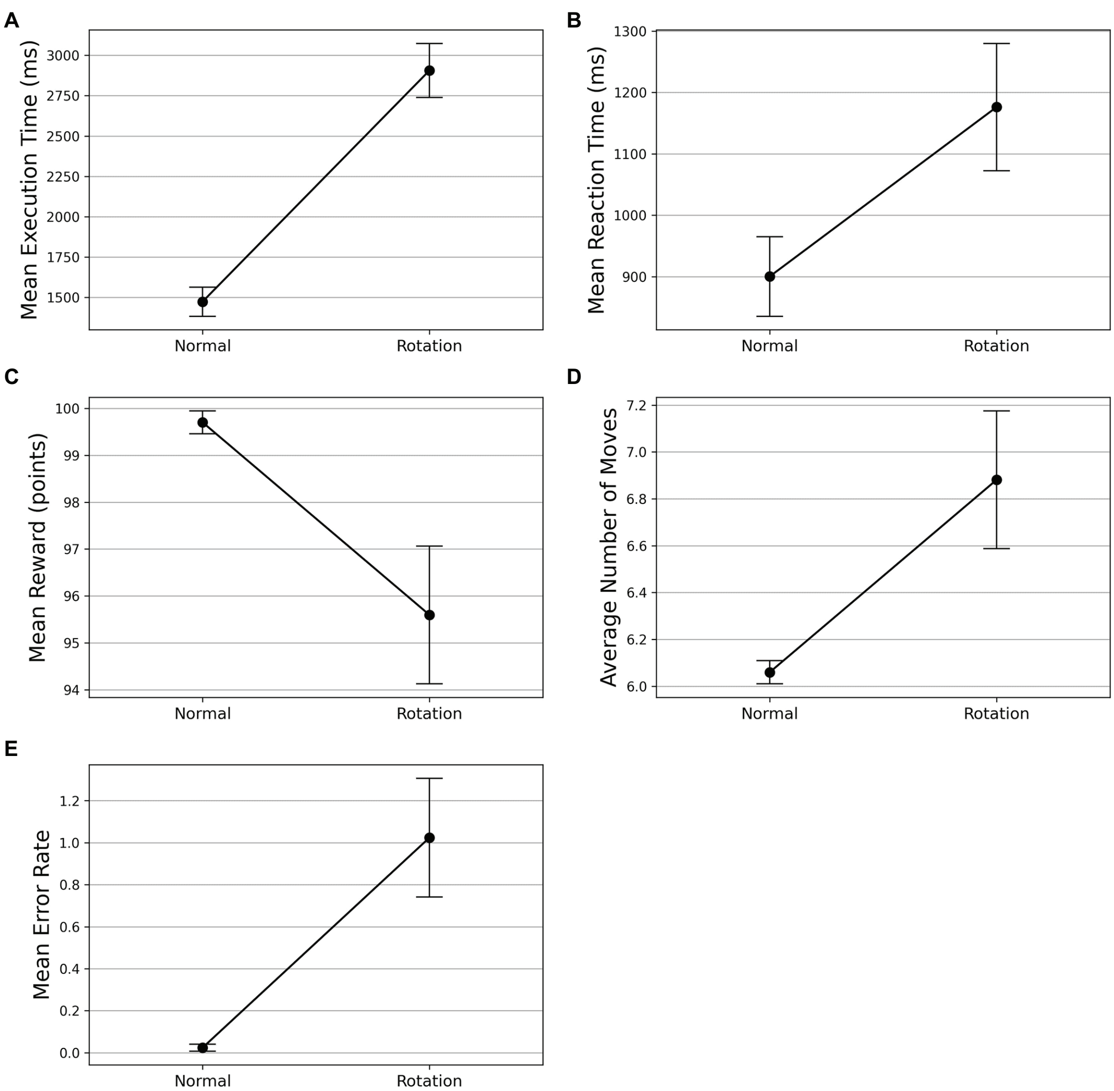

FIGURE 3 | Comparison of performance on normal and visuomotor rotation trials in Experiment-1. The bars on the plot data-points denote standard error in measurement. **(A)** Mean execution time on optimally-successful rotation trials is significantly higher than the average of preceding and succeeding optimally-successful trials. **(B)** Mean reaction time on successful rotation trials is significantly higher than the average of preceding and succeeding successful trials. On the rotation trial, the average reward obtained **(C)** is significantly lesser while the average number of moves **(D)** is significantly higher. **(E)** The mean error rate also increases in the rotation trials.

reaction time increased from 900 ms (SD = 420) in the normal trials to 1,176 ms (SD = 672) in the rotation trial (see **Figure 3B**). The Wilcoxon signed-rank test indicated that the difference in mean reaction time on the rotation trial and normal trials was significant ($df = 41, Z = 245.50, p = 0.010$). On following a similar procedure, we found that the mean reward obtained decreased from 99.702 (SD = 1.581) to 95.595 (SD = 9.513) on the rotation trials (see **Figure 3C**). The Wilcoxon signed-rank test suggested that the difference in mean reward score obtained on normal and rotation trials is significant ($df = 41, Z = 96.50, p = 0.006$). Similarly, the number of moves executed increased from 6.060 (SD = 0.316) in the normal trials to 6.881 (SD = 1.903) in the rotation trials (see **Figure 3D**). The Wilcoxon signed-rank test suggested that the increase in the number of moves is significant ($df = 41, Z = 8.50, p = 0.006$). The error rates also increased from 0.024 (SD = 0.108) to 1.024 (SD = 1.828) in the rotation trials (see **Figure 3E**). The Wilcoxon signed-rank test also suggested a significant difference in error rates ($df = 41, Z = 0, p < 0.001$) in both conditions.

Discussion

In line with previous GST studies and other skill learning tasks, the performance improvements in terms of speed (execution time, reaction time) and accuracy (reward) suggest the acquisition of skillful behavior (Nissen and Bullemer, 1987; Hikosaka et al., 1995; Willingham, 1999; Sakai et al., 2003; Fermin et al., 2010; Abrahamse et al., 2013). The practice-driven performance improvements in various behavioral measures in Single-SG trials suggest overall learning in GST. The practice-driven performance improvements in execution time provide evidence for motor learning that occurs due to the fine-tuning of motor movements. The Single-SG condition also included a visuomotor rotation trial to probe if the performance improvements in GST can be solely attributed to general motor improvements. The performance degradation on execution time and other measures such as reward, reaction time, and error rate suggests that the performance improvements in GST can be attributed to the sequence-specific learning processes (specifically, the acquisition of the motor program).

EXPERIMENT-2: MIXED-SG CONDITION

In Experiment-1, the participants repeatedly performed GST on a single SG condition using the same KM. The participants not only learned the motor program associated with the sequence of movements to reach the goal position but also internalized the navigation strategies related to the specific KM. The results of Experiment-1 established trajectory-specific motor learning. Further, to investigate KM-specific cognitive learning, we designed Experiment-2 (also referred to as the Mixed-SG condition) to test the transfer of KM-specific learning to novel SG conditions. We anticipate that the transfer of KM-specific learning will lead to efficient trajectory planning on novel SG conditions. The account can be empirically tested by comparing various performance measures during the initial trials of Experiment-1 and Experiment-2.

Materials and Methods

Participants

All the participants performed Experiment-2 after completing Experiment-1.

Apparatus

The experimental setup and apparatus were the same as in Experiment-1.

Procedure

In the Mixed-SG condition, the general task paradigm was the same as in Experiment-1 except for the SG-conditions. In the Mixed-SG condition, participants employed the previously learned KM (from Experiment-1) to perform grid-navigation on two novel SG conditions. The optimal number of steps in both the SG conditions were the same. During the experiment, each trial was randomly assigned to one of the two possible SG conditions. The participants performed GST on the randomized and mixed order of SG conditions. The experiment terminated when the participant performed 20 successful trials of each SG condition. The participants took about 15 min to complete the Mixed-SG condition task.

Behavioral Measures

The behavioral measures logged and analyzed were the same as in Experiment-1.

Results

A within-subjects repeated-measures ANOVA was used to test for the effect of practice (trials) on different behavioral measures. A series of Wilcoxon signed-rank tests was performed on various measures to test for the transfer of learning in Experiment-2. Repeated-measures ANOVA was used to probe any KM-specific or SG-specific effects on the performance. The first 20 successful trials of each SG condition were considered for analysis. Mean execution times and reaction times for a total of 40 successful trials were plotted against the trials. We observe that with practice, the participants become more accurate and efficient in performing GST on the Mixed-SG condition (see **Figure 4A**). Both the execution time and reaction time, as dependent measures of performance, decrease with practice (see **Figure 4B**). The learning is evident by the decrease in the mean execution time from 2,854 ms (SD = 971) in the first successful trial to 1,298 ms (SD = 428) in the last successful trial. And the mean reaction time decreased from 1,278 ms (SD = 623) to 733 ms (SD = 403). To evaluate whether the change across the trials is statistically different, we performed a non-parametric Friedman test of differences among repeated measures (within-subjects) for trials 1 through 40. We observed a significant effect of trials on the mean execution time [$\chi^2(39) = 423.35, p < 0.001$] as well as the mean reaction time [$\chi^2(39) = 210.40, p < 0.001$]. A Friedman test also indicated a significant effect of trials [$\chi^2(39) = 469.06, p < 0.001$] on normalized execution time. The mean reward scores improved from 97.50 (SD = 5.325) in the first trial to 99.52 (SD = 1.851) in the last trial. The effect of trials was significant on the mean reward obtained [$\chi^2(39) = 61.96, p = 0.011$; see **Figure 4C**]. The average number of moves required to reach the goal position decreased from 6.50 (SD = 1.065) to 6.095 (SD = 0.370) with practice. A Friedman test indicated a significant effect of trials on the average number of moves [$\chi^2(39) = 61.96, p = 0.011$; see **Figure 4C**). A Friedman test on mean execution time in optimally successful trials rendered a significant effect [$\chi^2(39) = 191.42, p < 0.001$] of trials. The mean error rates were computed by averaging the participant error rates while preserving the trial order. A steady decrease in error rates is observed with practice (see **Figure 4D**).

