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# Systems factorial technology provides novel insights into the cognitive processing characteristics of open-skill athletes

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ABSTRACT

Sport expertise has been shown to modulate the cognitive advantage in open-skill athletes, with evidence for a greater advantage for athletes practicing interceptive sports relative to strategic sports. However, this conclusion is solely based on central tendency measures such as accuracy or mean reaction time (RT), dismissing important information embedded in the intra-individual temporal dynamics of cognitive performance. This study aimed to better understand the cognitive advantage associated with open-skill sports, with a non-parametric approach assessing cognitive process at the level of RT distribution (i.e., systems factorial technology, SFT). Twenty-eight interceptive sport athletes, 27 strategic sport athletes, and 26 physically active non-athletes performed a go/nogo version of the redundant target task to assess their processing capacity of simultaneously monitoring multiple information channels. SFT was applied to assess resilience capacity, an estimate of workload capacity underlying inhibitory control. Our findings showed that interceptive sport athletes exhibited shorter mean RT relative to non-athletes selectively in the task condition involving distracting information, while strategic sport athletes showed greater resilience capacity over earlier responses relative to the other groups. These findings suggest that the two types of open-skill sports may be associated with different processing specificity, possibly reflecting the domain-specific rules and requirements.

## 1. Introduction

Promising evidence from previous research has demonstrated superior cognitive function of athletes over non-athletes (Chaddock, Neider, Voss, Gaspar, & Kramer, 2011; Koch & Krenn, 2021; Moreau, 2012; Wang et al., 2015). Because these findings are not constrained to sport-specific context and can be observed in domain-general tasks, it has been proposed that long-term athletic training results in general cognitive adaptations (Alves et al., 2013). Indeed, there is increasing evidence reporting a positive association between certain domain-general cognitive functions (e.g., executive function) and real-world sport performance (Hagyard, Brimmell, Edwards, & Vaughan, 2021; Scharfen & Memmert, 2019). Collectively, these observations have significant implications for increasing the likelihood of successful talent identification or functional capacity evaluation in elite sports.

Despite these encouraging findings, there remains mixed findings when assessing the relationship between sport expertise and domain-general cognition (Chang et al., 2017; Memmert, Simons, & Grimme, 2009). One major reason for the contradictory findings may be the type of sport disciplines that have been investigated. Typically, sports can be categorized into open-skill and closed-skill sports (Ludyga, Mücke, Andrä, Gerber, & Pühse, 2021; Poulton, 1957; Wang, Yang, Moreau, & Muggleton, 2017). Open-skill sports are performed in a dynamically changing, unpredictable and externally-paced environment, while the sporting environment in closed-skill sports is highly consistent, predictable, and self-paced. Athletes practicing open-skill sports have been repeatedly shown to be superior to those from closed-skill sports on a variety of domain-general tasks tapping higher order cognitive abilities, such as the flanker task (Wang, Liang, & Moreau, 2020), the go/nogo

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task (Ballester, Huertas, Pablos-Abella, Llorens, & Pesce, 2019), the stop-signal task (Wang et al., 2013), and the n-back task (Krenn, Finkenzeller, Würth, & Amesberger, 2018), presumably because of the higher levels of cognitive demand or extensive practice with certain cognitive aspects of open-skill sports (Gu, Zou, Loprinzi, Quan, & Huang, 2019).

Notably, the variety of sport characteristics within open-skill sports can be roughly categorized into two sub-types: interceptive and strategic sports (Dong, Pageaux, Romeas, & Berryman, 2022). Based on the definition of earlier sport-cognition studies (Mann, Williams, Ward, & Janelle, 2007; Voss, Kramer, Basak, Prakash, & Roberts, 2010), a sport is said to be interceptive when it requires coordination between any parts of an athlete's body or an implement (e.g., a racket) being used and an object (e.g., a ball) in the environment. Adapting to this overarching concept, our definition of interceptive sports is related to situations characteristically involving the interplay between two players (Hodges et al., 2021), which includes most of individual sports requiring interceptions such as tennis, table tennis, or fencing. Strategic sports, on the other hand, was defined as sports involving complex information processing about teammates, opponents, field position and ball concurrently with the strategy and tactics. In additional to some subset skills of sports (e.g., kicking, tackling, interceptive actions and etc.), sports in this category often refer to as collective team sports that require interpersonal interactions, multiple-signal processing and game reading skills (Hodges et al., 2021). Examples of strategic sports are basketball, soccer, or volleyball. Interestingly, a meta-analysis by Voss et al. (2010) has demonstrated that the domain-general cognitive advantage of athletes was more evident for those practicing interceptive sports relative to strategic sports, suggesting that the extent of athletes' cognitive superiority may depend on the specific type of open-skill sports. Nonetheless, the lack of consistency among studies may pose challenges to understand if and how cognitive functions affect and relate to performance in sports.

