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Time for a true display of skill: Top players in League of Legends have better executive control

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ABSTRACT

Research into the effects of action video gaming on cognition has largely relied on self-reported action video game experience and extended video game training. Only a few studies have focused on participants' actual gaming skills. However, whether superior players and average players have different executive control is still not fully demonstrated. This study had top-ranking League of Legends players (global top 0.17%; $N = 35$) and average-ranking League of Legends players (N = 35) perform two cognitive tasks that aimed to measure three aspects of executive functioning: cognitive flexibility, interference control, and impulsive control. We controlled self-reported gaming experience, so that top-ranking players and average-ranking players had similar years of play and hours of play per week. We found that compared to a group of average players, top players showed smaller task-switching costs and smaller response-congruency effects in a Stroop-switching test. In a continuous performance test, top players indicated higher hit rates and lower false alarm rates as compared to average players. These findings suggest that top players have better cognitive flexibility and more accurate control of interference in the context of task-switching. Moreover, top players exhibit better impulsive control. The present study provides evidence that players' gaming skills rather than gaming experience are related to cognitive abilities, which may explain why previous studies on self-reported gaming experience and those assessing supervised training and cognitive performance have shown inconsistent results.

1. Introduction

Action video games require players to vigilantly monitor the visual periphery while responding quickly to or switching rapidly among multiple targets. In the past two decades, numerous studies have reported that, compared to non-action video game players (nAVGP), action video game players (AVGPs) have increased abilities that are cognitive in nature (see a recent review by Bediou et al., 2018). Specifically, researchers found that experience and training on action video games led to improved allocation of visual attention and visual search (e.g., Castel, Pratt, & Drummond, 2005; Green & Bavelier, 2003, 2006, 2007; Azizi, Abel, & Stainer, 2017; but see Unsworth et al., 2015). Other studies have suggested better cognitive flexibility, interference control and impulsive control in AVGPs over nAVGPs (Andrews & Murphy, 2006; Dobrowolski, Hanusz, Sobczyk, Skorko, & Wiatrow, 2015; Strobach, Frensch, & Schubert, 2012). Nevertheless, these results are not without controversy.

1.1. Game experience and cognitive flexibility

Cognitive flexibility is an important aspect of executive function, which denotes the ability to flexibly switch between tasks or mental sets and avoid being stuck on ineffective strategies (Diamond, 2013). By applying a task-switching test, Boot, Kramer, Simons, Fabiani, and Gratton (2008) examined how video game experience impacted participants' cognitive flexibility in a longitudinal study and a cross-sectional study. In their cross-sectional study, it was found that AVGPs outperformed nAVGPs, with AVGPs showing smaller task-switching costs. The results from their longitudinal study in nAVGPs indicated that video game training did not produce any significant effect on the ability to rapidly switch between two tasks. Specifically, nAVGPs showed no improvements in task-switching performance after twenty-one hours of video game training (Boot et al., 2008). However, as shown by Green et al. (2013; Experiment 4), fifty hours of action video training reduced the task-switching costs in nAVGPs. Researchers concluded that task-

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switching ability may be improved in nAVGPs but not to the same level as in AVGPs (Green, Sugarman, et al., 2013). The switch benefit in AVGPs was not limited to the response mode. AVGPs exhibited smaller task-switching costs compared to nAVGPs in both the manual and vocal responding conditions (Green, Sugarman, et al., 2013; Experiment 1).

However, not all studies have established smaller task-switching costs in AVGPs as compared to nAVGPs (Cain, Landau, & Shimamura, 2012; Karle, Watter, & Shedden, 2010). For example, Cain et al. (2012) tested AVGPs' and nAVGPs' cognitive flexibility using a flanker-switching test, where participants had to alternate between a pro-response arrow task (the easier task; left arrow ⇒ press left; right arrow ⇒ press right) and an anti-response arrow task (the harder task; left arrow ⇒ press right; right arrow ⇒ press left). Cain et al. (2012) found that for nAVGPs switching from the relatively harder task to the relatively easier task caused greater task-switching costs than the other way around, whereas for AVGPs such asymmetry was attenuated. Nevertheless, Cain et al. (2012) did not find any significant differences in the overall task-switching costs between AVGP and nAVGP groups.

1.2. Game experience and interference control

Apart from cognitive flexibility (measured by task-switching cost), task-switching studies also examine control process, shedding light on the ability to resolve response conflict as measured by the response-congruency effect. Compared to congruent or neutral targets that associate with only one response, participants typically have delayed responses and make more errors in incongruent trials due to the response conflicts triggered by two possible target-response associations (Sudevan & Taylor, 1987; Schneider, 2015, 2018; Wendt & Kiesel, 2008; see Section 1.6.2 for more information).

We know little about the relationship between response-congruency effects and action video game experience/skills. Many existing game studies did not analyse response-congruency effects even though their empirical designs afforded such measurement (Boot et al., 2008; Green, Sugarman, et al., 2013; Strobach et al., 2012). In the studies that have reported response-congruency effects in the context of task-switching, results were inconsistent. In a study by Andrews and Murphy (2006) AVGPs showed smaller response-congruency effects compared to nAVGPs, but other researchers found no such differences between AVGPs and nAVGPs (Cain et al., 2012; Dobrowolski et al., 2015).

The ability to control conflicts was also investigated in studies that compare AVGPs and nAVGPs using other cognitive tasks. However, researchers found no evidence that AVGPs were better than nAVGPs in terms of the ability to resolve interference from the conflicting information. For example, the work of Gobet et al. (2014) indicated that both AVGP and nAVGP groups produced similar amount of congruency effect in a Flanker test. Consistent with Gobet et al. (2014), in Kowal, Toth, Exton, and Campbell (2018), AVGPs displayed similar Stroop effect to a group of nAVGPs.

1.3. Game experience and impulsive control

Impulsive control, the ability to inhibit instigated and prepotent responses, has been examined in recent studies on action video games and cognitive performance (Azizi, Stainer, & Abel, 2018; Colzato, van den Wildenberg, Zmigrod, & Hommel, 2013; Decker & Gay, 2011; Deleuze, Christiaens, Nuyens, & Billieux, 2017; Littel et al., 2012). For example, studies have shown that compared to non-players, World of Warcraft (a massively multiplayer online role-playing game, MMORG) players showed more risky response bias and were more likely to make a response in no-go trials in which responses should be inhibited, suggesting worse impulsive control in MMORG players (Decker & Gay, 2011; Littel et al., 2012). In a recent study, Azizi et al. (2018) provided seminal findings suggesting that although different genres of video game experience associated with different levels of impulsive control, multi-genre gamers had higher false-alarm rates and more risk-taking response bias compared to non-gamers in a continuous performance test that was used to measure sustained attention and impulsive response inhibition.

Contradictory results were reported in other studies indicating no differences between AVGPs and nAVGPs in terms of impulsive control (Colzato et al., 2013; see also Dye, Green, & Bavelier, 2009; Metcalf & Pammer, 2014; Mack & Ilg, 2014). For example, Colzato et al. (2013) compared performance between players who did not play First Person Shooting (FPS) games and those who played FPS games in a stop-signal task. Colzato et al. (2013) found no differences between players and non-players, with both groups showing similar RTs and ERs in the trials that required participants to inhibit responding. Similarly, Metcalf and Pammer (2014) indicated that non-addicted FPS players did not differ from non-players in the tasks measuring impulsiveness (e.g., go/no-go task), although addicted FPS players had increased impulsive responses in no-go trials and more missed detections in go trials.

1.4. Potential issue on assessing game experience

In short, a large body of previous studies examining the relationship between executive functioning and action video game experience have produced inconsistent results: Some empirical studies showed better executive functioning in AVGPs than in nAVGPs, whereas others failed to find differences. Inconsistent evidence were also from systematic reviews, meta-analysis studies and large scale correlation studies: Some studies indicated a positive relationship with large effect size between video game experience and various cognitive abilities (Powers, Brooks, Aldrich, Palladino, & Alfieri, 2013; Toril, Reales, & Ballesteros, 2014; Wang et al., 2016), but others did not find any meaningful relationships (Hambrick, Oswald, Darowski, Rench, & Brou, 2010; Sala, Tatlidil, & Gobet, 2018; Unsworth et al., 2015).

One potential limitation could be that many previous studies mainly categorized participants based on time spent on action video games (e.g., Azizi et al., 2017; Kowal et al., 2018; Unsworth et al., 2015; Waris et al., 2019). For example, in Kowal et al. (2018), participants were considered “hardcore players” if they reported having spent > 23 h per week in a game, or “casual players” if they reported having spent fewer than seven hours per week in a game. Likewise, correlational studies applied surveys which asked participants to indicate the average hours of various video games played per week as an index of game experience (e.g., options ranging from *never*, *0–1 h*, *1–3 h*, *3–5 h*, *5–10 h*, to *10+ hours* in Unsworth et al., 2015). In addition, previous training studies tried to establish whether action video game play can cause increased cognitive performance by asking participants to partake in a few hours of supervised video game training (e.g., Boot et al., 2008; Green, Sugarman, et al., 2013).