Additionally, we examined if the performance in the Mixed-SG condition was particular to KM. We performed 2 (KM: 1 and 2) × 40 (Trials: 1–40) mixed repeated-measures analysis of variance (ANOVA) on normalized execution time with KM as a between-subject factor and the trials as a within-subject factor. A Greenhouse-Geisser correction was applied when the ANOVA assumptions were violated. The ANOVA results suggested a significant main effect of trials [$F(13.09, 523.48) = 17.326, p < 0.001, \eta_p^2 = 0.302$], indicating that the normalized execution time varies across the trials. A non-significant main effect of KM [$F(1,40) = 0.782, p = 0.382, \eta_p^2 = 0.019$] indicated that the normalized execution times are not different for the two KM. Moreover, a non-significant Trial × KM [$F(13.09, 523.48) = 1.325, p = 0.193, \eta_p^2 = 0.032$] interaction suggested that the variation in normalized execution time across the trials is not dependent on KM.

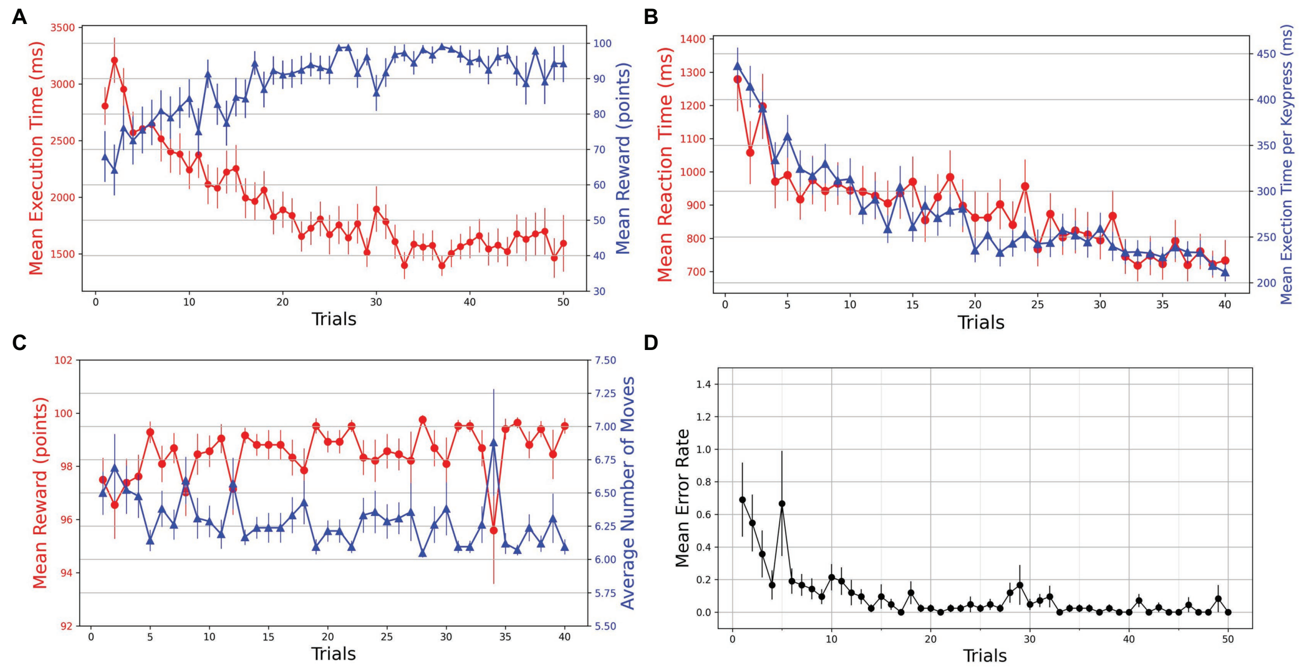

FIGURE 4 | Trial-by-trial course of performance improvement in Mixed-SG condition. The bars on the plot data-points denote standard error in measurement. **(A)** Evolution of learning behavior in the task. Mean execution time and mean reward across trials—averaged over both successful and error trials. **(B)** Mean reaction time and normalized execution time in successful trials. **(C)** Mean reward and average number of moves in successful trials. **(D)** Mean error rates in successful trials.

Since the participants used the same KM assignment as that in the Single-SG condition, we anticipate the transfer of learning to occur from the Single-SG condition to the Mixed-SG condition. We analyzed behavioral measures such as error rate, reward, and execution time for the first trial in both conditions to probe for transfer effects. The mean error rate improved from 2.857 (SD = 2.859) in the Single-SG condition to 0.690 (SD = 1.473) in the Mixed-SG condition. A Wilcoxon signed-rank test comparing the error rates during the first trials of both conditions reported significant differences ($df = 41, Z = 508.00, p < 0.001$). The mean reward score improved from 20.952 (SD = 40.714) in the Single-SG condition to 67.976 (SD = 46.224) in the Mixed-SG condition. A Wilcoxon signed-rank test revealed that the mean reward obtained is significantly higher ($df = 41, Z = 36.00, p < 0.001$) for the initial trial in the Mixed-SG condition as compared to the first trial in the Single-SG condition. Similarly, the mean execution time improved from 3,743 (SD = 1,380) ms to 2,807 (SD = 1,083) ms due to the transfer effects. A Wilcoxon signed-rank test suggested that the mean execution time for the first trial in the Single-SG condition is significantly different ($df = 41, Z = 743.00, p < 0.001$) as compared to the first trial of the Mixed-SG condition.

The Single-SG condition does not require participants to employ all three keys to reach the goal position. In both the KM groups, the participants only needed keys 4 and 5 to build the trajectory from the start to the goal position. Therefore, in both the KM groups, at the end of the Single-SG condition, the participants are highly trained with the response effects for two (keys 4 and 5) of the three keys. In the Mixed-SG condition, condition SG1 requires using keys 5 and 6 to build an optimal trajectory, whereas condition SG2 requires keys 4 and 5 to navigate to the goal position. Since the participants are highly trained on response-effect contingencies for keys 4 and 5 but not for key 6, the differential amount of practice may benefit performance on condition SG2 (employing keys 4 and 5) but not condition SG1 (employing keys 5 and 6). Thus, one can argue that performance will be influenced by a differential amount of practice based on SG conditions in the Mixed-SG condition. To probe this, we analyzed the effect of SG on execution time in the Mixed-SG condition. We performed 2 (SG: 1 and 2) × 20 (successful trials: 1–20) repeated-measures ANOVA on the mean execution time for each KM. A Greenhouse-Geisser correction was applied when the ANOVA assumptions were violated. For KM1, the ANOVA results reported a main effect of trials [$F(4.875,112.123) = 27.583, p < 0.001, \eta^2 = 0.402$], suggesting practice-driven learning. The test reported a non-significant main effect of SG [$F(1,23) = 3.915, p = 0.060, \eta^2 = 0.006$] and Trial × SG interaction [$F(6.983,160.601) = 1.081, p = 0.378, \eta^2 = 0.010$]. Similarly, for KM2, the ANOVA results reported the main effect of trials [$F(19,323) = 13.192, p < 0.001, \eta^2 = 0.263$], suggesting practice-driven performance improvements. It suggested a non-significant main effect of SG [$F(1,17) = 0.035, p = 0.854, \eta^2 = 0.0001$] and Trial × SG interaction [$F(19,323) = 1.204, p = 0.252, \eta^2 = 0.023$]. The results suggest that the execution time is not different for the two SGs in the Mixed-SG condition in both the KM groups. Therefore, the performance is not influenced by the differential amount of practice based on SG conditions in the Mixed-SG condition.

Discussion

The randomized and mixed order of SG conditions in Experiment-2 minimized the trajectory-specific performance improvements that occur due to the repeated execution of the keypress sequences. Significant performance improvements were observed for normalized execution time in successful trials and execution time in optimally-successful trials. Other performance measures such as reward and reaction time also improved with practice. This efficient performance of GST on new and randomly-ordered SG conditions can be attributed to the ability to use a previously learned KM-specific internal model for planning navigation strategies. As the learned KM relations can be successfully applied to new SG conditions, the participants could generalize the learning from the Single-SG condition to the Mixed-SG condition. The positive transfer effects support the idea of cognitive learning because the participants cannot simply transfer a learned motor sequence in the Mixed-SG condition.

In both the KM groups, the Single-SG condition employed only two (keys 4 and 5) of the three possible cursor movements to construct an optimal trajectory. One can raise the question that the transfer of learning would be better on the novel SG condition that employed the same practiced keys (namely, condition SG2) compared to the other novel SG condition (namely, condition SG1) in Experiment-2. However, the analysis revealed no difference in performance in execution time in both the SG conditions. This suggests that the transfer of the internal model related to the KM is not contingent on the specific keys that are practiced in various SG conditions.

GENERAL DISCUSSION

We investigated the nature of learning in internally-guided sequencing. We argued that GST-like grid-navigation tasks are exemplars of such a paradigm and hypothesized the role of motor and cognitive learning processes in learning in GST. We proposed a novel use of GST in two behavioral experiments to this end. In Experiment-1 (Single-SG condition), we investigated the progressive nature of learning, as evidenced by improvements in various behavioral measures. We provide evidence for the role of trajectory-specific motor learning in GST by showing the effect of trials on execution time in the Single-SG condition. The performance degradation on the introduction of a visuomotor rotation trial suggests that the learning in GST involves the acquisition of a motor program and therefore, it cannot be solely attributed to the general motor improvements. In Experiment-2 (Mixed-SG condition), we provide evidence for the role of KM-specific, trajectory-independent learning in GST. The transfer-related performance improvements in the Mixed-SG condition provide evidence for the acquisition of a KM-specific internal model that translates as cognitive learning in GST.