These conflicting findings may be the result of the specific type of dependent variable being tested. Typically, mean processing speed of cognitive functioning has been used; however, there have been ambiguous findings in studies using this type of cognitive measurement. For example, Yu and Liu (2021), using an attentional network task, observed that the cognitive advantage of athletes was observed on response accuracy for strategic sports athletes, but on reaction time (RT) for interceptive sport athletes. While there is research demonstrating superior processing speed when examining executive functions in strategic sports athletes (Krenn et al., 2018), such effects were not seen in many of the previous studies that have examined a variety of cognitive domains (Alves et al., 2013; Memmert et al., 2009; Pesce, Tessitore, Casella, Pirritano, & Capranica, 2007; Simonet, Ruggeri, Sallard, & Barral, 2022; Verburgh, Scherder, van Lange, & Oosterlaan, 2014; Wylie et al., 2018). Further, Di Russo and colleagues found that differences in performance on a go/nogo task between two different types of physically disabled athletes (i.e., wheelchair basketball players and swimmers) were manifest when considering RT variability but not mean RTs (Di Russo et al., 2010). It is possible that the distinct cognitive characteristics resulting from differences in cognitive demands or processing strategies inherent to game play and practice in different types of open-skill sports were differentially captured across different cognitive domains as well as levels (i.e., central tendency versus temporal dynamic) of behavioral measures.

To address this issue, the current study adopted a theory-driven mathematical tool, Systems Factorial Technology (SFT) (Wang, Lin, Moreau, Yang, & Liang, 2020; Yang, Hsieh, et al., 2019; Yang, Wang, Chang, Yu, & Little, 2019), to further elucidate the cognitive mechanisms underlying perceptual decision-making in athletes. SFT provides different aspects of cognitive processing measures, including cognitive architecture, stopping rule and workload capacity (Little, Eidels, Fific, & Wang, 2015; Townsend & Nozawa, 1995). First, cognitive architecture denotes the order of multiple-signal processing, that is, signals from multiple channels may be processed in a serial fashion or in a parallel fashion. Second, stopping rule denotes the way of how a decision is terminated. To elaborate, a self-terminating stopping rule is adopted when a decision is made based on the completion of one of the signals from different channels, while an exhaustive stopping rule is adopted when participants exhaustively process all signals from sources before making a decision. Finally, workload capacity denotes the change of processing efficiency as a function of workload. If the individual-channel processing efficiency (e.g., response time) is not affected by the processing of an additional information channel, the decision system can be defined as an unlimited-capacity system. In contrast, if the individual-channel processing efficiency increases or decreases due to an increase in the workload, the decision system can be defined as a super-capacity or limited-capacity system, respectively. Of these, workload capacity has been demonstrated to be capable of revealing the cognitive advantage of strategic sport athletes independent of mean-level performance. For example, Wang, Lin, et al. (2020) showed greater workload capacity in soccer players compared to physically active non-athletes despite the null differences in mean measures (i.e., accuracy and mean RT), suggesting that soccer expertise may be associated with the cognitive advantage when the processing of multiple sources of information is required. Accordingly, the measure of workload capacity via SFT can provide an alternative perspective to examine the cognitive superiority of athletes from open-skill sports.