Researchers typically assume that the longer the time spent playing action video games, the better the players' gaming skills should be. However, there is no guarantee that more video game experience is always equivalent to becoming a game expert. If we consider playing action video games as a self-regulated training process on gaming skills, then without any objective control (e.g., players may have different motivations), gaming skills could hardly be improved and the training effect could vary across individuals. In fact, even under typical laboratory conditions, effects of game training are hard to verify due to limited training durations, compliance with training instructions and various training methods (c.f., Green, Strobach, & Schubert, 2013; Green et al., 2018).

There is no guarantee that a three-hour session of video game play would improve gaming skills and/or cognitive performance compared to a one-hour training. Although studies demonstrated that gaming skills and gaming experience are positively correlated (Bonny, Castaneda, & Swanson, 2016; Röhlcke, Bäcklund, Sörman, & Jonsson, 2018), the general conclusion that the more one plays, the higher gaming skills one can get may not apply to every player. It is still possible that people who spend less time playing video games (e.g.,

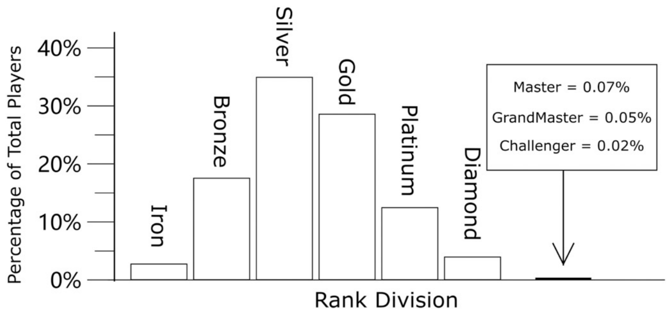

Fig. 1. Distributions of the nine LOL rank divisions. The histogram displays the player distribution by divisions. Iron is the lowest tier and Challenger is the highest tier. Data were gathered by "Rank distribution" (2019) considering all players around the world.

casual players in Kowal et al., 2018) actually have better gaming skills compared to those who play a great deal (e.g., hardcore players). In other words, evaluating one's gaming skills based on the hours of game playing may be inappropriate. An imprecise classification of expertise may account for the discrepancy in the results in past video-game literature (Latham, Patston, & Tippett, 2013).

Appropriate classifying participants as an expert or novice game player may require direct and objective assessment of their gaming skills (Latham et al., 2013; Sala et al., 2018). Gaming skills can be considered as the expertise or talent needed to win a game. Ranking systems in typical MOBA (multiplayer online battle arena) games such as Defense of the Ancients (DOTA) and League of Legends (LOL) may provide a more objective measurement of players gaming skills. MOBA game ranking scores are usually calculated based on ELO rating (Elo, 1986) which has been used in many traditional sports (e.g., chess), and have been used to indicate the relative skill levels of players. Taking LOL ranking as an example of the ELO system, there are nine rank divisions (from Iron division to Challenger division), with each division representing a different skill level (Fig. 1). The system matches players of a similar skill level within a rank division to play with and against each other. Players within each division are ranked using a system of points called League Points: League Points increase per win and decrease per loss. Players will be promoted to a higher division once they accumulate enough League Points. In contrast, if players lose too many League Points, they will be demoted. Therefore, we can expect that players in higher rank divisions should have better gaming skills compared to players in lower rank division.

Recent research has utilized ranking scores in MOBA games to measure AVGPs' gaming skills (Bonny et al., 2016; Gong, Ma, Liu, Yan, & Yao, 2019; Kokkinakis, Cowling, Drachen, & Wade, 2017; Röhlcke et al., 2018). In Bonny et al. (2016), DOTA gaming skills were assessed by ranking scores obtained on the DOTA ranking system. Their results indicated that players with greater DOTA game expertise were more likely to have faster speed of processing on the task specifically relying on spatial long-term memory (but see Röhlcke et al., 2018). Using a similar approach, Kokkinakis et al. (2017) found that LOL gaming skills, as indicated by game rankings, correlated with fluid intelligence. Empirical evidence was also provided by Gong et al. (2019) who studied the impact of game expertise on human brain development using resting-state fMRI. Gong et al. (2019) deliberately selected top-ranking LOL players with reasonably high standard (top 1.77% of all players worldwide; but note that we used a higher criterion including players ranking at top 0.15%), and lower-ranking players as a comparison. Their results showed that compared to lower-ranking players, higher-ranking players had superior local functional integration in the executive areas and higher levels of local functional connectivity density in brain regions related to memory and planning, suggesting better executive functioning in players with higher gaming skill levels (Gong et al., 2019).

Nevertheless, previous studies focusing on players' gaming skills (assessed by game ranking system) and cognitive abilities still have two potential limitations. Firstly, many studies, except Gong et al. (2019), recruited AVGPs without intentionally selecting top-ranking players, and only required experience in the game or attending/staffing the tournament; participants in those studies were thus generally of average skill and could hardly be considered experts (Bonny et al., 2016; Kokkinakis et al., 2017; Röhlcke et al., 2018). Therefore, their results on gaming expertise and cognitive abilities may not generalize well to players with the highest game ranking scores.

Secondly, in the previous studies that investigated cognitive abilities across game players without controlling game experience (Bonny et al., 2016; Kokkinakis et al., 2017; Röhlcke et al., 2018), the relationship between gaming skills and cognitive abilities can be confounded with time spent in the game. In other words, it was unclear if the enhanced cognitive ability could be related to higher gaming skills or more gaming experience, or both. Gong et al. (2019) did not control players' gaming time either, which means any differences between neural networks in higher-ranking players and lower-ranking players can be confounded with gaming experience.

1.5. Aim of the current study

The present study sought to further investigate and elaborate on the relationship between actual gaming skills as measured by game ranking system and executive functioning. We examined whether those with superior gaming skills in an action video game (ranking at global top 0.15%) would have better executive functions compared to average players after controlling for self-reported time spent on the action video game. As in previous studies (Gong et al., 2019; Kokkinakis et al., 2017), we focused on one particular action video game—League of Legends (LOL)—for three reasons. First, LOL is currently one of the most popular action video games in the world. According to Riot (one of the largest American video game developers and e-sports tournament organizers), as of September 2019 LOL has nearly eight million concurrent players during peak hours of the day around the world (https://na.leagueoflegends.com/en/news/game-updates/special-event/join-us-oct-15th-celebrate-10-years-league).

In addition, the LOL ranking system provides an objective assessment of the actual skill level of each participant, so that we can make sure those with higher ranks would have improved game skills. Details of the LOL ranking system can be found on "League system" (2019).

Finally, playing MOBA games such as LOL requires a variety of cognitive abilities. LOL involves two opposing teams of players. Players need to control a game character called a "champion" with unique spells and battle against a team of other players in a preset battle arena. In order to destroy the opponent's base and win the game, players have to constantly adjust their team and personal tactics according to current battle conditions, while ignoring bait information that is used for distracting attention. Both of such filters require high cognitive flexibility and interference control. Moreover, LOL players must not only make quick decisions about when to cast their spells against opponents, but also when not to; both types of decisions may require quick reaction time and efficient impulsive control.

We explored whether players who were close to the highest ranking score in LOL performed differently—compared to average-ranking LOL players—in cognitive experiments requiring frequent switching between different tasks while resolving the interference and/or the ability to resist impulsive responding.

1.6. Stroop-switching test

In the present study, we employed a Stroop-switching test, in which participants were required to switch between the color-naming and word-reading tasks. This classic Stroop-switching test has been employed by many researchers of cognitive flexibility during the frequent switching and interference control when conflicts occur (e.g., Allport, Styles, & Hsieh, 1994; Monsell, Yeung, & Azuma, 2000; Kalanthroff & Henik, 2014; Saban, Gabay, & Kalanthroff, 2018; Wu et al., 2015; Yeung & Monsell, 2003).

1.6.1. Cognitive flexibility

Cognitive flexibility in Stroop-switching experiments has been indicated by "task-switching cost": Response times (RTs) and error rates (ERs) are increased in trials where the task switches from that of the preceding trial (e.g., color-naming ⇒ word-reading) compared to task repetitions (e.g., color-naming ⇒ color-naming; Allport et al., 1994; Kalanthroff & Henik, 2014; Saban et al., 2018; Yeung & Monsell, 2003). It has been suggested that fast disengaging from the previous task and efficient preparation for the task in the upcoming trial would be associated with smaller task-switching costs and thereby with better cognitive flexibility (e.g., Kramer, Cepeda, & Cepeda, 2001; Kray, Karbach, Haenig, & Freitag, 2012; Mayr et al., 2014).