General Stages of Learning in GST

Improvements in various behavioral measurements such as execution time, reaction time, and reward score indicate learning in GST (see **Figure 2**). In the Single-SG condition, the participants initially tried to learn the possible movement directions and the corresponding key-map (KM) by trial and error. As the participants became familiar with the association between keypresses and corresponding cursor movements, they learn the effects of their responses. In further attempts, using the learned KM, the participants execute the keypresses to move the cursor in the direction of the target. Further practice enables them to plan simple and optimal navigation strategies to reach the goal. In the late phase, the repeated execution of the optimal trajectory drives performance improvements due to motor learning. We anticipate the role of motor chunking, due to which the planned trajectory to the goal position is segmented into sub-sequences of individual motor actions (keypresses). The late stage of practice would be characterized by an "automatic" mode of execution with reduced cognitive and attentional demands. Motor chunking would enable the participants to perform the sequence as a whole without relying on individual response-effect contingencies. The practice-driven performance improvements in GST due to chunking are investigated in another study (Bera et al., 2021).

The trajectory planning was guided by feedback from the reward score and the number of moves (see **Figure 2A**). The reward feedback gives a measure of the optimality of the trajectory followed. A steep decrease in the number of error trials (error rates) is observed after the first successful trial (see **Figure 2D**). Further practice enabled planning of optimal trajectories, as evident from the increase in mean reward. The participants quickly hit the reward ceiling (reward = 100) within 10–15 trials, implying that they have learned to navigate optimally. After a substantial amount of practice, as the KM model and SG trajectories are thoroughly learned, the (reward) feedback became less consequential for task accuracy (see **Figure 2C**). Nevertheless, we saw a further performance improvement in normalized execution time (task speed) of successful trials (see **Figure 2B**). To control the number of moves over which the execution time is computed in successful trials, we performed the normalized execution time analysis. A statistically significant improvement in normalized execution time shows growing expertise in performing the sequence. While multiple optimal trajectories are possible for a given SG position, the performance improvements due to repeated execution of the same trajectory can be attributed to motor learning. Therefore, we also performed the execution time analysis with a control on the number of moves and the sequential keypresses of the trajectory traversed. A statistically significant improvement in execution time confirms the role of motor learning due to repeated execution of the same trajectories.

Cognitive Aspects of Internally-Guided Sequencing

In addition to motor learning, the performance in internally-guided paradigms is also contingent on the ability to plan the sequence of actions efficiently. In GST, determining the sequence of keypress execution corresponds to planning a trajectory from the start to the goal position. Such planning and trajectory-generation are analogous to the goal-directed behavior in the knight's tour on a chessboard. To reach a given goal position on the chessboard, goal-directed planning is employed to generate an optimal sequence of moves (analogous to a trajectory in GST) using an internal map based on possible movement directions of a knight (similar to a KM in GST). In both cases, the conceived reach pattern used for planning trajectories is KM-specific. The acquisition of such a KM-specific internal model helps in planning trajectories and amounts to cognitive learning in GST.

Therefore, we hypothesized that cognitive learning processes contribute to the learning in GST. The role of cognitive learning could be confirmed if the participants can generalize the learning from a learned SG condition to other novel SG conditions. To test this, we performed Experiment-2, where we asked the participants to perform GST on randomized and mixed order of novel SG positions using the learned KM from Experiment-1. The transfer-related performance improvements in various behavioral measures confirm the role of cognitive learning. Since the participants cannot readily utilize the previously learned motor sequences on novel SG conditions, the transfer-related performance gains occur due to a trajectory-independent learning component. The two experiments are not independent because the same participants employed the same KM. Therefore, the improvements suggest that the KM-specific internal model is acquired and transferred from the Single-SG condition to facilitate efficient trajectory planning in the Mixed-SG condition. The acquisition of an internal model involves learning the KM relations between the possible cursor movements and the keypress buttons. This internal model is employed while planning the trajectories to generate a new sequence of keypresses that can be executed to solve a novel SG condition. Therefore, the cognitive component in GST is a form of the trajectory-independent learning process and it involves the acquisition of a KM-specific internal model.

The participants were able to employ the learned KM (from the Single-SG condition) to plan trajectories to the goal position with minimal failed attempts, as evident from a significant decrease in the error rate from 2.857 in the Single-SG condition to 0.690 in the Mixed-SG condition. The error rates denote the average number of error trials attempted to complete each successful trial. The fraction of participants who performed the first trial without any errors increased from 21% in the Single-SG condition to 69% in the Mixed-SG condition. Moreover, a qualitative examination of the evolution of trajectories in the early and late phases of the Mixed-SG condition suggests the role of a KM-specific learning component in GST. It is apparent from **Figure 5** that the participants employed the learned KM-specific internal model to improvise on non-optimal trajectories in the early phase. Thus, the late phase is characterized by optimal trajectory planning and increased trajectory density.

This account of transfer of learning is also corroborated by improvements in other behavioral measures such as the mean execution time and average reward score. The mean execution time decreased from 3,743 to 2,807 ms as the participants were able to quickly plan trajectories using the acquired KM on novel SG conditions. The mean reward score also improved from 20.952 in the Single-SG condition to 67.976 in the Mixed-SG condition. In summary, these results suggest that the participants are faster, more accurate, and quickly discover the optimal trajectory in the Mixed-SG condition as compared to the Single-SG condition. It suggests a key contribution of transfer of the acquired key-map from the Single-SG condition to the Mixed-SG condition.

In addition, we observed a significant effect of practice on the reaction time in Single-SG and Mixed-SG conditions (see **Figures 2B, 4B**). This result is rather intriguing because no improvements in reaction time were expected in line with the previous findings (Fermin et al., 2010). The reaction time denotes the latency of the first keypress, reflecting the time cost of pre-planning the whole trajectory from the start to the goal position. A steady decrease in reaction time implies that the participants become more adept at using the previously acquired KM-specific internal model to plan trajectories with practice. The reaction time trend provides additional evidence for the involvement of cognitive learning in GST.

The Single-SG condition involved a rotation trial. One possible way to complete the rotation trial efficiently, would be to execute the learned sequence of keypresses after performing a mental rotation of the KM and SG positions to "undo" the rotation. If participants employed this strategy, we would anticipate that the reaction times increase but not the execution times. However, we observed an increase in execution time and reaction time even on multiple attempts on the rotation trial (see **Figure 3**). This indicates that the participants may have attempted the rotation trial as a novel KM-SG condition. Consequently, the execution time increased due to the additional time cost of planning trajectories using a novel KM. The performance degradation is also evident from other behavioral measures such as reward score and error rates. We further examined the differences in the trajectories traversed in the normal and rotation condition (see **Figure 6**). We observed many qualitative differences between trajectories traversed in normal and rotation conditions, irrespective of the number of attempts on the rotation trial. Overall, the results in the rotation trials suggest that the trajectory-specific motor program learned in the normal condition could not be transferred to the rotation condition successfully.

Theoretical Perspectives on Internally-Guided Sequencing

Fermin et al. (2010) provide evidence for model-based action planning in GST by demonstrating that the participants benefit from previously learned state transition models (or KM) if an additional delay is given before the start of the movements. For learned KM, such a delay would favor model-based planning using internal simulations of sequential action selection. In our case, such acquisition of the internal model is evidenced by the ability to efficiently navigate in a randomly-ordered mixed-SG condition where trajectory/sequence-specific learning