Among the various cognitive tasks that allow the application of SFT to obtain a workload capacity measure, this study used a redundant-target task, as it has a long history in cognitive and mathematical psychology and has been well-validated (Little et al., 2015; Townsend & Nozawa, 1995). This task was designed to include the go/nogo paradigm requiring a color-shape discrimination to induce processes of inhibitory control (Kao et al., 2022; Yang, Hsieh, et al., 2019), which is not only a central executive function (Miyake & Friedman, 2012) but also a determinant of individual differences in open-skill sports (Krenn et al., 2018; Wang et al., 2013). In this task, participants are asked to make a positive response when one or more operationally-defined targets are present (i.e., the single- and redundant-target conditions), while suppressing a response when no targets are detected (i.e., the no-target condition). As such, the redundant-target task allows for an examination of some specific aspects of inhibitory control (e.g., conflict suppression and response inhibition) (Kao et al., 2022). Specifically, we adopted the resilience capacity—which compares the processing efficiency in the condition containing two target features (i.e., the redundant-target condition)—to the expectation predicted by the conditions containing one target feature and one distractor (i.e., the single-target condition). This expectation is generated by assuming that two features are processed with unlimited-capacity, independently and in parallel, which is known as the UCIP assumption (Little et al., 2015). By comparing the actual performance of the redundant-target condition with the UCIP prediction, we can assess workload capacity when dealing with conflicting information. Specifically, if there is no difference between the actual performance and the expectation, we can conclude that the processing system is of unlimited capacity. By contrast, if the actual performance outperforms the expectation or even performs worse than the expectation, we can conclude that the processing system is of super-capacity or limited capacity. Thus, this measure of resilience capacity reflects the cognitive ability to process multiple sources of information with the presence of a distractor (Little et al., 2015). It is worth nothing that resilience capacity has been successfully employed to characterize individual difference in performance such as cognitive aging (Yang, Hsieh, et al., 2019), exercise effects (Kao et al., 2022; Wang et al., 2023), and athletic cognitive superiority (Wang, Lin, et al., 2020), and may have the potential to shed light on the possible cognitive advantage associated with open-skill sports.

The purpose of this study was to use SFT to determine the difference in cognitive superiority beyond the behavioral measures of cognitive performance at the mean-level between types of open-skill sports (i.e., interceptive vs. strategic sports). Based on a previous meta-analysis (Voss et al., 2010) and empirical studies (Wang, Lin, et al., 2020), it was hypothesized that mean-level measures and resilience capacity are independent determinants of individual differences in inhibitory control associated with sport expertise, and that their joint contribution provides a better characterization of cognitive superiority in open-skill sports.

## 2. Materials and methods

### 2.1. Participants

A total of 90 male university undergraduate and graduate students were recruited in the study, including 30 athletes practicing interceptive sports, 30 athletes practicing strategic sports, and 30 non-athletic controls. Two interceptive sports athletes, 3 strategic sports athletes, and 4 non-athletic controls were excluded from further data analysis because they failed to meet the criteria of the cognitive task (i.e., their response accuracy in the no-target condition was less than 80%), resulting in a final sample of 81 subjects (Table 1). Despite this, the current sample size still outranged most of previous studies investigating cognitive difference between athlete practicing different sport types (Jacobson & Matthaeus, 2014; Wang et al., 2013; Yu, Chan, Chau, & Fu, 2017). In order to avoid any influence of gender-sport interactions on cognitive function (Alves et al., 2013; Voss et al., 2010), this study only recruited male participants. An athlete was operationally defined as an active player at the expertise level of National Collegiate Athletic Association Division II. The interceptive sports group consisted of 12 badminton players, 10 table tennis players, and 8 tennis players with professional training experience of 6–11 years. The strategic sports group consisted of 17 soccer players and 13 volleyball players with professional training experience of 5–13 years. A non-athlete in the control group was operationally defined as a student who reported no historical specialty in any sport but engaged in at least 30 min of moderate-intensity physical activity on at least 3 days per week for the past 3 months, in line with the defining criteria of a physically active individual based on ACSM's guideline (ACSM, 2017). No individuals reported a history of neurological problems or cardiovascular diseases, nor were any taking medications known to affect cognitive function. Informed consent was obtained from all participants prior to the study, and approval was obtained from the Human Research Ethics Committee (HREC) of National Cheng Kung University. In accordance with guidelines of the HREC, the data acquired in the present study cannot be shared with researchers without the written re-consent of the participants.