Moreover, studies that employed Stroop-switching test have also reported asymmetrical switching costs: Switching from the relatively harder color-naming task to the relatively easier word-reading task caused greater task-switching costs than the other way around (e.g., Allport et al., 1994; Wu et al., 2015; but see Monsell et al., 2000; Yeung & Monsell, 2003). Schneider and Anderson (2010) suggested that the asymmetrical switch costs arise from sequential difficulty effects. Since performance was impaired after a difficult trial, response times were longer when switching to an easy task and when repeating a difficult task leading to asymmetrical switch costs. In addition, asymmetrical switching costs may reflect the proactive interference from previous tasks: the harder the previous task, the stronger the proactive interference and thereby greater task-switching costs when switching to trials with an easy task (Allport et al., 1994).

1.6.2. Interference in Stroop-switching test

Stroop-switching experiments can consist of three types of target stimuli: neutral target stimuli, congruent target stimuli, and incongruent target stimuli (Kalanthroff & Henik, 2014; Steinhauser & Hubner, 2009). Neutral target stimuli (e.g., the word RED printed in black, or meaningless symbols like &&& printed in red or green) have only one task-relevant feature and are presented in one task; as such, they are mapped to only one response in the experiment. In contrast, congruent and incongruent target stimuli have features for both tasks. Congruent target stimuli (e.g., RED printed in red or RED_{red}) have two task-relevant features that are mapped to the same response in the two tasks, whereas incongruent target stimuli (e.g., $\text{GREEN}_{\text{red}}$) have two task-relevant features that require different responses in the two tasks. In such an experimental setup, one would typically find two types of interference effects: *response-congruency effects* and *reverse-facilitation effects* (Kalanthroff & Henik, 2014; Steinhauser & Hubner, 2009; see Appendix D, Figure D1 for an illustration of both effects).

The response-congruency effects were measured by the performance differences between trials with incongruent and neutral target stimuli. It has been found that participants showed increased RTs and ERs in incongruent trials than in neutral trials because the former is associated with two possible feature-response associations which resulted in interference (see also Guo, Li, Yu, Liu, & Li, 2019; Li, Li, Liu, Lages, & Stoet, 2019a, 2019b; Schneider, 2015, 2018; Sudevan & Taylor, 1987; Wendt & Kiesel, 2008).

The reverse-facilitation effects were measured by the performance differences between trials with congruent and neutral target stimuli. Although both congruent and neutral trials afford only one possible response in the experiment, researchers have shown that neutral stimuli led to faster responses and fewer errors compared to congruent stimuli. This is because compared to congruent stimuli, neutral stimuli are related to information in one task causing smaller or no task interference during response retrieval (Kalanthroff & Henik, 2014; Steinhauser & Hubner, 2009).

1.7. Continuous performance test

In the present study, in order to measure impulsive control in top- and lower-ranking LOL players, we employed a *go/no-go* Continuous Performance Test (CPT), which has been used to investigate impulsive performance and action video-game experience (e.g., Azizi et al., 2018; Metcalf & Pammer, 2014). The CPT test requires participants to respond quickly to the target stimuli in *go* trials (i.e., when letters other than "X" are presented) and to inhibit the response in *no-go* trials (i.e., when the letter "X" is presented). According to Egeland and Kovalik-Gran (2010), four key variables are the mean RTs in the correct go trials; rate of false alarms (i.e., probability of responses in no-go trials); hit rate (i.e., probability of responses in go trials); and response bias, which takes both the hit rate and false alarm rate into account, reflecting the tendency to respond to both targets and non-targets.

Response bias (β) in the CPT test is estimated based on signal detection theory and is calculated using the formulas shown below. Hit rate (H) is calculated as the proportion of responses to target stimuli in *go* trials, and false alarm rate (F) is calculated as the proportion of responses in *no-go* trials. Larger β indicates more conservative responding, while smaller β indicates more risky responding.

$$\beta = (5 - 4H)/(1 + 4F);\ when\, F \le 0.5 \le H$$

$$\beta = (H^2 + H)/(H^2 + F);\ when\, F < H < 0.5$$

$$\beta = [(1 - F)^2 + (1 - H)]/[1 - F)^2 + (1 - F);\ when\, 0.5 < F < H$$

1.8. Hypotheses

This study sought to investigate whether top-ranking AVGPs would show superior performance in the two cognitive tasks, when compared to average-ranking AVGPs with similar game experience. According to the previous brain imaging results (Gong et al., 2019), higher ranking in LOL was found to be associated with better executive control. Therefore, we hypothesized that players who were close to the highest ranking score in LOL may outperform average players in the tests that measure different aspects of executive functioning (i.e., cognitive flexibility, interference control and impulsive control).

Specifically, we predicted that compared to average-ranking LOL players, top-ranking LOL players would produce smaller task-switching costs associated with better cognitive flexibility in the Stroop-switching test. In addition, top players would show smaller response-congruency effects and reverse facilitation effects associated with more efficient interference control. For the CPT test, we predicted that top-ranking LOL players would exhibit lower false alarm rate and larger response bias associated with better impulsive control compared to average-ranking players.

2. Method

2.1. Research ethics

The present study was approved by the Fudan University Department of Psychology Ethics committee and complied with the Declaration of Helsinki. Prior to the study, all participants were informed about the procedures of the experiments. All participants provided written informed consent before taking part in the present study.

2.2. Participants

2.2.1. Top LOL players

We first recruited thirty-five LOL expert players (2 females; mean age = 22.8 years, SD = 4.42) ranked higher than the Diamond tier (i.e., Master, GrandMaster and Challenger tiers) to participate in the present experiments. Fewer than 0.2% of the LOL players have a chance

Table 1
Demographics information.

	Top players	Average players	Sig. difference
Demographics			
Gender	M/F = 33/2	M/F = 31/4	$p > .05$
Age (years)	22.8 (*SD* = 4.42)	23.1 (*SD* = 4.55)	$p > .05$
Educational Levels	5.08 (*SD* = 1.12)	5.71 (*SD* = 0.93)	$p = .012$
LOL Game Experience			
Years	5.07 (*SD* = 1.67)	5.14 (*SD* = 1.57)	$p > .05$
Hours Per Week	13.26 (*SD* = 8.51)	14.69 (*SD* = 8.62)	$p > .05$
Rank Division	8.31 (*SD* = 0.90)	3.83 (*SD* = 0.92)	$p < .001$

Note: Educational levels were measured by the education subscale of *the Social and economic status scale of residents in the Chinese metropolis* (Li, 2002): doctorate and master degree = 7, bachelor degree = 6, junior college = 5, high school, technical secondary school and professional high school = 4, middle school = 3, elementary school = 2, no education = 1; For rank division: Iron = 1, Bronze = 2, Silver = 3, Gold = 4, Platinum = 5, Diamond = 6, Master = 7, Grand Master = 8, Challenger = 9; M = male, F = female.

to reach beyond the Diamond tier (Fig. 1); therefore, we called them “top-ranking LOL players” or “top players.” Top players were recruited through advertisements posted in online game communities, and via word of mouth.

2.2.2. *Average LOL players*

We recruited a large group of average-ranking LOL players (*N* > 50). Average players had LOL ranks ranging from Iron to Diamond tier, and were assigned to a waiting list. After we collected all top players, 35 average-ranking LOL players (four females; mean age = 23.1 years, *SD* = 4.59) were invited from the waiting list (N > 50): We deliberately selected a group of players whose game experience, age and gender distribution were not significantly different from the top players (Table 1).

All participants provided their LOL account names before taking part, so that researchers could verify their rank division in the game using a third-party smartphone app called WeGame. All participants reported that LOL was the only action video game they played on a weekly basis. All reported having normal or corrected-to-normal visual acuity. Participants were paid ￥100 (≈$12) for their participation.

2.3. *Apparatus*

Both the Stroop-switching test and the CPT test were programmed using PsyToolkit (Stoet, 2010, 2017). All stimuli were presented at the center of a 21-in. Dell computer monitor with black background. A QWERTY keyboard was used to record participants' responses with ± 1 ms precision. In the Stroop-switching test, participants gave left and right responses by pressing the “A” key or “L” key on the keyboard with their left and right index finger, respectively. In the CPT test, participants pressed the spacebar on the keyboard to give their response.