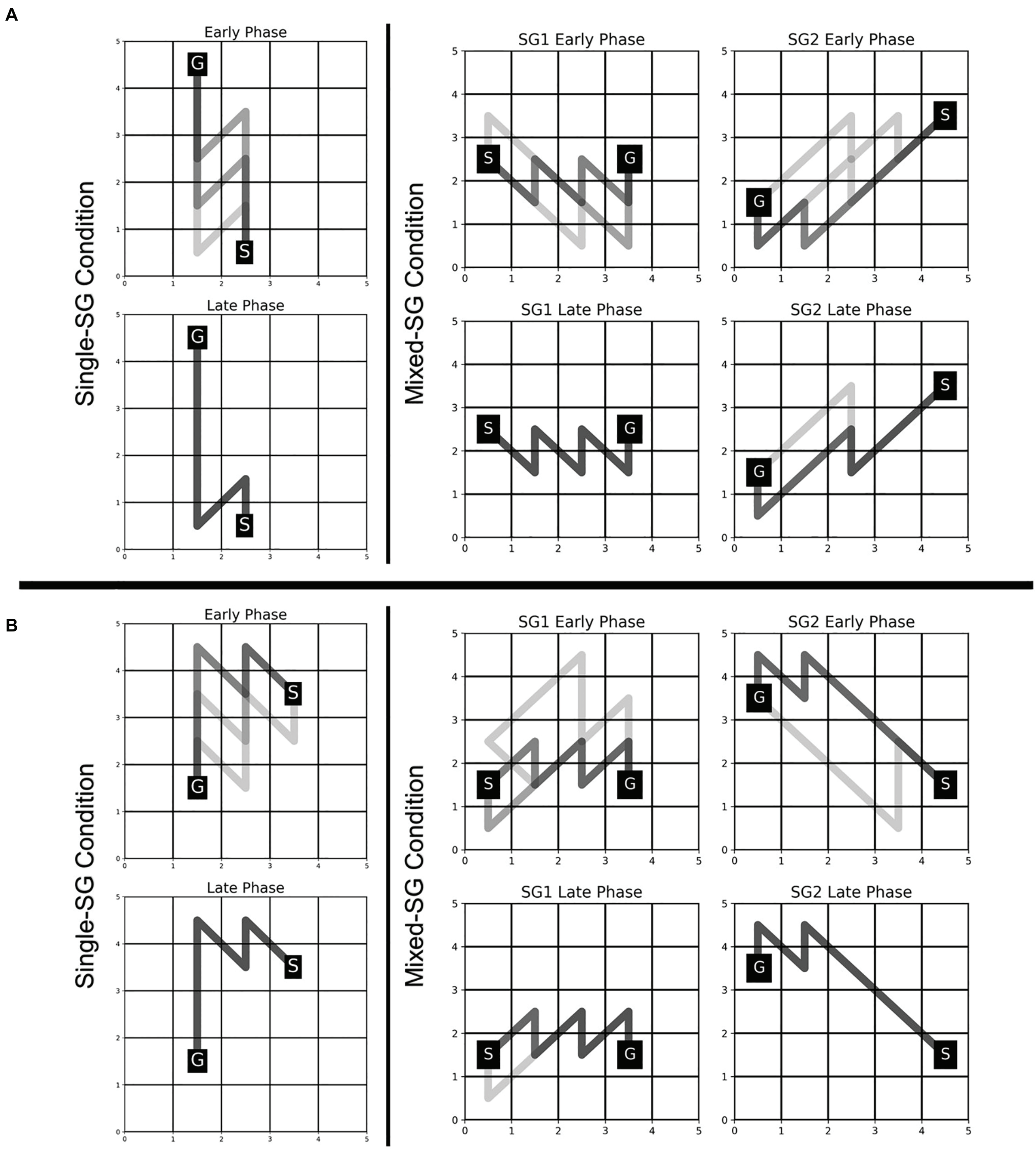

FIGURE 5 | Evolution of trajectories in Single-SG and Mixed-SG condition in two representative participants—MD **(A)** and AS **(B)**. Participants MD and AS are assigned key-maps KM1 and KM2, respectively. The comparison of trajectories in early vs. late phase is shown. The early and late phase correspond to the first and last five successful trials, respectively, in each condition. A darker trajectory shade denotes more frequented trajectory.

due to visuomotor associations is minimized. While Fermin and colleagues established the progressive nature of learning in different stages based on model-based and model-free action selection strategies, we examined the behavior in GST in terms of cognitive-motor dichotomy in internally-guided sequencing. We provide evidence to establish the role of cognitive as well as motor learning in GST. Numerous studies have tried to reconcile the computational (model-based vs. model-free) and behavioral

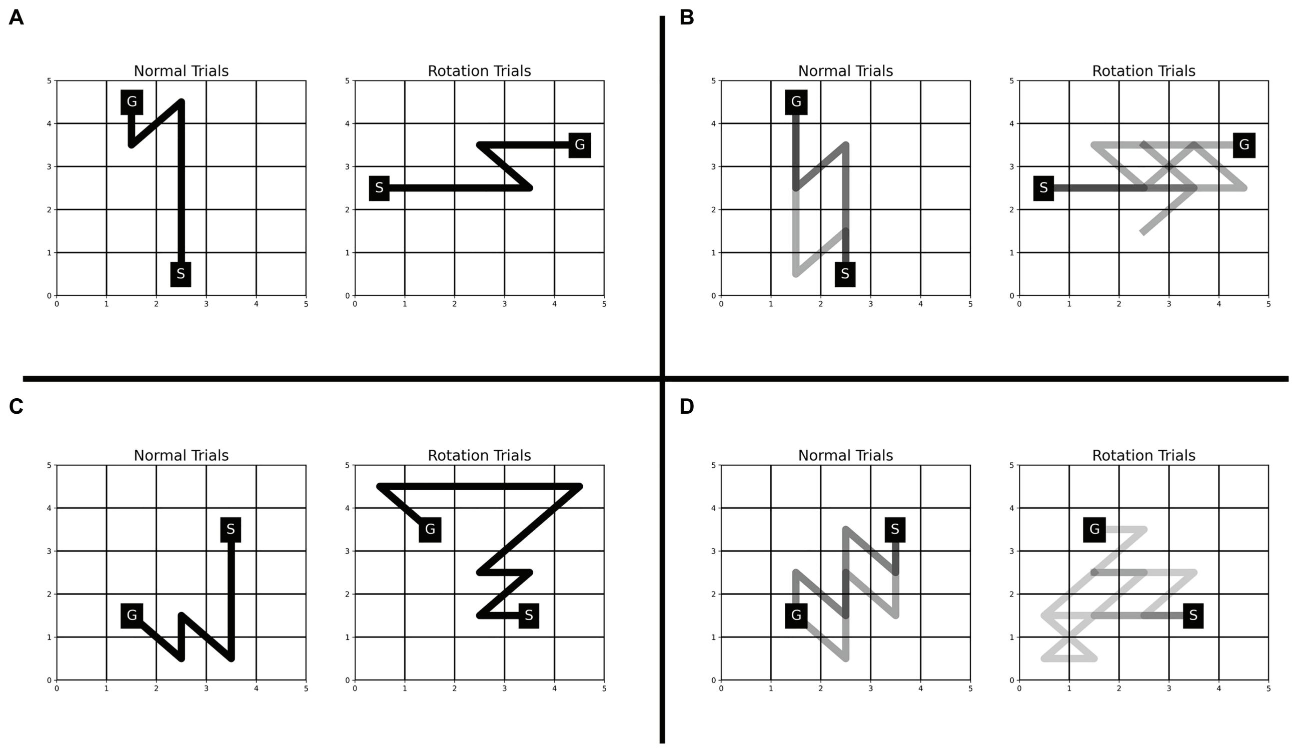

FIGURE 6 | Comparison of trajectories traversed during normal and rotation trials in Experiment-1 for four representative participants—JK **(A)**, LM **(B)**, RS **(C)**, and CP **(D)**. The trajectories for all the rotation trials are plotted for each participant. The number of trajectories plotted for the normal condition is matched with that from the rotation condition. The number of trajectories (or trials) plotted for participants JK, LM, RS, and CP is 1, 3, 1, and 5, respectively. A darker trajectory shade denotes more frequented trajectory.

(cognitive vs. motor) perspectives in understanding the distinct, parallel processes involved in motor learning (Keele et al., 2003; Wolpert et al., 2011; Dezfouli and Balleine, 2012; Wolpert and Landy, 2012; Savalia et al., 2016; McDougle and Taylor, 2019). In line with Fermin et al. (2010), we show evidence for the role of the cognitive learning process as part of goal-directed, model-based action planning in GST. The implications of our findings are two-fold—while establishing the role of cognitive and motor processes in the non-trivial planning and sequence execution in GST, we call for a renewed interest in understanding a class of practical, internally-guided motor sequence learning tasks. In sum, sequencing behavior in GST involves both general motor learning and acquisition of an internal model. Learning the association between the movements and the corresponding keypresses allows for the acquisition of sequence as participants learn to "react" appropriately and efficiently to the motor intention or plan as circumscribed by the KM-specific internal model. General motor learning results in quick and efficient performance with repeated execution of finger movements in response to visual cues. The performance improvements due to motor learning may be driven by motor chunking. In GST-like internally-guided tasks, practice-driven motor learning is constrained by a goal-directed internal plan of sequential actions. The internal model in GST involves the acquisition of a general structure or organization which guides the sequential order of keypress execution. A salient feature of such paradigms is that motor learning is influenced by the structure and organization of practiced sequences. It is guided internally and not externally imposed. Consequently, internally-guided paradigms involve developing internal representations for both the response-effect mappings for KM and the sequence of keypresses (trajectory) to reach the goal. These internal representations are subject-specific even when the participants were using the same KM on a similar SG condition. Our account is again in line with the previous studies on the ideomotor framework of voluntary action control. The action-effect (or R-E) bindings emerge during action planning, integrating components of the forward and inverse models of motor control (Ziessler et al., 2004; Nattkemper et al., 2010).

GST involves the role of interleaved cognitive and motor learning components. This parallel trajectory planning and motor learning induce a natural duality in the task. We speculate the role of working memory and visuospatial attention in GST. The task involves divided attention where information such as KM and the current trajectory is actively maintained online in the working memory. In contrast, SG information in the visual buffer helps in directing the cursor towards the goal position. The executive control inhibits the natural tendency of executing a response to generate the appropriate sequence of keypresses, given the constraints of the KM-specific internal plan. The early practice phase would be characterized by high attentional and cognitive demands as the participants learn response-effect mapping for the KM. With trial and error, as they learn to move the cursor towards the goal, the visuospatial attention and working memory are actively engaged to strategize navigation to the goal position. Further practice allows for optimizing the trajectories to reach the goal position in an optimal number of moves. Once an optimal path is discovered in the late practice phase, the performance improvements occur predominantly due to motor learning. We speculate that motor chunking characterizes automatic and habitual control with reduced attention.

Grid-sailing task is a simple canonical paradigm that does not require any complicated experimental setting, yet it offers rich insights into the planning and sequencing behavior. Unlike other discrete sequencing tasks such as SRT, DSP, or $m \times n$ task, GST involves learning self-generated motor sequences. In GST, the sequential keypresses are not guided by an external series of stimuli but are instead self-initiated by a KM-specific internal model. The behavior in GST can be organized into the "planning" and "executing" phases. These distinct phases enable natural dissociation of cognitive and motor strategies involved in internally-guided sequence learning. This is a unique and helpful characteristic of GST that can be leveraged to investigate the role of different learning processes involved in internally-guided sequencing. The cognitive phase in GST can be distinctly associated with acquisition of the trajectory-independent and KM-specific internal model, which is employed while navigating the grid. The learned KM could also enable a selective transfer of the learned model to other tasks where the KM is compatible. Therefore, GST can also be used to study skill transfer and related behavioral phenomena. Moreover, the GST task paradigm affords variations in different aspects. The GST instances can differ in various factors such as grid-size, start-goal (SG) positions used, KMs associated with the task, and the number of cursor movement directions. Owing to many possible variations in the GST paradigm, the instances cover a broad spectrum of grid-navigation tasks that vary across aspects such as the difficulty of solving, execution time required, and cognitive effort demanded—providing reasonable experimental control that is necessary to study different factors involved in sequence learning tasks.