### 2.2. Tasks and measures

*Redundant-target task.* This study adopted the same redundant-target task programmed with E-prime 2.0 (Psychology Software Tools, Inc, Sharpsburg, PA) as prior studies in our group (Wang, Lin, et al., 2020; Yang, Hsieh, et al., 2019). All athletes were tested on days without training to prevent potential fatigue effects induced by physical training on task performance. In addition, experimenters ensured that all participants had not engaged in any specific activity prior to cognitive testing known to bias cognitive functioning (e.g., exercising or drinking alcohol).

In the redundant-target task, the test display consisted of a letter that was either an O or an X, either green or cyan, 1° (horizontal) × 1° (vertical) presented at the center of the screen. The target shape was defined as X and the target color was defined as green. The distractor shape was defined as O and the distractor color was defined as cyan. There were four types of test displays: both target features were presented (i.e., redundant-target trial: a green X); a single target feature and a distracting feature were presented simultaneously (i.e., single-target trial: a green O or a cyan X); or neither target features were presented (i.e., no-target trials: a cyan O). Each condition was equally distributed and was randomly intermixed within each block such that the participants would not be able to anticipate the presence of redundant-target trials. There were 20 practice trials and four blocks of 100 formal test trials, yielding 400 formal test trials in total.

The experiment was conducted in a dimly-lit and soundproof room and the participants sat in front of a screen at a viewing distance of 100 cm. All the visual stimuli were presented against a black background on a 21-inch cathode-ray tube (CRT) display. A trial began with a 1000 ms fixation cross (0.5° × 0.5°). Afterwards, a central-colored letter was presented until the participant made a response or 2000 ms had elapsed. Then, a central fixation cross (0.5° × 0.5°) appeared for a duration ranging from 1500 ms to 2000 ms, regarded as the inter-trial interval (ITI). Participants were instructed to press the "/" key as quickly and accurately as possible when they detected one of the target features (either color green or shape X); otherwise, they were instructed to hold their responses when neither target features were detected.

### 2.3. Data reduction and statistical analyses

*Behavioral data.* E-prime 2.0 was used to record behavioral performance (RTs and accuracy). RTs were excluded from analysis if they were from: (1) non-response trials, (2) error trials, and (3) correct trials with latencies more than three standard deviations above the mean.

*SFT and workload capacity.* This study used a modified capacity coefficient, the resilience coefficient $R(t)$, to estimate the workload capacity when dealing with conflicting information; that is, the degree of how multi-signal processing is resilient to the distractor processing (Little et al., 2015; Yang, Hsieh, et al., 2019). The $R(t)$ was computed according to the following equation:

$$R\,(t) = \left(\frac{H_{C+,S+}(t)}{H_{C+,S-}(t) + H_{C-,S+}(t)}\right)$$

where $H_{C+,S+}(t)$, $H_{C+,S-}(t)$, and $H_{C-,S+}(t)$ denote the integrated hazard functions of the redundant-target conditions and two single-target conditions, respectively. The integrated hazard function, $H(t)$, is expressed as $H(t) = \int_0^\infty \frac{f(t)}{S(t)} dt$, which denotes that given the process has not been completed, the instantaneous rate of completion at any time $t$; that is, the information processing efficiency. $f(t)$ denotes the density function, and $S(t)$ denotes the survival function (Townsend and Nozawa, 1995). Specifically, the ranges of values of $R(t)$ and their implications are as follows: (1) a value of $R(t) > 1$ suggests the system is of super-capacity: increasing the workload speeds up the processing speed for an individual channel; (2) a value of $R(t) = 1$ suggests the system is of unlimited capacity: the change in workload does not affect the processing efficiency of an individual channel; (3) a value of $R(t) < 1$ suggests the system is of limited capacity: increasing the workload slows down the processing speed for an individual channel.