2.4. *Stroop-switching test*

2.4.1. *Stimuli*

Our Stroop-switching test was identical to Kalanthroff and Henik (2014) except that the word-reading task cue and all target stimuli were written in a different language. As per a previous study that showed language barrier might obscure the task-switching cost (Li et al., 2019a), we applied Chinese characters as the task cue and target stimuli in a sample of Chinese participants. Two critical Chinese characters were 绿 (GREEN) and 红 (RED) displayed in red and green, so that 绿 (GREEN) displayed in green and 红 (RED) displayed in red were congruent target stimuli and they were incongruent target stimuli if 绿 (GREEN) was shown in red and 红 (RED) was shown in green. The

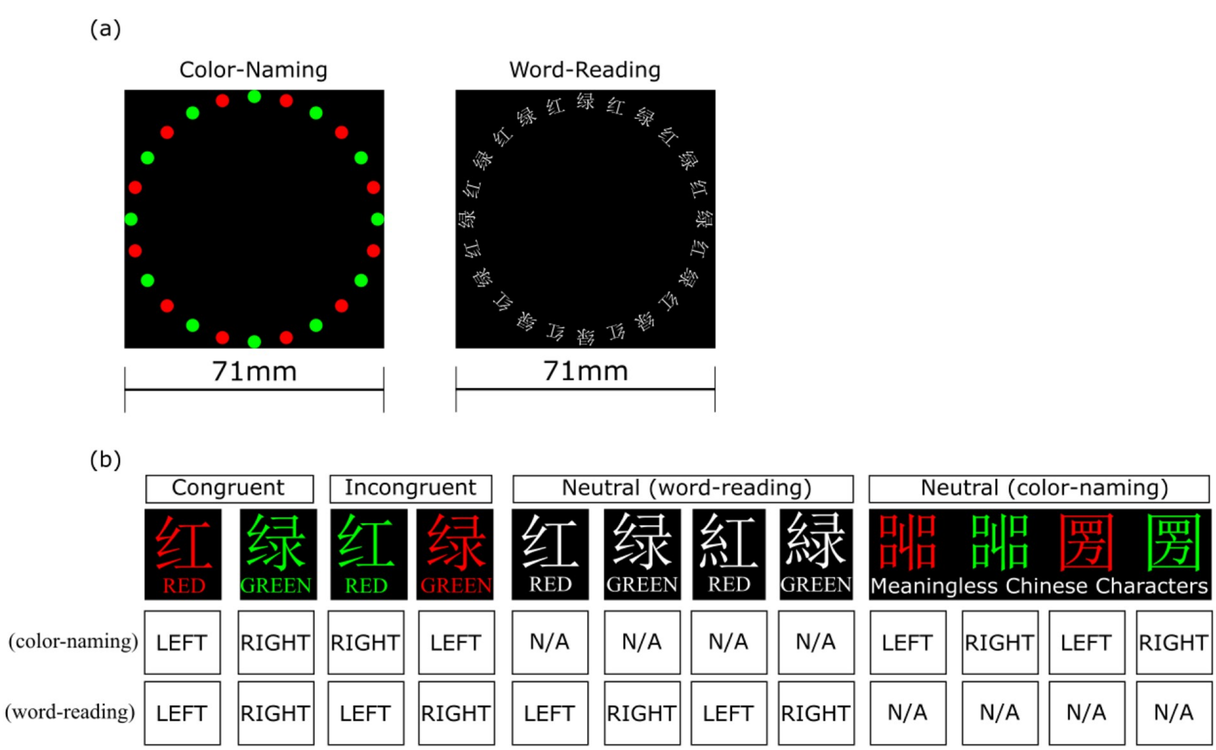

Fig. 2. Illustration of the task rules and target stimuli in the Stroop-switching test. (a) The color-naming task cue was a circular ring consisting of red and green dots, and the word-reading task cue was a circular ring consisting of Chinese characters in white. (b) Target stimuli were twelve Chinese characters displayed in red, green, and white. LEFT and RIGHT correspond to pressing the “A” and “L” keys on the QWERTY keyboard, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

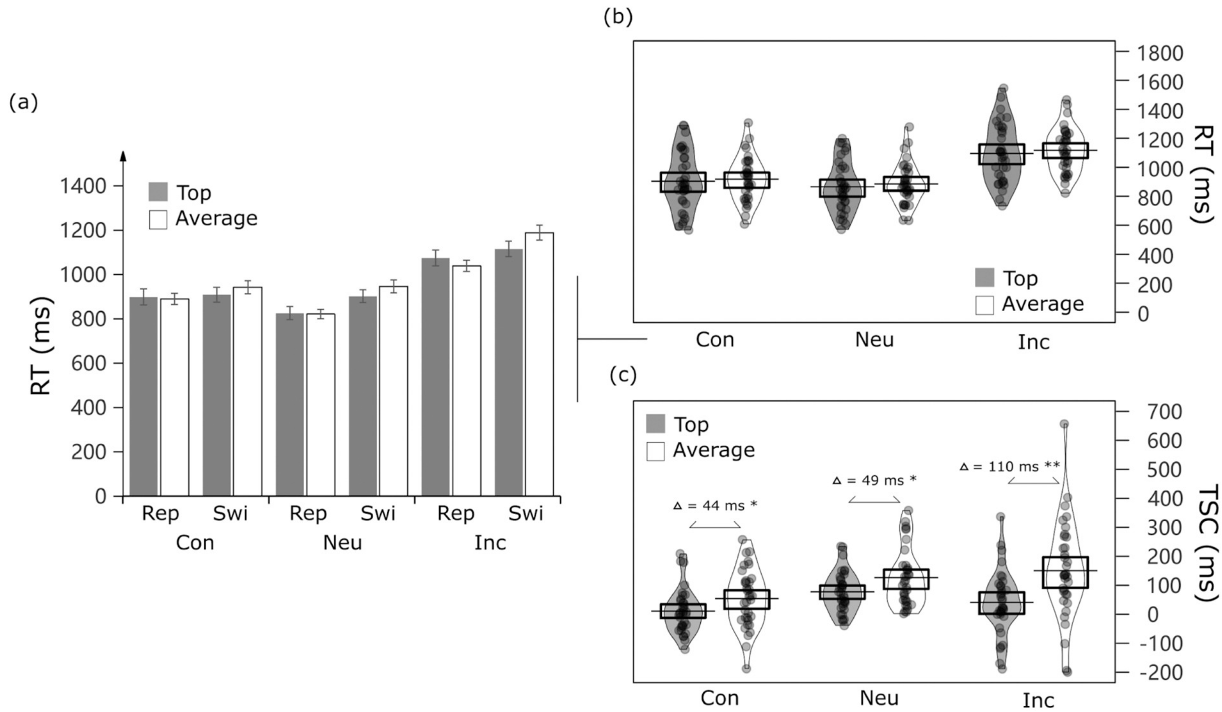

Fig. 3. RT results of the Stroop-switching experiment. (a) Bar charts display mean RTs in each trial condition (repeat–congruent, switch–congruent, repeat–neutral, switch–neutral, repeat–incongruent, switch–incongruent). The error bars indicate ± 1 *SEM*. (b) The violin plot illustrates RT distribution for the congruent, neutral, and incongruent condition in each player group (top players, average players). Jittered dots inside the violin plots represent average RTs for each participant. The black horizontal bar and the box around it represent the mean and 50% CI of the mean in each condition, respectively. (c) The violin plot illustrates RT task-switching costs (TSC) for the congruent, neutral, and incongruent condition in each player group. The difference between top and average players in the TSC was denoted by symbol "Δ". Con = Congruent; Neu = Neutral; Inc. = Incongruent; Rep = Repeat; Swi = Switch. $^{**}p < .01$, $^{*}p < .05$.

experiment also included two simplified Chinese characters 绿 (GREEN) and 红 (RED) as well as two traditional Chinese characters 緑 (GREEN) and 紅 (RED) displayed in white serving as neutral target stimuli in the word-reading task; and two meaningless characters 嘂 and 圐 displayed in red and green serving as neutral target stimuli in the color-naming task. The size of each character was 38 mm × 38 mm. In total, there were twelve combinations of Chinese characters and colors: two congruent stimuli, two incongruent stimuli and eight neutral stimuli (four for each task; see Fig. 2b). A circular ring consisting of two white Chinese characters 绿 (GREEN) and 红 (RED) served as the word-reading task cue and a circular ring consisting of colored dots served as the color-naming task cue. The diameter of each task cue was 71 mm (Fig. 2a). In the word-reading task, participants had to decide whether a target stimulus was word *red* or *green* (red ⇒ press the left key; green ⇒ press the right key). In the color-naming task, participants had to decide whether a target stimulus was displayed in red or green (red ⇒ press the left key; green ⇒ press the right key).

2.4.2. Procedure

In each trial, a circular task cue and a target Chinese character appeared simultaneously and were located at the center of the screen. The target always appeared inside the task cue, with both staying on the screen until a response was made or a maximum of 2500 ms was exceeded. A correct response would trigger the next trial after an intertrial interval of 300 ms. If the participant failed to respond within 2500 ms, a "time out" message appeared for 3 s. If the participants made an incorrect response, a "mistake" message appeared for 3 s. The Stroop-switching experiment consisted of three training blocks of 32 trials followed by two experimental blocks of 128 trials. Note that the present Stroop-switching test was demanding because both the task cue and target stimuli were presented simultaneously. In a pilot study we found that training with three blocks of 32 trails helped participants to better recall the task rule and show reasonable accuracy.