CONCLUSION

Using GST as an exemplar paradigm of the grid-navigation task, we provide evidence for cognitive and motor learning in internally-guided sequencing. In the Single-SG condition, we show that the overall learning in GST is evident from the performance improvements in various behavioral measures. We further show increasing dexterity on repeated execution of the same trajectories as evidence for motor learning. A rotation was introduced in the Single-SG condition to probe if the performance improvements can be solely attributed to general motor learning. The performance degradation on the rotation trial suggests that the learning is not occurring only due to general motor learning. We further hypothesized that cognitive learning contributes to the learning in GST. The role of such a cognitive learning process is confirmed by showing transfer-related performance improvements on the randomized and mixed order of previously unseen SG conditions in the Mixed-SG condition. We show that the participants generalize and transfer a KM-specific internal model from the Single-SG condition to the Mixed-SG condition. We further advance the use of grid-navigations tasks in investigating internally-guided sequencing.

LIMITATIONS AND FUTURE DIRECTIONS

The experimental paradigm can be modified to incorporate a within-subject control over the executed trajectories to probe motor chunking. Future work can also attempt to examine the differences in trajectory traversals in different conditions statistically. For example, a hypothetical measure of trajectory density can be used to understand the evolution of trajectories in Single-SG conditions. A categorical comparison of the trajectory features in Single-SG and Mixed-SG conditions can reveal further evidence for the "transfer" of KM-specific learning. The role of KM-specific learning can be further validated by introducing a new KM on the same SG conditions. Future studies can also employ a retention task by extending the experimental task over a period of days to dissociate the cognitive and motor learning in GST. We anticipate that the KM-specific internal model will be retained longer than the fine-tuned motor movements specific to the trajectory. Consequently, we can expect to see that the participants quickly recall the learned KM and perform better than they had initially performed at the beginning of the task.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the corresponding author on reasonable request.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institute Review Board (IRB), IIIT-Hyderabad, India. Written informed consent to participate in this study was provided by the participants, and where necessary, the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

KB and RB conceptualized the study. KB and AS designed the experiment. KB collected the data. KB, AS, and RB contributed to data analysis, interpretation, and manuscript writing. All authors contributed to the article and approved the submitted version.

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Adaptive Esports for People With Spinal Cord Injury: New Frontiers for Inclusion in Mainstream Sports Performance

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Introduction: People with Spinal Cord Injury (SCI) are at risk of feeling socially disconnected. Competitive esports present an opportunity for people with SCI to remotely engage in a community. The aim of this study is to discuss barriers to esports participation for people with SCI, present adaptive solutions to these problems, and analyze self-reported changes in social connection.

Materials and Methods: We presented a descriptive data collected in the process of a quality improvement initiative at Mount Sinai Hospital. In 2019, seven individuals with cervical SCI and quadriplegia participated in a special interest group on esports. Group scores were then analyzed for evidence of between subjects variability using a single sample *t*-test. A Pearson's correlation was conducted to determine the relationship between social connectedness and demographic data.

Results: All players experienced functional limitations as a result of their injury but managed to design personalized gaming setups with adaptive equipment that allowed them to successfully compete in esports. All players reported a positive change in perceived social connectedness ($p < 0.001$) after participating in the special interest group. Score on Social Connectedness Scale negatively correlated with Time since injury (years).

Discussion: It is feasible to create adaptive gaming setups that can be used by people with differing degrees and severity of SCI in a competitive esports environment. Technology and adaptive competitive esports have a potential to improve social connectedness and inclusion in people with quadriplegia. Further research on efficacy and effectiveness of these inclusive environments and their effects on quality of life, activity, and participation is warranted.

Keywords: spinal cord injuries, video games, sports for persons with disabilities, community participation, social isolation

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INTRODUCTION

The National Spinal Cord Injury Statistical Center estimates that there are a total of 291,000 people living with Spinal Cord Injury (SCI) in the United States of America and another 17,730 spinal cord injuries occur every year (National Spinal Cord Injury Statistical Center, 2019). Life after SCI often involves a significant change in lifestyle due to the changes in physical capabilities that are brought about by the injury. In addition, secondary medical conditions that occur due to SCI significantly affect all aspects of life, including employment, mobility, independence and dignity (Post and Noreau, 2005). This issue is compounded by the fact that access to appropriate medical and social support services is often limited for people with SCI (Stillman et al., 2014).

Social support and employment are consistently rated by people with SCI as important for successful post-injury functioning (Bamford et al., 1986; Krause, 1992; Kennedy et al., 2006). Feelings of loneliness and social isolation weigh heavily on many individuals with SCI, and can often contribute to negative health and well-being outcomes (Barclay et al., 2016; Tsai et al., 2017). Work by Guilcher et al. (2019) has shown that the size of one's social network is uncorrelated to feelings of loneliness, rather the frequency and quality of authentic social interactions were the most important factors for reducing loneliness and social disconnectedness. As a result of the global SAR-CoV-2 pandemic, mandated social distancing has intensified the social isolation of high health-risk individuals, and healthcare and social support accessibility is of greater concern than ever before (Jumreornvong et al., 2020).

Competitive organized online gaming (i.e., *esports*) has been steadily growing in popularity since the first esports competition occurred in 1972. In the decades following, esports leagues, competitions, and tournaments have been increasing in frequency, skill, and competitiveness. In recent years, esports has transcended the status of "hobby" for many of its participants to be now considered a serious activity with a professional participatory element and resulting in the formation of multiple distinct subcultures (Seo and Jung, 2016). Online gaming involves trust, respect, and cooperation, and these foundational elements have fostered a global and inclusive community of gamers (Freeman and Wohn, 2017).

Universal Design (UD) is a guiding principle developed to promote equal access to products, environments, and services (Lid, 2014). Many individuals with physical differences wish to engage in esports but are unable to do so due to lack of accessible technology. Previous work describing video-game interventions in individuals with spinal cord injury focuses on gamified rehabilitation interventions eliciting cardiorespiratory fitness response (O'Connor et al., 2000; Burns et al., 2012) or enhancing muscle activation (Sayenko et al., 2011; Jaramillo et al., 2019). However, the exploration of esports in a non-therapeutic, recreational context, and its role in promoting social connectedness and reducing isolation has not been reported and is a novel aspect of this quality improvement (QI) initiative.

The purpose of this study is to identify specific issues that have hindered participation in esports activities in seven individuals with quadriplegia secondary to SCI. Additionally, we examine the different ways that these individuals have created (or plan to create) adaptive environments to overcome these issues and enable more active participation in the esports community. Finally, we evaluate whether the recent inclusion of these players in esports activities has changed their perception of their own social isolation.

MATERIALS AND METHODS

Settings and Participants

We present results from a quality improvement initiative to enhance social support services for the SCI patient population at Mount Sinai Hospital.

Within the hospital system there is a social support infrastructure in place to assist patients with spinal cord injury (SCI) in reintegrating into society after their injury. Within the main support groups, consisting of up to 30 active members, a number of participants expressed interest in esports and video gaming. These participants, in partnership with the study team, formed a special interest group on esports and people with SCI. Individuals were eligible to participate in this group if they had cervical spinal cord injuries (SCI), were participating in a social support group for people with SCI at Mount Sinai and had sufficient degree of cervical motor control (rotation and/or flexion/extension) and range of motion to use the adaptive gaming devices. There were no specific exclusion criteria.

As part of the special interest group, participants worked with the study team to create personalized gaming setups and participated in online and offline gaming sessions. These sessions were conducted individually or as part of group practice. All seven members of the special interest group were contacted to engage in this QI initiative, and all seven individuals responded. All participants gave verbal permission for the use of the de-identified data that was collected as part of this QI initiative.

Gaming Customization

Each participant in the focus group had access to a Maingear Vybe Desktop PC, MSI Optix MAG27C, Logitech G703 Lightspeed wireless gaming mouse, and Logitech G915 Lightspeed wireless gaming keyboard. Additionally, each player was given access to adaptive equipment that could meet their needs, including the Xbox adaptive controller (Microsoft Corporation, Redmond, WA) and an accompanying Logitech G Adaptive Gaming Kit (Logitech International S.A., Lausanne, Switzerland), the "QuadStick" controller (QuadStick, Great Falls, MT), Tobii Eye X eye tracking technology (Tobii AB, Stockholm, Sweden) and Warfighter Engaged joysticks (Warfighter Engaged, Inc., Wayne, NJ). Each player then created a custom gaming setup for optimal participation in esports competition. Gaming environment setups were continuously optimized based on qualitative feedback from players and quantifiable success at selected games. Need for specific optimizations was generally dictated by each player's functional capacity and level of injury, and thus was highly individualized and required specific customizations. The need for equipment upgrades to enhance gaming ability was continuously assessed and addressed. All players had access to a clinical coordinator from the hospital to assist with equipment setup and/or technical support on request.

Data Collection and Outcome Measures

Study data were collected over phone and video calls with members of the study team, and via SurveyMonkey (SurveyMonkey Inc., San Mateo, CA). Baseline demographics included age, gender, SCI level (ASIA's score) (Kirshblum et al., 2011), time since SCI, level of independence (SCIM III), and past gaming experience. Outcome measures included Social Connectedness Scores (SCS), perception of change in social connectedness, current gaming setup, opinions on current gaming setup, and ideal gaming setup (**Table 1**).