Moreover, two inequalities were computed to provide supporting evidence in the interpretation of the workload capacity. Here we employed a recent interpretation of these inequalities, developed by

**Table 1**
Mean and standard deviation of the demographic characteristics of the participants.

| Variable | Interceptive sports athletes | Strategic sports athletes | Non-athletes |
|---|---|---|---|
| Age (years) | 20.96 [4.38] | 22.29 [2.22] | 22.58 [1.47] |
| Height (cm) | 173.82 [5.72] | 175.89 [6.75] | 173.08 [5.43] |
| Weight (kg) | 65.44 [5.75] | 66.20 [6.85] | 65.42 [7.29] |
| BMI (kg/$m^2$) | 21.64 [1.41] | 21.43 [2.21] | 21.80 [1.77] |
| BDI (points) | 5.14 [3.24] | 4.33 [2.45] | 5.92 [4.71] |

Note: All comparisons did not reach the significance level ($BF_{10} < 0.623$; *Fs* (2, 78) < 2.26, *ps* > .111)

Townsend and Eidels (2011), in terms of the capacity coefficient. In that article, both inequalities were explicitly formalized within the same space as the capacity coefficient, allowing one to interpret the inequalities as bounds on unlimited-capacity performance. The first is the race-model inequality (Miller, 1982), the second is the Grice inequality (Grice, Canham, & Boroughs, 1984). These inequalities place upper and lower boundaries on super- and limited-capacity processing, respectively. A violation of the race-model inequality indicates super-capacity processing, whereas a violation of the Grice inequality suggests very limited-capacity processing.

*Functional principal component analysis of the resilience function.* This study employed functional principal components analysis (*f*PCA) with varimax rotation to decompose the $R(t)$ coefficient function into several principal components (Burns, Houpt, Townsend, & Endres, 2013). *f*PCA is a structural extension of standard PCA (Ramsay & Silverman, 2005) that has the capacity to describe the entire functions using a small number of scalar values (i.e., the loading of the principal component) (Burns et al., 2013), which enabled us to determine which part of the function-level property is crucial for distinguishing the effect of sport expertise on the resilience capacity as a function of RT. Specifically, it has been suggested that *f*PCA can provide comprehensive information about individual differences in the resilience function (Houpt & Little, 2017). Thus, *f*PCA is useful for discovering the capacity differences in multi-signal information processing across subjects.

*Statistical analyses.* Analyses were performed in JASP version 0.12 (JASP Team, 2020). We used Bayesian analyses throughout, to allow quantifying evidence across a range of hypotheses, including the null. For convenience, we complemented Bayesian analyses with their frequentist counterparts. In line with previous research (Moreau, Kirk, & Waldie, 2017; Wang et al., 2019), all the priors were the default scales (Morey & Rouder, 2015). According to this framework, a Bayes Factor (BF) greater than 3 is considered moderate evidence in favor of the hypothesis tested (i.e., the null or the alternative), whereas a BF between 1 and 3 suggests the data are inconclusive (Dienes, 2014). All analyses were set to $10^4$ iterations, with diagnostic checks for convergence. One chain per analysis was used for all analyses reported in the paper, with a thinning interval of 1 (i.e., no iteration was discarded). Bayesian one-way ANOVA and one-way ANOVA tests were conducted to examine the group differences in demographics and each *f*PCA component of $R(t)$. Bayesian mixed-design ANOVAs with default prior scales and mixed-design ANOVAs was conducted to analyze the accuracy performance, the mean RTs. All tests for significance were set at alpha level .05.

## 3. Results

### 3.1. Mean behavioral performance

*Accuracy*. The results showed very strong support for the main effect of *condition* [$BF_{10} = 2.002e{+}15$; Greenhouse-Geisser corrected: $F(1.09, 85.10) = 166.41$, $p < .001$, $\eta_p^2 = 0.68$], with higher accuracy in the redundant-target condition (99.80 ± 0.07%), intermediate accuracy in the single-target condition (99.40 ± 0.10%), and lower accuracy for the no-target condition (92.70 ± 0.40%) (all $BF_{10} > 3.339$ and $p_{tukey}$ $p <$ .001). However, evidence for the main effect of *group* [$BF_{Inclusion} = 0.112$; $F(2, 78) = 0.81$, $p = .448$] and *group* × *condition* interaction [$BF_{Inclusion} = 0.201$; $F(4, 156) = 1.93$, $p = .109$] was extremely weak.