2.5. Continuous performance test (CPT)

2.5.1. Stimuli and procedure

Our CPT test was similar to the CPT in previous studies (e.g., Azizi et al., 2018), except that we provided feedback immediately following either correct, incorrect or delayed response. This is because in LOL players receive immediate feedback on almost all of their actions. We also applied a narrower response window (450 ms), which was extremely demanding, in order to simulate the rapid response mode in the LOL game.

The target stimuli were green (RGB 0,255,0) English letters (32 mm × 30 mm). In each trial of the CPT test, the stimuli appeared in the center of the screen, one at a time (as one trial), for 250 ms. The trials were presented in 18 consecutive blocks where each block contained inter-stimulus intervals (ISI) of 1000, 2000, or 4000 ms in a random order. Transitions from one block to the next occurred unannounced and without delay. Participants were asked to press the spacebar on the keyboard as quickly as possible whenever letters except "X" show up on the screen (*go* trial) and to suppress the response when "X" shows up (*no-go* trial). If participants respond too slow in a *go* trial (> 450 ms) a "timeout" message appeared for 300 ms. If the participants could not suppress the response in the *no-go* trials (i.e., participants pressed the spacebar within 700 ms), a "mistake" message appeared for 300 ms. The CPT test consisted of a block of 10 training trials and 18 blocks of 20 experimental trials.

2.6. General procedure

Experiments took place in a psychology lab at Fudan University. After participants provided demographics information, they sat with their eyes at a distance of approximately 80 cm from the computer screen. All participants were asked to complete the Stroop-switching test before the continuous performance test. They received verbal and

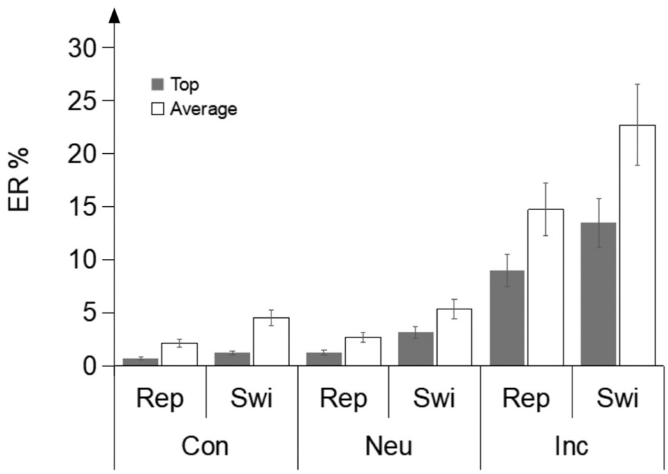

Fig. 4. ER results of the Stroop-switching experiment. The bar graphs display ERs of each trial condition (repeat–congruent, switch–congruent, repeat–neutral, switch–neutral, repeat–incongruent, switch–incongruent). The error bars indicate ± 1 *SEM.* Con = Congruent; Neu = Neutral; Inc. = Incongruent; Rep = Repeat; Swi = Switch.

on-screen instructions before each test. All participants took a five-minute break between the tests.

3. Results

The data that support the findings of this study are openly available in Open Science Framework at https://osf.io/mygz7/?view_only=ef6eb4e8d88b4653909776fdbbecfa01.

3.1. Stroop-switching test

All participants performed better than chance, with error rates lower than 15% in the Stroop-switching test. Error trials were excluded from all RT analyses. For the analyses of the Stroop-switching experiment, all training trials, the first trial of each block, and the trial immediately following incorrect trials were excluded. If participants made a mistake in *trial n* – 1, *trial n* cannot be categorized as a task-switch trial or task-repeat trial. As a result, we excluded 9.12% of trials. Mean RTs and ERs for each trial condition and group of players are shown in Figs. 3, 4 and listed in the Appendix A.

We first applied a 2 (Trial transition: repeat, switch) × 2 (Task: color-naming, word-reading) × 3 (Congruency: congruent, incongruent, and neutral) × 2 (Player group: top, average) mixed-factors multivariate analyses of variance (MANOVA), with Player group as a between-subjects factor and other factors as within-subject factors. Two dependent variables were RTs and ERs. We listed the results of the MANOVA in Appendix B. In short, the main effects of Trial transitions, Congruency and Player groups were significant ($p < .001$), but the main effect of Task was not significant ($p = .643$) with no differences between the color-naming and word-reading task. There were also two-way and three-way interactions ($p < .001$). In order to further understand whether top and average LOL players differed in the Stroop-switching performance, we submitted their RT and ER data in two separate analyses of variance (ANOVA) with the design identical to the MANOVA. The results of the ANOVAs are summarized in Table 2 and illustrated in Figs. 3 and 4.

3.1.1. Analysis of RT

The mean RTs were similar for top (948 ms) and average players (963 ms), and in the color-naming task (958) and word-reading task (956 ms). We found significantly longer RT in switch trials (992 ms) than in repeat trials (917 ms). In the following, post-hoc pairwise *t*-test comparisons were used for multiple comparisons after Holm (1979). The results showed that there were significant RT differences between neutral (874 ms) and congruent trials (910 ms), $p < .001$, $d = -0.70$; between incongruent trials (1105 ms) and congruent trials, $p < .001$, $d = 2.41$; and between neutral trials and incongruent trials, $p < .001$, $d = -2.83$.

There was a significant interaction between Trial transition and Task type. Participants showed larger task-switching costs when switching to the color-naming task (switch - repeat = 94 ms) compared to switching to the word-reading task (switch - repeat = 54 ms); the difference was significant, $p = .003$, $d = 0.36$. There was a significant interaction between Trial transition and Congruency. The task-switching costs were smaller in the trials with congruent target stimuli (switch - repeat = 32 ms) compared to trials with neutral target stimuli (switch - repeat = 95 ms), $p < .001$, $d = -0.44$, and trials with incongruent target stimuli (switch - repeat = 94 ms), $p < .001$, $d = -0.74$. However, switch costs were not statistically different between neutral and incongruent conditions ($p > .05$).

As predicted, we found a significant two-way interaction between Player group and Trial transition; task-switching costs were smaller in top group (switch - repeat = 37 ms) than in average group (switch - repeat = 91 ms). The three-way interaction between Player group, Trial transition and Congruency was also significant. In order to better understand whether there were group differences in different conditions, we compared the task-switching costs (switch–repeat) between top players and average players in congruent, neutral, and incongruent conditions. The results showed that top players had smaller task-switching costs compared to average players in the congruent condition (10 ms vs. 54 ms, $p = .043$, $d = -0.49$), neutral condition (77 ms vs. 126 ms, $p = .041$, $d = -0.57$), and incongruent condition (40 ms vs. 150 ms, $p = .006$, $d = -0.77$). The switching-cost difference between groups of top and average players was larger in the incongruent condition compared to the neutral and congruent conditions. There was also a significant interaction between task and congruency. However, such interaction was not predicted. No other effects in RT reached statistical significance.

3.1.2. Analysis of ER

An equivalent four-way ANOVA with mixed effects was conducted on mean ERs between and within conditions. The results of this analysis are summarized in Table 2 and illustrated in Fig. 4. Top players had lower ER (5.02%) compared to average players (8.81%). ERs were higher in switch trials (8.04%) than in repeat trials (5.09%), and in the word-reading task (7.21%) than in the color-naming task (6.63%). For the main effect of Congruency, pairwise *t*-test comparisons showed a significant ER difference between neutral (3.15%) and congruent trials (2.26%), $p = .023$, $d = 0.28$; between incongruent (15.35%) and congruent trials, $p < .001$, $d = 1.66$; and between incongruent and neutral trials, $p < .001$, $d = 1.55$.

As predicted, there were significant two-way interactions between Player group and Trial transition, and between Player group and Congruency. Top players (2.32%) showed smaller task-switching costs (switch–repeat) compared to average players (4.29%), $p = .020$, $d = -0.57$.

Moreover, in order to better understand whether there were group differences in the effect of Congruency, we analyzed the reverse-facilitation effects (congruent–neutral) and response-congruency effects (incongruent–neutral) in both player groups. The results showed that the reverse-facilitation effects were significant in the group of top players (−1.18%, $p = .036$, $d = -0.42$), but were not significant in the group of average players (−0.59%, $p = .344$, $d = -0.12$). The response-congruency effects were significant in both the top players (9.44%, $p < .001$, $d = 1.26$) and average players (14.95%, $p < .001$, $d = 1.26$); however, the effect was smaller in the top players than in the average players, $p = .003$, $d = -0.74$. Further analysis showed that top players had significantly lower ER compared to average players in

Table 2
Stroop-Switching Test: Results of two mixed-measures ANOVAs on RT and ER data, using Trial transition (repeat, switch), Task (color-naming, word-reading), Congruency (congruent, incongruent, neutral) as within-subject factors, and Player group (top, average) as a between-subjects factor.