To evaluate participant's level of function and independence, we used The Spinal Cord Independence Measure (SCIM III). The scale evaluates three domains of function: self-care (score range 0–20), respiration and sphincter management (0–40), and mobility (0–40). The total score ranges from 0 to 100 where higher scores indicate higher levels of independence (Itzkovich et al., 2018). SCI level was classified according to the American Spinal Injury Association (ASIA)'s International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) (Kirshblum et al., 2011). The scale describes the neurological level of injury and five impairment classification levels (A, B, C, D, and E) ranging from complete loss of neural function in the affected area (A) to completely normal (E) (**Table 2**).

Perception of connection to others in their social environment was self-reported using the Social Connectedness Scale (SCS). The scale presents 8 negative perception statements (i.e., "I feel disconnected from the world around me") rated on a 6 point Likert scale ranging from 1 (strongly agree) to 6 (strongly disagree). Scores were summed with a potential range of 8–48 with a higher score denoting a higher level of perceived social connectedness (Lee and Robbins, 1995) (**Table 2**).

To evaluate players' perception of change in social isolation and social connection, players were presented with the statement "Since becoming involved in an adaptive esports team, I feel less socially isolated and more socially connected" and asked to rate their agreement on a 5-point Likert scale ranging from 1(strongly agree) to 5 (strongly disagree) (**Table 2**).

TABLE 1 | Phone interview questionnaire.

1. When did you start gaming?
2. What gaming setup have you traditionally used?
   a. Why do you like it?
   b. Why do you dislike it?
3. Are you using the same setup now?
   a. Why do you like it?
   b. Why do you dislike it?
4. Have you used the keyboard from Logitech?
   a. Why do you like it?
   b. Why do you dislike it?
5. Have you used the mouse from Logitech?
   a. Why do you like it?
   b. Why do you dislike it?
6. What is your ideal setup
   a. Why do you like it?
   b. Why do you dislike it?

Data Analysis

Statistical analysis was conducted on the "perception of change in social isolation" data using MATLAB (MathWorks, Inc.). Likert scale data were analyzed by normalizing responses around a zero score for the neutral "not sure" response, a two point score for a "strongly agree" response and a minus two point score for a "strongly disagree" response. Group scores were then analyzed for evidence of a significant non-zero mean using a single sample *t*-test; effect size was calculated using Cohen's d. Associations between demographic, clinical, and social connectedness information were conducted in R (R Core Team, 2017) using a Pearson's correlation.

RESULTS

The Special Interest Group

Between January and December of 2019, seven individuals (age: 29–45; male/female: 6/1) with quadriplegia participated in a special interest group on esports. Details on neurological level

TABLE 2 | Player demographics, clinical details, and social connectedness data.

	Age	Gender	NLI	AIS	Time since injury (years)	SCIM: self-care	SCIM: respiration and sphincter management	SCIM: mobility	SCS	Perception of change in social connectedness
Player 1	29	F	C3	A	11	0	13	0	41	1
Player 2	36	M	C7	A	5	10	17	10	48	1
Player 3	43	M	C4	D	18	10	29	11	46	2
Player 4	30	M	C5	B	13	14	35	14	48	1
Player 5	39	M	C5	A	25	6	19	4	25	2
Player 6	45	M	C3	A	15	0	13	0	40	2
Player 7	34	M	C5	A	12	9	29	2	45	2

ASIA, American Spinal Injury Association (ASIA)'s International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI); NLI, ASIA Neurological Level of Injury; AIS, ASIA Impairment Score; SCS, Social Connectedness Scale (SCS); SCIM, Spinal Cord Independence Measure.

The AIS has five classification levels, ranging from complete loss of neural function in the affected area to completely normal: (A) the impairment is complete and there is no motor or sensory function left below the level of injury. (B) The impairment is incomplete and sensory function (but not motor function) is preserved below the neurologic level while some sensation is preserved in the sacral segments. (C) The impairment is incomplete and motor function is preserved below the neurologic level, but more than half of the key muscles below the neurologic level have a muscle grade <3/5. (D) The impairment is incomplete and motor function is preserved below the neurologic level, and at least half of the key muscles below the neurologic level have a muscle grade of 3/5 or more. (E) The patient's functions are normal and all motor and sensory functions are preserved.

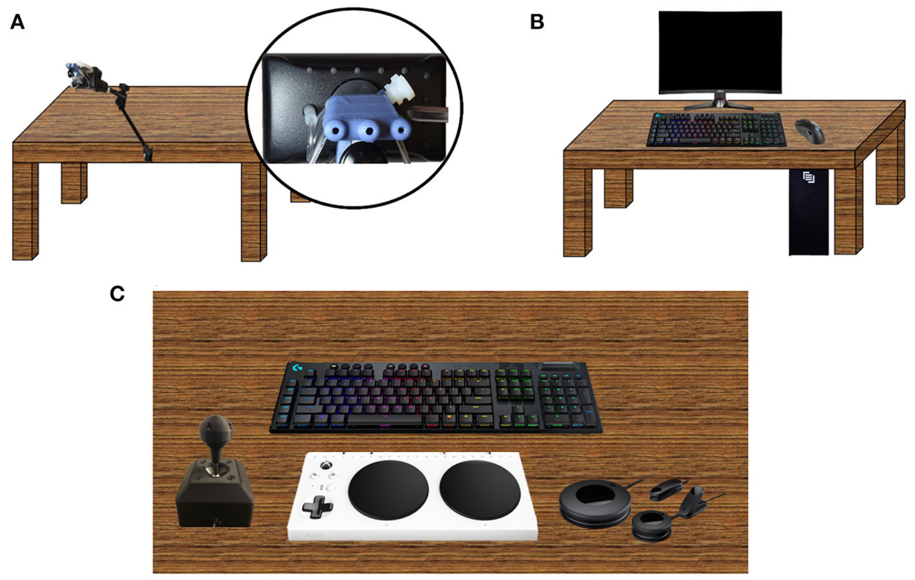

FIGURE 1 | Gaming setups. **(A)** Gaming setup of P1 and P6 using a QuadStick device. The Quadstick requires only the use of the head and neck. The QuadStick utilizes a coded mapping of sips and puffs to controller commands on a gaming system (Xbox, Playstation, or PC). There are three main tubes into which a user can sip or puff. Each sip or puff corresponds with a command on the gaming system and is controlled through oral orbicularis and diaphragmatic muscle activation. The sip and puff tubes are mounted on a joystick that is controlled through cervical movement (rotation and flexion/extension). The QuadStick sensor sensitivity can be tailored according to each individual's neck movement and sip/puff intensity. The joystick movement corresponds with movement of the player's character in the game. Multiple different controller mappings can be uploaded to the QuadStick at one time and the user is able to dynamically switch between them through the use of a side sip and puff tube. See **Supplementary Figure 1** for an example of the button mapping used by the two QuadStick players presented here. **(B)** Original gaming setup of P2, P3, P5, and P7 using the Logitech keyboard and mouse with the MSI Optix screen **(C)** P4's current gaming setup. This setup includes a combination of the Xbox Adaptive controller, the Logitech Adaptive Gaming Kit, one joystick from Warfighter Engaged, and the Logitech keyboard.

of injury, ASIA impairment score and time since injury can be found in **Table 2**.

All participants presented motor impairments in both upper and lower extremities. Two individuals had high level complete injuries and were fully dependent for feeding, bathing, dressing, grooming, toilet use, transfer, and mobility. All individuals were able to breathe independently. Six of the seven individuals had motorized wheelchairs while one was fully dependent for mobility in a manual wheelchair.

Gaming Setups

Most participants ($n = 5$) had previous experience playing video games but none had played competitively. All players managed to create a gaming setup that allowed them to successfully play a wide variety of games. Players engaged in a variety of different games including Fortnite, Rocket League, and Call of Duty. Players had the option to play games independently or online with the remainder of the team.

Player One (P1)

History

Player One is a 29-year-old woman with an 11 year history of C3 ASIA A SCI. P1 has limited cervical movements and no upper limb or lower limb movements due to her high level of injury.

Prior Gaming Experience

Prior to joining the special interest group, P1 did not engage in any esports activities as she was unaware of options that were suitable for her adaptive needs.

Adaptive Gaming Experience

P1's preferred esports environmental setup is a QuadStick connected to the Maingear Desktop PC (**Figure 1A**). She plays the game while sitting in her wheelchair with the need of neck support. She uses her cervical control and range of motion (rotation and flexion/extension) to move the joystick. The joystick movement corresponds with movement of the player's character in the game. Player 1 uses her oral orbicular and diaphragmatic muscle control to sip and puff on the three mounted tubes of the QuadStick.

Player Two (P2)

History

P2 is a 36-year-old male with a 5 year history of C7 ASIA A SCI.

Prior Gaming Experience

After his injury, P2 was already engaged in esports activities using PlayStation console and a standard PS4 controller, but reported significant functional difficulties with hand grip and release, as well as participation in games that required individual finger movements. This limited his enjoyment of esports-related activities.

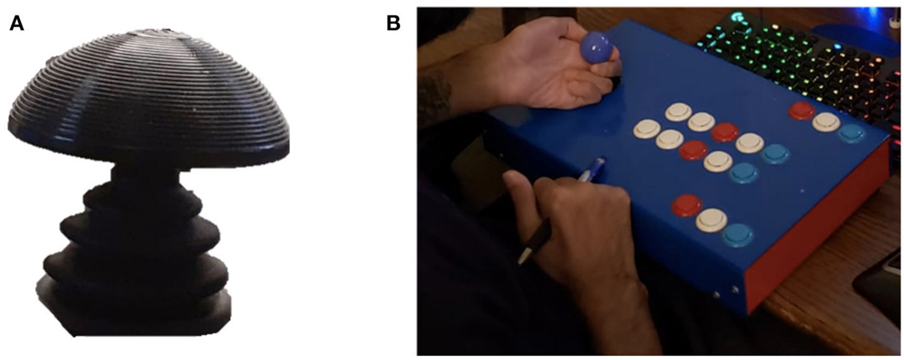

FIGURE 2 | (A) The joystick from P2's powered wheelchair, with a height of 2.5 cm and a diameter of 6.5 cm. **(B)** P5's custom controller.