*Mean RTs*. Figure 1 shows mean RTs of correct trials across groups and conditions. The results showed very strong support for the main effect of *condition* [$BF_{10} = 3.226e{+}14$; $F(1, 78) = 859.45$, $p < .001$, $\eta_p^2 = 0.92$], with faster RTs for redundant-target condition than the single-target condition, consistent with prior research showing the redundancy gain (Miller, 1982). Moreover, we observed moderate evidence for the main effect of *group* [$BF_{Inclusion} = 4.22$; $F(2, 78) = 2.17$, $p = .121$] and strong evidence for the *group* × *condition* interaction [$BF_{Inclusion} = 17.525$; $F(2, 78) = 4.88$, $p = .010$, $\eta_p^2 = 0.11$]. Decomposition of this interaction by comparing *group* within each *condition* revealed faster RT for the interceptive sports athletes than non-athletic controls ($BF_{10} = 3.589$; $p_{tukey} = .045$) in the single-target condition (see Figure 1), whereas no other group differences were observed (all $BF_{10} < 1.088$; $p_{tukey} > .164$). In terms of the redundant-target condition, no differences in any comparisons were found among groups (all $BF_{10} < 0.663$; $p_{tukey} >$ .310).

### 3.2. Systems factorial technology and resilience

Figure 2 shows the resilience capacity coefficient function for each group. The results showed that the $R(t)$ of strategic sports group was

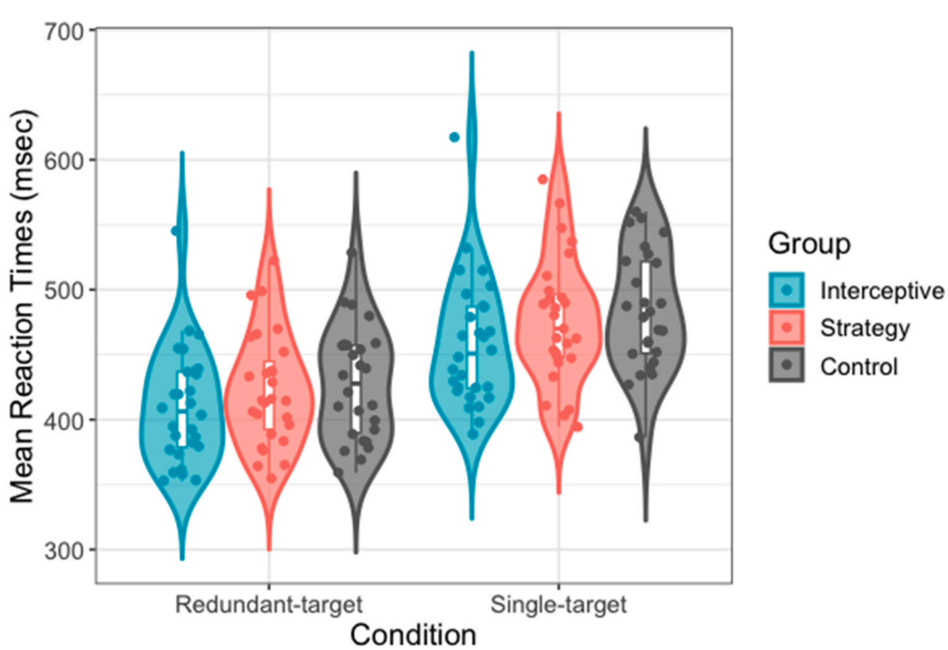


**Fig. 1.** Mean RTs for redundant-target and single-target conditions, split by groups. The plots show the distributions (violin) of mean RT together with the mean (box central dot), median (box central line), first and third quartile (box edges), minimum and maximum (whiskers), and each participant (dots).