Effect	RT				ER			
	F	df	p	η_p^2	F	df	p	η_p^2
Player group (G)	0.24	1, 68	0.623	0.004	15.67	1, 68	**< 0.001**	0.187
Trial transition (TT)	60.62	1, 68	**< 0.001**	0.471	157.38	1, 68	**< 0.001**	0.698
Congruency (C)	414.75	2, 136	**< 0.001**	0.859	144.22	2, 136	**< 0.001**	0.678
Task (TK)	< 0.01	1, 68	0.962	< 0.001	5.86	1, 68	**0.018**	0.079
G × TT	12.48	1, 68	**< 0.001**	0.155	8.09	1, 68	**0.006**	0.106
G × C	0.13	2, 136	0.876	0.002	10.02	2, 136	**< 0.001**	0.128
G × TK	0.13	1, 68	0.718	0.002	1.83	1, 68	0.179	0.026
TT × C	14.14	2, 136	**< 0.001**	0.172	71.90	2, 136	**< 0.001**	0.514
TT × TK	12.07	1, 68	**< 0.001**	0.151	8.93	1, 68	**0.004**	0.116
C × TK	8.68	2, 136	**< 0.001**	0.113	10.69	2, 136	**< 0.001**	0.136
G × TT × C	3.76	2, 136	**< 0.001**	0.052	1.74	2, 136	0.179	0.025
G × TT × TK	0.27	1, 68	0.599	0.004	0.33	1, 68	0.565	0.005
G × C × TK	0.45	2, 136	0.654	0.006	1.14	2, 136	0.322	0.017
TT × C × TK	2.22	2, 136	0.112	0.032	16.25	2, 136	**< 0.001**	0.193
G × TT × C × TK	0.52	2, 136	0.595	0.007	2.11	2, 136	0.126	0.030

congruent trials (1.07% vs 3.45%, $p = .005$, $d = -0.77$), and incongruent trials (11.71% vs 19.00%, $p < .001$, $d = -0.93$), but in neutral trials the group difference was not statistically significant (2.25% vs 4.05%, $p = .109$, $d = -0.38$).

We found a significant two-way interaction between Trial transition and Congruency. Task-switching costs were larger in incongruent condition (switch–repeat = 6.27%) than in neutral condition (switch–-repeat = 2.27%), $p < .001$, $d = 0.43$, and congruent condition (switch–repeat = 1.44%), $p < .001$, $d = 0.51$. Task switch costs were similar in congruent and neutral conditions, $p = .137$.

The interaction between Trial transition and Task type was also significant. Participants showed significant task-switching costs when switching to the color-naming task (switch–repeat = 3.94%, $p < .001$, $d = 0.84$) and when switching to the word-reading task (switch–-repeat = 2.68%, $p < .001$, $d = 0.50$), but the difference between the two tasks did not reach statistical significance, $p = .124$.

The significant two-way interaction between Task and Congruency, and the significant three-way interaction between Trial transition, Congruency and Task were not predicted. No other effects in ER reached statistical significance.

3.2. Continuous performance test

In the CPT test, we focused on four dependent variables: mean RT, the hit rate in the *go* trials, the rate of false alarms in the *nogo* trials, and the response bias. The descriptive data and correlations between the four dependent variables were listed in Appendix C. All training trials and *go* trials with RTs that were shorter than 150 ms were excluded. The results of the CPT test are illustrated in Fig. 5.

We conducted a one-way MANOVA to test the difference between top and average players on the linear combination of the four dependent variables. The results showed a significant multivariate effect for the four dependent variables as a group in relation to the Player groups. In general, top players performed differently to average players, $F(3, 68) = 3.09$, $p = .007$, Pillai's Trace = 0.19, $\eta_p^2 = 0.193$. We studied the univariate effects in order to examine whether top and average players differed on each dependent variable (Fig. 5). We found that the group of top players did not differ from the group of average group in mean RT ($F < 1$, $p > .05$), and response bias, $F(1, 68) = 1.01$, $p = .319$. However, top players had a significantly lower false alarm rate (38.46%) compared to average players (48.72%), $F(1, 68) = 8.34$, $p = .005$, $\eta_p^2 = 0.109$. Moreover, top players had significantly higher hit rate (91. 28%) compared to average players (87.54%), $F(1, 68) = 9.30$, $p = .003$, $\eta_p^2 = 0.120$.

4. Discussion

The main purpose of the present study was to investigate whether video game experts (i.e., top-ranking LOL players) have superior cognitive ability than average players after controlling for self-reported gaming times. We applied a Stroop-switching test in order to examine players' abilities of flexible switching and interference control. Moreover, we also applied a continuous performance test in order to examine players' impulsive control. We found that top-ranking players had better performance in both the Stroop-switching test and continuous performance test compared to average-ranking players.

4.1. Cognitive flexibility and gaming skill

In line with our hypothesis, both the top- and average-ranking LOL players showed significant RT and ER task-switching costs, but the task-switching costs were smaller in the group of top-ranking players. Importantly, in top-ranking players the decreases in switching costs were not accompanied by the increased error rates given that top players showed overall fewer errors compared to average-ranking players. Therefore, the advantage of top-ranking players in the Stroop-switching test cannot be explained by the speed-accuracy trade off. Top-ranking players might have better cognitive flexibility, possibly with fast task-set reconfiguration when switching between tasks (Grange & Houghton, 2014; Kiesel et al., 2010; Vandierendonck, Liefooghe, & Verbruggen, 2010). Our results are in line with the previous fMRI study (Gong et al., 2019) that better action video gaming skills were linked to improved executive control abilities such as cognitive flexibility.

It is less likely that we can attribute the flexible switching in the top-ranking players to extended gaming experience alone, because there were no differences in the gaming tenure and times (i.e., years of play and hours of play per week) between top and average players. It has been suggested that task-switching costs are sensitive to training and can be reduced significantly after a few experimental sessions (e.g., reduced switching costs after six training sections in Wendt, Kähler, Luna-Rodriguez, & Jacobsen, 2017; see also Strobach, Liepelt, Schubert, & Kiesel, 2011). However, in a study by Stoet and Snyder (2007) who asked four participants to practice task switching for > 20,000 trials, researchers found that 1 participant showed reduced task-switching costs whereas the cost was roughly constant or even increased in other participants. Perhaps there is an interplay between task-switching strategies and duration of training in the effect of task-switching training. Similarly, it is also possible that game skills interplay with game experience, influencing the training effect of game playing. That is, only top-ranking players can have improved cognitive flexibility and

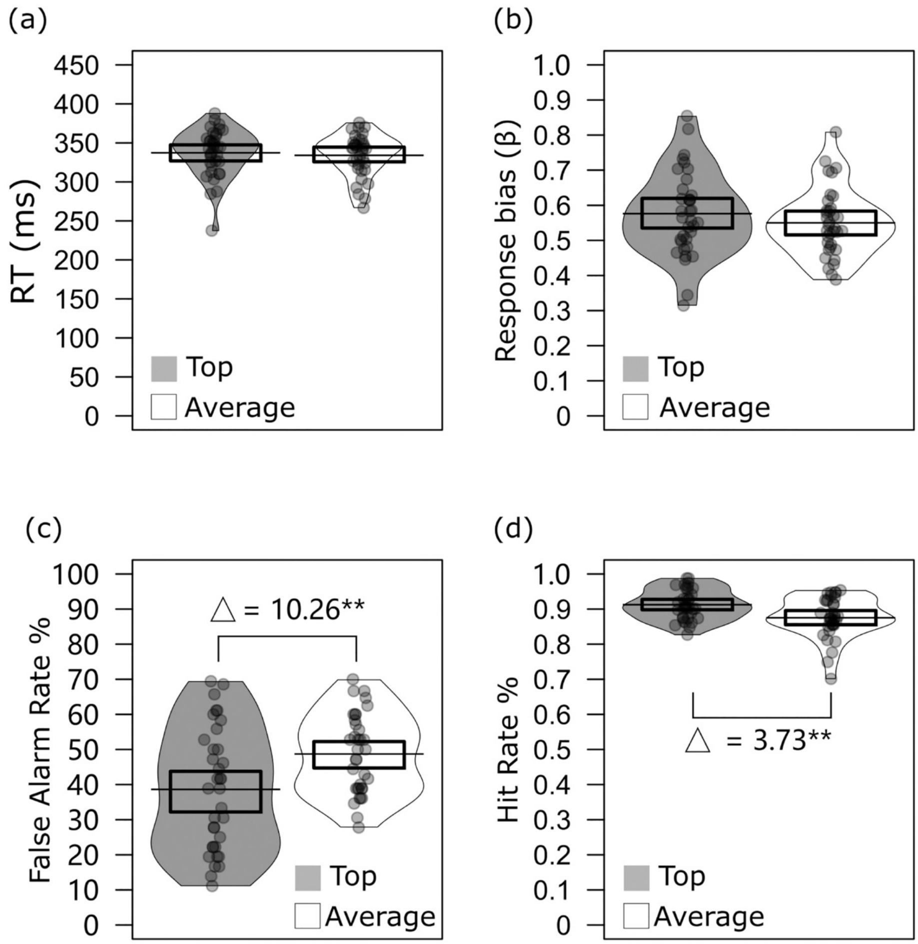

Fig. 5. Results of the Continuous Performance Test. (a) The violin plot illustrates RT distribution in *go* trials for the top and average players. The jittered dots inside each bean represent averaged RTs of each participant. The black horizontal bar and the box around it represent the mean RT and 50% CI of the mean RT in each group, respectively. (b) The violin plot illustrates the distribution of response bias (β) for the top and average players. (c) The violin plot illustrates the distribution of false-alarm rate for the top and average players. (d) The violin plot illustrates the distribution of hit rate for the top and average players. $^{**}p < .01$.

facilitated task-switching performance as gaming experience increases (see Section 4.4 for further discussion).