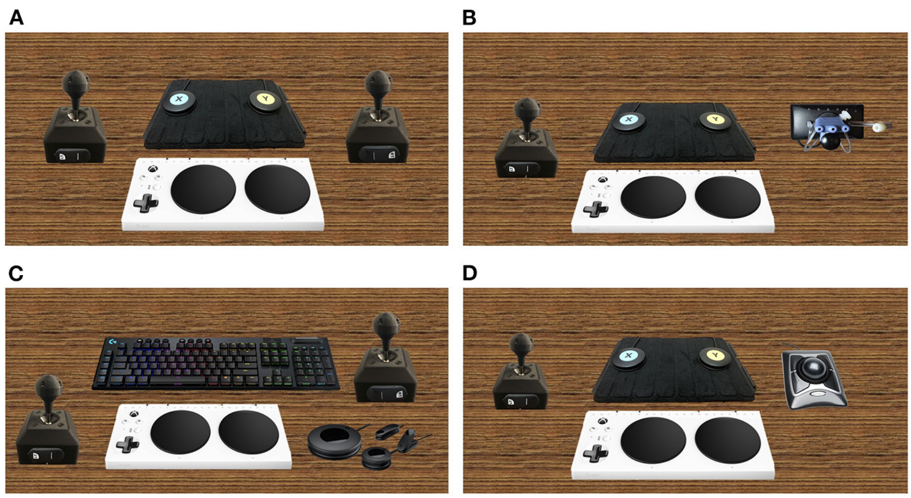

FIGURE 3 | Ideal or planned gaming setups. **(A)** Ideal setup of P2 and P7. This setup includes the adaptive Xbox controller, the Logitech Adaptive Gaming Kit, and two joysticks from Warfighter Engaged with an analog switch from the Adaptive Gaming Kit on the base of each joystick. **(B)** P3's ideal gaming setup. This setup includes the adaptive Xbox controller, the Logitech Adaptive Gaming Kit, one joystick from Warfighter Engaged with an analog switch from the Adaptive Gaming Kit on the base, and one QuadStick. **(C)** P4's current gaming setup. This setup includes a combination of the Xbox Adaptive controller, the Logitech Adaptive Gaming Kit, one joystick from Warfighter Engaged, and the Logitech keyboard **(D)** P5's ideal gaming setup. This setup includes the adaptive Xbox controller, the Logitech Adaptive Gaming Kit, a Warfighter Engaged joystick with an analog switch from the Adaptive Gaming Kit on the base, and a trackball mouse.

Adaptive Gaming Experience

Since joining the esports special interest group, P2's initial esports environmental setup was a Maingear desktop gaming PC using the Logitech keyboard and mouse (**Figure 1B**). However, P2 experienced initial difficulties with this setup, reporting that the "sleek design [of the mouse] makes it very difficult to handle. [It] easily slips from my hand." He enjoyed using the keyboard but found the keys too small to be practical for him, particularly with the more complex games requiring fast reactions such as Fortnite. He explained, "I think it's just the fact that Fortnite has so many different commands to use that it becomes difficult for somebody with limited use of the fingers to use the keyboard."

P2 worked with staff at the ARC to develop a gaming setup more tailored to his individual needs. Inspiration for his ideal setup came from existing equipment that he currently uses with ease and precision. For instance, P2 uses a powered wheelchair for mobility that is controlled by a ball-shaped joystick (**Figure 2A**). He has an expert ability to navigate complex environments in his chair using this joystick, and expressed interest in creating a gaming joystick with a design that mirrored his chair's joystick. P2 is currently designing a personalized gaming setup that is based around the main module of the adaptive Xbox controller, as well as the accompanying accessories kit. In addition, he is collaborating with Warfighter Engaged to create two joysticks of the same dimensions as his chair joystick for him to use while gaming. He plans to attach a small analog switch from the Xbox adaptive accessories kit to the base of the two joysticks that he can press with his palm while playing. This will allow him easy access to the most vital controls during gameplay (**Figure 3A**).

Player Three (P3)

History

P3 is a 43-year-old male with an 18 year history of C4 ASIA D SCI.

Prior Gaming Experience

P2's initial esports environmental setup was a Maingear desktop gaming PC using the Logitech keyboard and mouse (**Figure 1B**). Before his injury, P3 played video games with a PlayStation console and controller. After his injury he found the PlayStation controller to be too small, making it difficult for him to use tactile feedback to discriminate between different buttons. He soon transitioned to an Xbox controller, finding the larger controller to be more conducive to his needs. P3 enjoyed playing with this configuration for years, but still felt limitations in his overall esports ability due to the inadequacy of the equipment. In particular, P3 identified lower mobility in his right index finger, as a significant barrier for operating a standard gaming controller, and he reported finding it difficult to use the trigger buttons on the controller. As a result, P3 often ended up using only his thumbs during a game. He developed a successful rhythm and routine that allowed him to play that way, but expressed interest in using adaptive technology to enhance his setup.

Adaptive Gaming Experience

P3 was familiar with the QuadStick as he used the controller for simple computerized activities, such as lifting his hospital bed and turning on the television immediately following his injury. Through physical and occupational therapy, he was able to regain some motor function, and thus transitioned away from using the QuadStick. With a renewed interest in adaptive gaming, P3 has expressed interest in finding a way to integrate the QuadStick into his gaming setup. He appreciates the flexibility that the "sip-and-puff" control functionality allows him, and believes that using that in conjunction with a joystick and the Xbox adaptive controller would provide him with the ideal setup.

More specifically, P3 finds his playing to be most limited by the movement of his left and right pointer fingers, as well as his right hand more broadly. In traditional first person shooter (FPS) games, the right thumb moves a joystick to control the movement of the player's field of view, the left pointer finger aims a weapon, and the right pointer finger presses a trigger to shoot the weapon. P3 plans to use the QuadStick to aim and shoot a weapon. He plans to combine the QuadStick with a joystick that he can use with his left hand, and larger buttons from the Xbox adaptive controller that he can press with his right hand (**Figure 3B**).

Player Four (P4)

History

P4 is a 30 year old male with a 13 year history of SCI C5 ASIA B.

Prior Gaming Experience

He has been playing video games since he was a young child, using various gaming systems such as a Sega Genesis, a Nintendo Gameboy, and a PlayStation 4. Before joining the Quad Gods, P4 primarily used his PS4 to game. He explained, "I normally rest my PS4 controller on my chest or on my lap. When I play, I always use L1 to aim and R1 to shoot; that is more ideal for me because of my injury." In contrast, the traditional PS4 control settings use L2 and R2 to aim and shoot. Because of the position that P4 held his controller in, those buttons were inaccessible to him.

Adaptive Gaming Experience

P4's adaptive gaming setup utilizes the Maingear desktop PC, accompanying Logitech keyboard and mouse and the Xbox adaptive controller with the accompanying Adaptive Gaming Kit (**Figure 1C**). P4 reported high satisfaction with the Logitech keyboard and mouse. He specifically appreciated the programmable G-keys that allowed him to save important key combinations; this has allowed him to perform complicated maneuvers in-game that he would otherwise be unable to execute. In addition to his keyboard and mouse setup, P4 has also created a personalized setup using the Xbox adaptive controller and accessories kit, and one controller from Warfighter Engaged. He reported positively on the ease of mobility that the joystick provides him, but stated the need for two joysticks in order to effectively play most games with this setup. P4 plans to obtain a second joystick from Warfighter Engaged and attach an analog switch to each of them for integration into his adaptive setup (**Figure 3C**).

Player Five (P5)

History

P5 is a 39 year old male with a 25 year history of C5 ASIA A SCI.

Prior Gaming Experience

P5 began playing video games as a child, but after his injury he was unable to use a traditional controller. P5 designed and oversaw the fabrication of his own custom controller with 16 programmable buttons and one joystick that was designed to support an underhand grip (**Figure 2B**).