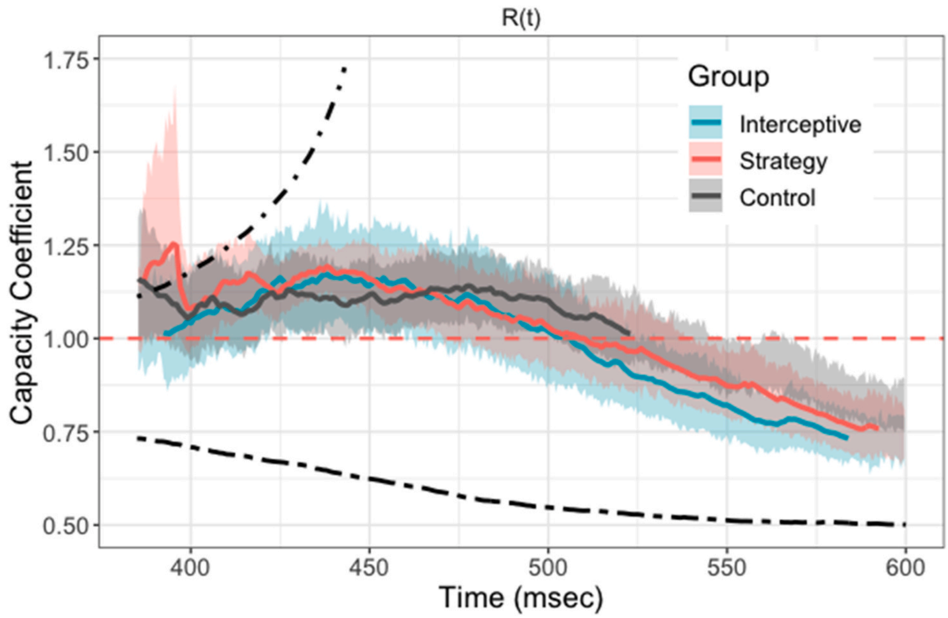


**Fig. 2.** Plots of the capacity coefficient $R(t)$ for the interceptive sports athletes, strategic sports athletes, and non-athletic controls in the redundant target task. Mean and 95% CIs of $R(t)$ were calculated from collapsing participants' $R(t)$ from each group. $R(t)$ was calculated from each individual's empirical distribution of RTs. The upper and lower dash-dotted lines represent the race-model bound and Grice bound, separately.

larger than 1 at the faster RT but included 1 at the slower RT. Similarly, the bootstrapped 95% confidence interval of the $R(t)$ exceeded the race-model bound at the faster RTs but did not exceed the race-model bound and the Grice bound at the slower RTs, suggesting super-to unlimited-capacity processing. On the other hand, for the interceptive sports group and non-athletic group, the $R(t)$ did not significantly differ from 1 over all times $t$ and the bootstrapped 95% confidence interval of the $R(t)$ over all RTs did not exceed the race-model bound and the Grice bound, suggesting unlimited-capacity processing.

### 3.3. fPCA of the resilience function

We averaged all the participants' data to estimate the mean resilience capacity function (Figure 3a) and the capacity functions for each individual and group (Figure 3b), allowing for the investigation of overall trend and variance across groups. Figure 4a is a scree plot that shows the amount of variance accounted for by each eigenfunction, and the results suggested a two-component solution. Figure 4b shows the component with the mean function on the left and relative to the mean on the right. The first principal component accounted for 47% of the variance and indicates a general increase of the resilience function around the middle to late parts of RT distribution. The second principal component explained 18% of the variance and indicates that a change in the slope of the function, with an increase in capacity for early part and a decrease in capacity for the middle part of RT distribution. One-way ANOVAs showed clear evidence for group-level difference in factor score for the second component ($BF_{Inclusion} = 4.887$; $F(2, 78) = 4.962$, $p = .009$, $\eta_p^2 = 0.11$), while no meaningful group difference was found for the first component ($BF_{Inclusion} = 4.828$; $F(2, 78) = 0.51$, $p = .602$). The post-hoc analysis of the second component revealed higher factor scores for strategic sport athletes than for interceptive sport athletes ($BF_{10} = 2.777$; $p_{tukey} = .026$) and controls ($BF_{10} = 7.832$; $p_{tukey} = .018$), whereas no group difference was found between interceptive sport athletes and controls ($BF_{10} = 0.280$; $p_{tukey} = .978$) (Figure 4c, 4d).

## 4. Discussion

Previous studies examining athletic cognitive superiority have often focused on cognitive measures at the mean-level such as accuracy or mean RTs. However, contradictory findings have been reported, possibly because intra-individual differences have not been considered (MacDonald, Nyberg, & Bäckman, 2006). As a result, it leaves unanswered the question of whether the time course of cognitive functioning provide a better account of cognitive individual differences associated with sports expertise, which can be particularly interesting given the dynamic nature of sport. We therefore assessed resilience capacity via SFT, which analyzes and compares the entire RT distribution of each condition rather than merely the mean, to infer the process dynamics of inhibitory control during a go/nogo task. The principal and novel results of this study are that (1) interceptive sports athletes exhibited faster mean RTs than non-athletes selectively in the single-target condition which demands perceptual conflict; (2) strategic sports athletes showed super-capacity processing over earlier responses, whereas interceptive sports athletes and non-athletes tended to exhibited unlimited-capacity processing across overall responses; and (3) greater resilience capacity over earlier responses was found in strategic sports athletes relative to interceptive sports athletes and non-athletes. Together, these findings suggest that interceptive sports athletes exhibit superior processing speed to deal with distracting information, while strategic sports athletes exhibit greater workload capacity for multiple signal processing. The present study provides evidence that analysis of resilience capacity via SFT can yield new insights into the cognitive advantage of athletes that were opaque to mean RT measures. We further discuss these findings hereafter.