4.1.1. *Asymmetrical switching costs*

Inconsistent with our predictions, top players indicated asymmetrical task-switching costs similar to average players. Unexpectedly, both groups had smaller task-switching costs when switching from the relatively easier word-reading task to the relatively harder color-naming task than the other way around, which contradicted previous results (e.g., Allport et al., 1994; Wu et al., 2015; but see Monsell, et al., 2000; Yeung & Monsell, 2003).

Task-switching costs have at least two origins (cf., Grange & Houghton, 2014; Kiesel et al., 2010; Vandierendonck et al., 2010). Firstly, task-switching costs can be due to proactive interference from the task set activated in the previous trial with a different task (Allport et al., 1994; Allport & Wylie, 2000; Waszak & Hommel, 2007). For example, in the present study, when participants switched from a color-naming task to a word-reading task, the color feature became irrelevant and interfered with the processing of the relevant word feature, thereby delaying responses. In addition, task-switching costs can reflect the time needed to reconfigure or to retrieve a relevant task set from memory before participants could give a response in task-switching trials (Meiran, 2000; Monsell & Mizon, 2006; Rogers & Monsell, 1995).

The phenomenon that switching from a harder task to a relatively easier task causes larger task-switching costs rather than the other way around has been attributed to the larger and persisting proactive interference elicited by the harder task compared to the easier task (Allport et al., 1994; Wu et al., 2015). However, the task cues in the present study were very transparent in task meaning: The word-reading task cue was a circular ring consisting of the words "green" and "red" in white in Chinese, and the color-naming task cue was a circular ring consisting of green and red dots. Those cues may have helped participants focus on the task-relevant feature in each trial. Therefore, the amount of interference from the irrelevant task may be reduced during task-switching (Gade & Steinhauser, 2019). Alternatively, it is likely that in our study, the task-switching costs are primarily caused by the additional task-reconfiguration process in switch trials. Task-reconfiguration may take longer when switching to a hard task, associated with large RT switching costs. Similar results have been reported by Yeung and Monsell (2003), suggesting that when the interference between tasks was reduced, participants showed reversed asymmetrical task-switching costs, which means larger switching costs when switching to the color-naming task compared to the word-reading task.

In previous task-switching studies that investigated the task-switching performance in the neutral target condition and the bivalent target condition, researchers typically found smaller task-switching costs for neutral target stimuli compared to bivalent target stimuli (e.g., Allport & Wylie, 2000; Rogers & Monsell, 1995; Wylie & Allport, 2000). However, in our study participants showed task-switching costs in trials with neutral target stimuli (95 ms) at a similar level to trials with incongruent target stimuli (96 ms). An in-depth discussion is beyond the scope of the present study, but perhaps our neutral target stimuli contained redundant information irrelevant to both tasks. For example, the structure of the two meaningless Chinese characters was very complex (Fig. 2b), which may also attract attention and could delay the task-set reconfiguration process.

4.2. Resolving interference and gaming skills

We found differences between top-ranking players and average-ranking players in ER response-congruency effects, which was in line with our prediction. The response-congruency effects reflect the involvement of cognitive efforts in resolving interference between two potential feature-response associations in incongruent trials (Li et al., 2019a, 2019b; Schneider, 2015, 2018; Sudevan & Taylor, 1987; Wendt & Kiesel, 2008). Top-ranking LOL players appeared to have better abilities to control and resolve interference during response selections, inconsistent with a number of previous studies (Cain et al., 2012; Gobet et al., 2014; Kowal et al., 2018; but see Andrews & Murphy, 2006). However, we found that the advantages of top players were limited in accuracy. In other words, although top-ranking players made fewer errors compared to average-ranking players in trials with incongruent targets, both groups of players responded more slowly in incongruent trials than in neutral trials. Top players may take a long time to complete the rule-based feature-categorization process before they made a response in some trials, whereas average players may even occasionally forget the task rules so that they failed to categorize the relevant target feature and therefore made frequent errors in a large proportion of incongruent trials.

Another important finding was that top players responded with higher accuracy in the congruent condition compared to the neutral condition, showing a significant facilitation effect. In contrast, average players showed no ER differences between congruent and neutral conditions. The ER results were inconsistent with previous results suggesting that participants typically have higher ERs in congruent trials than in neutral trials because of the extra task interferences: Congruent stimuli consisted of features and afforded responses for the two tasks, whereas neutral stimuli appeared in only one task (Kalanthroff & Henik, 2014; Steinhauser & Hubner, 2009). Among top-ranking players, both relevant and irrelevant features of a congruent target were processed efficiently and may have given rise to a synergistic effect on response retrieval that facilitated response accuracy. However, average players made generally more mistakes than top players in each trial condition, which may account for the null effect. Note that the difference between top- and average-ranking players was limited in accuracy. Both groups had similar RT results and showed delayed responses in congruent trials than in neutral trials, replicating previous studies indicating a reverse-facilitation effect (Kalanthroff & Henik, 2014; Steinhauser & Hubner, 2009).

Overall, our results suggested that top players responded more accurately in the task-switching experiment compared to average players. We suggest that top players have better cognitive ability to resolve task interference exhibiting higher accuracy but similar speed of response to average players.

4.3. Impulsive control and gaming skills

We used a continuous performance test to measure participants' impulsive control. The results showed that top- and average-ranking LOL players had no difference in RTs in the *go* trials. Normally in CPT testing, participants can respond until the next target/non-target onset or having a response window of at least 1000 ms (Azizi et al., 2018; Egeland & Kovalik-Gran, 2010). With a narrower response window of 450 ms, our participants experienced more time pressure and may be more motivated to respond faster in each *go* trial, which may attenuate the RT difference between top and average players. In addition, we found no difference between groups on response bias; this finding provided evidence that top players and average players had similar response tendencies.

However, compared to average players, top players had significantly higher hit rates and lower false alarm rates, suggesting that top-ranking players were more able to differentiate between targets and non-targets which may be associated with better impulsive control. Our results are inconsistent with previous studies either showing no differences between AVGPs and nAVGPs (Colzato et al., 2013; Metcalf & Pammer, 2014), or showing that AVGPs (Decker & Gay, 2011; Littel et al., 2012) and players with multi-genre gaming experience (including action video games; Azizi et al., 2018) had worse impulsive control compared to nAVGPs.

4.4. Top players and top performance

Two possible interpretations were proposed for the results of the present study. First, it is possible that only individuals who have superior cognitive abilities (e.g., cognitive flexibility, interference, and impulsive control) can achieve a higher ranking in the game or become a top-ranking player. In other words, video game training and experience may not be the key point; all top players may simply be the cognitively gifted individuals. Boot et al. (2008) proposed a similar explanation, arguing that playing video games may not improve cognitive abilities; instead, people with better cognitive abilities may be more likely to play video games because they can do better than others in the game, reflecting a self-selected process into video game play.

The second potential explanation could be that cognitive flexibility, interference, and impulsive control can be better trained and improved by video game experience in players who have a strong motivation to constantly hone their game skills and earn promotions. This is because winning at the highest level of competition would require players to mobilize a variety of cognitive resources. In contrast, if a player only wants to relax and pass the time by playing games, the cognitive resources will not be fully mobilized and cognitive abilities may not be enhanced.

Taking impulsive control as an example, at the primary/average level of the competitions in LOL, false alarms or impulsive behaviors (e.g., wasting a spell against an unimportant target) are not punished by opponents because the spells in LOL have relatively short cooldown times. However, during the highest level of competition, top players have to always take advantage of opponents' cooling down time despite its brevity for harassing or attacking. Therefore, reducing impulsive behaviors and casting spells only on the most valuable targets are important goals for top players. If players do not have the motivation to win a game and get top ranks, they would not tend to improve their gaming techniques related to impulsive control. Accordingly, we suggest that players' motivation toward video games may determine how games impact their cognition.