Adaptive Gaming Experience

P5 has set up his desktop PC to use the Logitech gaming keyboard and mouse (**Figure 1B**). P5 prefers using a computer over a gaming console because of the advanced ability to personalize his gaming experience using a PC. However, he acknowledged the bigger financial investment required to purchase an acceptable gaming computer as opposed to a standard gaming console. P5 enjoyed using the Logitech gaming keyboard because of his ability to program the macro buttons. He explained, "this helped me a lot playing Assassin's Creed where I created a macro enabling me to hold a button that allowed me to run." P5 had extreme difficulty holding the Logitech gaming mouse due to the lack of voluntary movement in his hands and therefore preferred to use a trackball mouse. A trackball mouse requires no grip strength as players can simply rest their hand on the trackball to move it. His ideal setup will combine the Warfighter Engaged solid ball cap joystick in his left hand with a trackball mouse in his right hand. With this setup he could control the direction of a character's body by pushing the joystick to one direction and holding it there with a combination of his body weight and gravity. Additionally, P5 can use the fluidity of the trackball mouse to move his character's gaze smoothly across the playing

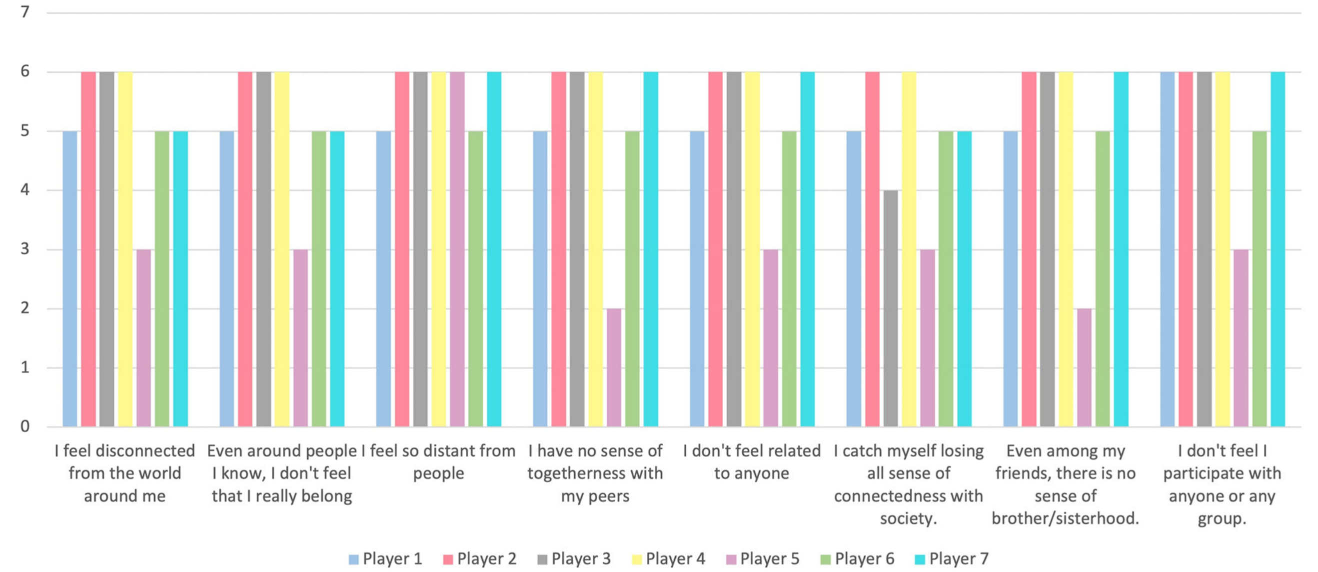

FIGURE 4 | Variability in Social Connectedness Scale (SCS) scores between players by question.

field. He would also attach an analog switch to the joystick so that he can combine movement with action (**Figure 3D**). For example, that setup would allow him to aim and shoot a weapon without requiring fine motor movement. He explained, "I have the hand eye coordination, I just don't have the dexterity to do that on a small controller."

Player Six (P6)

History

P6 is a 45 year old male with a 15 year history of C3 ASIA A SCI.

Prior Gaming Experience

Prior to joining the special interest group, P6 did not engage in any esports activities as he was unaware of options that were suitable for his adaptive needs.

Adaptive Gaming Experience

P6 connects a QuadStick to the Maingear Desktop PC in order to play video games. He finds first person shooter (FPS) games to be enjoyable but challenging, as the QuadStick uses only one joystick for both aiming and body movement (**Figure 1A**).

Player Seven (P7)

History

P7 is a 34-year-old man with a 12 year history of C5 ASIA A SCI.

Prior Gaming Experience

P7 began playing video games when he was 5 years old, alternating between console gaming and computer gaming throughout the years. P7 has a deep love of gaming, but after his injury, he has always had difficulties being able to reach and press all of the buttons on a controller or keyboard.

Adaptive Gaming Experience

P7 set up his desktop PC to use with the Logitech gaming keyboard and mouse. He found the keyboard to be user friendly, but stated that the keys protruded a bit too much, and were too easy to press; because of this, he would often unintentionally press keys when reaching for a further key. The mouse was smooth and accurate, but the buttons were difficult for him to press (**Figure 1B**).

Ideally, P7 aims to create a computer setup that provides him with the same expansive set of controls as a keyboard and mouse does, but with keys and buttons more tailored to his needs. He is currently developing a setup with the Xbox adaptive controller and the Logitech adaptive kit, and plans to add to it two Warfighter Engaged joysticks. He will place an analog switch on the base of each joystick so that he can trigger it with his palm (**Figure 3A**).

Social Connectedness

Players responded with an average score of 41.2/48 to the SCS (**Figure 4**), and 1.57/5 to the question on perceived change in social connection (**Table 2**). The report on perceived change was significantly non-zero ($M = 1.57$, $SD = 0.53$), $t_{(6)} = 7.79$, $p < 0.001$, and $d = 2.96$.

There was a significant negative correlation between Time since injury (years) and the social connectedness score (SCS) [$r_{(5)} = -0.78$, $p = 0.04$]. In other words, longer time since injury was correlated with a lower SCS, and therefore a lower sense of social connectedness (**Figure 5**). There were no other relationships between SCS or perception of change and other baseline or outcome measures.

DISCUSSION

To our knowledge, this is the first paper to share adaptive strategies and technologies that enhance, and in some cases permit, full participation in esports for individuals with SCI. In addition, this study identifies common issues with existing

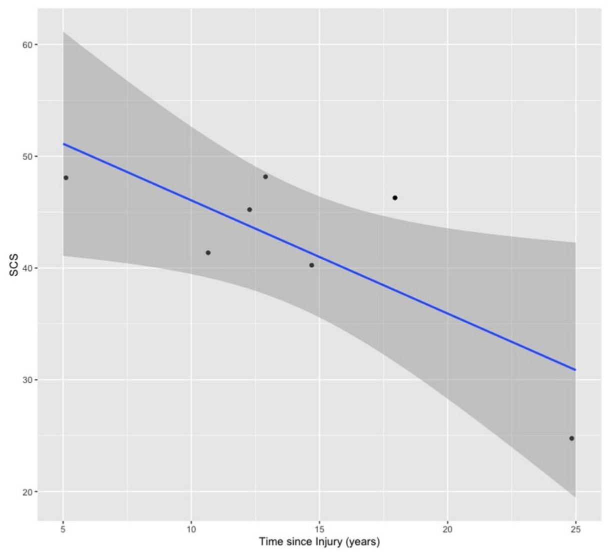

FIGURE 5 | Negative correlation between Time since Injury (years) and SCS scores.

esports controller technologies that can prevent full participation in esports for prospective athletes who have physical capabilities that are different to mainstream esports athletes. The aim of Universal Design (UD) is to promote equal opportunity and participation for all people (Lid, 2014), and the findings of this study highlight a critical need to apply UD principles to the development of gaming technology. Notably, the work that has been completed by companies such as Logitech and Microsoft in creating adaptive controller technology demonstrably added value to the experience of the participants in this QI initiative. In addition, the QuadStick was instrumental in permitting participation of two individuals who otherwise could not have engaged in gaming activities because of the severity of their SCI.

Among the surveyed individuals, the most commonly reported motor difficulties were impaired grip strength and lack of individuated finger movements. These motor impairments lead to activity limitations in goal-directed tasks such as pressing buttons, grasping a mouse and smoothly maneuvering a controller, hindering optimal participation in esports. In addition, two individuals with high-level cervical injuries (C3) were completely hindered from playing esports after their injury due to their functional limitations and lack of access to proper adaptive equipment. With the assistance of appropriate technology, all players, regardless of their motor or functional status, were able to competitively participate in esports activities. At the time of writing this manuscript, all of the players continue to actively participate in esports on a daily basis. This work highlights why concepts of UD should be applied to all product design endeavors: accessibility is a fundamental human right (Giannoumis and Stein, 2019), and individuals with motor, cognitive or social/emotional differences should not be limited in their participation in chosen activities. However, the results of this QI initiative also showed that enhanced participation in esports resulted in positive pro-social impact.

All participants in the QI initiative reported that participation in the esports special interest group made them feel more socially connected and less isolated. It is well-established that access to technology is beneficial to people with SCI, as it has the potential to promote independence and foster connection with the general communities (Goodman et al., 2008; Barclay et al., 2016). Moreover, diminished participation in community activities due to SCI physical impairments is associated with a negative impact on mental well-being (Post and Noreau, 2005), emphasizing the need for measures to create maximal inclusion for virtual activities such as esports, especially in the time of COVID-19.

There are notable limitations in the reported data. This study included a small sample with no control group, and as these are QI data from a specific health system, there was no way to ensure recruitment was representative of other cohorts with SCI. Additionally, the lack of baseline SCS scores limited our ability to accurately determine changes in social connectedness. Nonetheless, this work highlighted the capacity of technology to promote inclusion and social connectedness.

We concluded that: (1) It is feasible to create adaptive gaming setups that can be used by people with differing degrees and severity of SCI in a competitive esports environment. (2) Technology and adaptive competitive esports have a potential to improve social connectedness and inclusion in people with quadriplegia. (3) Further research on efficacy and effectiveness of these inclusive environments and their effects on quality of life, activity and participation is warranted.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, upon request.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

LT and DP conceptualized the work. SD conducted player interviews. SD, LT, and DP performed data analysis and interpretation, and manuscript preparation. All authors read and approved the final version of the manuscript.

ACKNOWLEDGMENTS

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2021.612350/full#supplementary-material

Supplementary Figure 1 | A sample of the button mapping created for users of the QuadStick to play a shooting game on an Xbox. Column A holds the button representations of the gaming console in use. Column C holds the controls of the QuadStick that are mapped onto the button representations of the gaming console. Column B holds any special formulas for mapping the buttons—none are in place in this example. Column D holds an explanation of the function of each control. This spreadsheet is created in google sheets and loaded into the QuadStick through a USB connection using the QuadStick Manager Program (QMP). The Quadstick is then connected to the gaming console of choice through a USB or bluetooth connection.

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