Although top players can be highly motivated to get higher rankings in the game, their motivation to game playing might be different from those with video game addiction. Previous studies have already shown that game addiction can moderate the impact of gaming experience on cognition in a negative way: Addicted video game players tend to have worse cognitive abilities compared to non-addicted players and non-players (Metcalf & Pammer, 2014; see a review by Ioannidis et al., 2019). For example, Metcalf and Pammer (2014) showed that addicted FPS game players had higher levels of disinhibition and higher trait impulsivity compared to non-addicted players and non-players whereas no differences were found between non-addicted FPS players and non-players in neuropsychological deficits associated with impulsivity. According to Metcalf and Pammer (2014) results, it is unlikely that top players in our study were addicted to the game because we found that top players had better executive control compared to average players. Future research should compare between top-ranking players and addicted players in order to understand their motivation and attitudes toward video games playing.

Whether individual differences in players' cognitive functions predetermined the variances in game skills, or players' motivation to win a game can help to improve cognitive functions, or both, warrants further investigation. For example, future training studies may ask nAVGPs varying in cognitive functioning to practice MOBA games (e.g., LOL) for some period of time, whilst controlling motivation levels. If the game skills are related to cognitive functions, those with better cognitive ability would show more improved performance in the MOBA games as training duration increases, indicating a higher probability of reaching high ranks. Similarly, by controlling cognitive ability, one can also investigate how players' motivation interplay with the training effect on video games.

Our results also provide some insights for the e-sports industry: Perhaps performance in similar cognitive experiments could be used as an important criterion when selecting professional game players in the future.

4.5. Conclusion and future directions

Few researchers to date have studied whether players with different game skill levels would differ in their cognitive abilities (e,g., Bonny et al., 2016; Gong et al., 2019; Kokkinakis et al., 2017; Röhlcke et al., 2018). This may be due in part to the difficulty of finding experts who are willing to participate in research (Gobet et al., 2014). The present study provided evidence that top-ranking LOL players exhibited greater cognitive flexibility, improved skills at resolving interference, and better impulsive control, even after we controlled for self-reported gaming tenure and time. Since these cognitive abilities are core aspects of executive functions (Diamond, 2013), we suggest that top players' superior performance in cognitive tasks may be related to better executive functioning (see also Bonny et al., 2016; Gong et al., 2019). Moreover, our results indicate that compared to a few weeks of game training or extended gaming experience, players who are highly skilled in video games may be more likely to have improved cognitive abilities.

One limitation of the present study is that we did not control players' gaming experience other than with League of Legends (LOL). Although all players reported LOL was the only action video game they played on a weekly basis, it is still possible that skills learned in other games can also interfere with our results. Previous studies suggested that game genres may require or train different cognitive abilities (Azizi et al., 2018; Deleuze et al., 2017; Dobrowolski et al., 2015); future studies can therefore focus on top-ranking players in different video game genres and their cognitive performance.

The present study primarily aimed to explore whether cognitive abilities were improved in AVGPs with superior game skills but similar hours of playing to a group of AVGPs with average game skills. Therefore, we did not include nAVGPs (i.e., participants without action video game experience). Future studies can compare the difference between nAVGPs, average- and top-ranking AVGPs to further isolate the impact of game skills from game experience on executive functioning. Nevertheless, our results highlight the importance of having a robust classification of people with gaming skills and those without in future experiments (cf. Latham et al., 2013; Sala et al., 2018). This may provide an avenue for better understanding of how action video game training could help boost certain cognitive abilities.

Declaration of competing interest

The authors declare that the present research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Xiangqian Li and Liang Huang share first authorship.

Appendix A. Stroop-switching: mean (SD) of RT ms and ER % of each trial condition and player group

	Congruent		Neutral		Incongruent	
	RT ms	*ER* %	*RT* ms	*ER* %	*RT* ms	*ER* %
Color-naming task						
TP Rep	868(205)	0.55(1.92)	835(176)	1.01(3.90)	1073(212)	6.76(10.63)
AP Rep	850(174)	1.61(4.38)	815(132)	2.61(6.70)	1040(184)	14.90(11.70)
TP Swi	912(191)	1.25(2.33)	921(175)	2.83(4.39)	1127(209)	13.20(12.34)
AP Swi	930(163)	5.14(5.48)	979(179)	5.77(8.86)	1212(203)	22.75(13.87)
Word-reading task						
TP Rep	928(238)	0.92(2.36)	814(196)	1.59(3.14)	1079(245)	11.54(9.18)
AP Rep	933(174)	2.72(4.40)	827(152)	2.74(4.88)	1041(180)	14.79(12.02)
TP Swi	901(224)	1.21(2.34)	884(206)	3.61(5.71)	1104(240)	13.75(12.53)
AP Swi	947(197)	4.00(5.93)	925(181)	5.07(6.79)	1185(232)	22.81(13.55)

Note. TP = Top player; AP = Average player; Rep = Repeat; Swi = Switch

Appendix B. Stroop-Switching Test: Results of mixed-measures MANOVAs on the linear combination of RT and ER data, using Trial transition (repeat, switch), Task (color-naming, word-reading), Congruency (congruent, incongruent, neutral) as within-subject factors, and Player group (top, average) as a between-subjects factor

Effect	*F*	*df*	*p*	*Pillai's Trace*	η_p^2
Player group (G)	7.86	2, 67	< **0.001**	0.190	0.190
Trial transition (TT)	49.09	2, 67	< **0.001**	0.594	0.594
Congruency (C)	63.72	4, 272	< **0.001**	0.968	0.484
Task (TK)	0.44	2, 67	0.643	0.013	0.013
G × TT	7.62	2, 67	**0.001**	0.185	0.185
G × C	3.94	4, 272	**0.004**	0.109	0.055
G × TK	1.00	2, 67	0.372	0.029	0.029
TT × C	12.42	4, 272	< **0.001**	0.309	0.154

TT × TK	6.48	2, 67	**0.003**	0.162	0.162
C × TK	4.92	4, 272	**0.001**	0.135	0.067
G × TT × C	2.12	4, 272	0.078	0.061	0.030
G × TT × TK	0.21	2, 67	0.811	0.006	0.006
G × C × TK	0.35	4, 272	0.844	0.010	0.005
TT × C × TK	1.30	4, 272	0.271	0.037	0.019
G × TT × C × TK	0.99	4, 272	0.413	0.029	0.014

Note: In the multivariate context, sometimes Pillai's Trace is equal to η_p^2.

Appendix C. CPT: Mean (SD) of RT ms, response bias, false alarms % and hit rate % for each player group and the correlations between the four dependent variables

	1	2	3	Top players Mean (*SD*)	Average players Mean (*SD*)
1. RT (ms)	–			337 (30)	334 (30)
2. Response Bias	0.17	–		0.57 (0.12)	0.54 (0.09)
3. False Alarm Rates (%)	- 0.34**	−0.61***		38.62 (17.32)	48.72 (11.29)
4. Hit Rates (%)	0.16	−0.35***	−0.40***	91.27 (4.28)	87.54 (5.76)

** $p < .01$.
*** $p < .001$.

Appendix D. Schematic illustrations of three types of target stimuli and the associated response-congruency effect and reverse-facilitation effect in Stroop-switching test

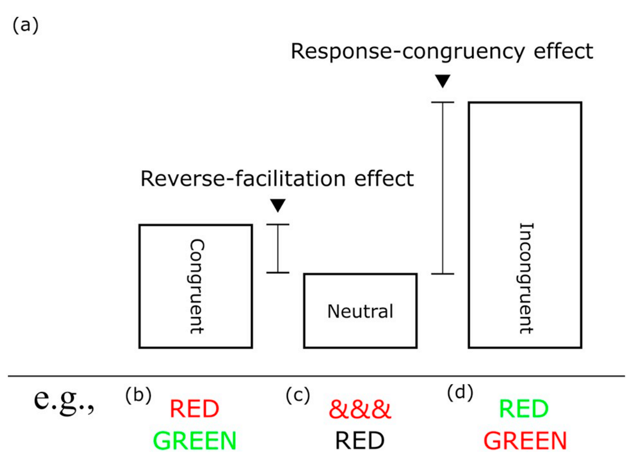

Fig. D1. (a) Reverse-facilitation effect = congruent trial - neutral trial; Response-congruency effect = incongruent trial - neutral trial. (b) Example of the congruent target stimuli, in which the ink color and the word meaning are mapped to the same response in the color-naming and word-reading tasks. (c) Examples of the neutral target stimuli, in which only the color (upper) or word printed in black (lower) are displayed and only appear in one task. (d) Examples of the incongruent target stimuli, the ink color and the meaning of the word are mapped to different responses in the color-naming and word-reading tasks.

Please note that the neutral target stimulus $\mathrm{RED}_{\mathrm{black}}$ also has a color because it is printed in black. However, in the present study, the color-naming task rule only required participants to judge between two colors: green and red, which means black is not included. As a result, the target $\mathrm{RED}_{\mathrm{black}}$ did not appear in the color-naming task and should be considered as a neutral target stimulus appearing only in the word-reading task.

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