Previous meta-analyses on mean measures have shown superior domain-general cognition of open-skill sports athletes, in particular for those practicing interceptive sports (Voss et al., 2010). As most previous studies that contributed to these observations merely focused on basic processing speed and visual attentional processing, this study extends prior research by investigating inhibitory control, which is essential in open-skill sports (Hsieh, Kao, & Wang, 2022). Interestingly, although no group differences in response accuracy or commission error were observed, interceptive sports athletes showed faster RTs in the single-target condition which simultaneously presents evidence pointing to "go" and "no-go" decisions, suggesting that long-term training experience in interceptive sports may be associated with improved processing speed during the condition involving conflict suppression. This finding is in line with previous studies using inhibitory control tasks

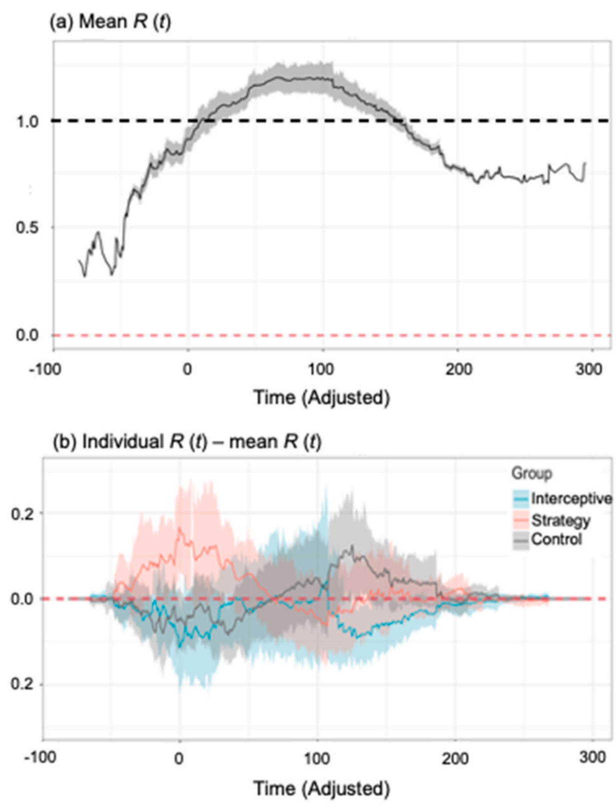


**Fig. 3.** The two figures allow for the inspection of group-level trends and variability across different groups, respectively. (a) All participants' data were averaged to estimate the overall trend of the resilience capacity function. Figure 3a illustrates the mean capacity function and 95% CIs averaged cross all participants. Note that this mean capacity function is based on the individual calculated functions. (b) In order to evaluate the individual variance relative to the mean capacity function, the subtraction of the mean capacity function from each participant was conducted to acquire the mean centered capacity function. Figure 3b illustrates the mean subtracted capacity functions and their 95% CIs for each group. Blue line indicates the capacity function for interceptive sports athletes, red line indicates the capacity functions for strategic sports player, and black line indicates the capacity function for non-athletic controls.

tapping perceptual conflict (e.g., the flanker task) (Wang et al., 2017; Wang, Liang, & Moreau, 2020) and response inhibition (Simonet et al., 2022). For example, Yu and Liu (2021) observed that interceptive sports athletes showed overall faster RT and lower flanker effect as compared to strategic sports athletes and non-athletes. Further, Wang et al. (2017) also found that interceptive sports athletes displayed faster RTs than closed-skill sports athletes selectively in the incongruent flanker condition. Moreover, Simonet et al. (2022), using a domain-general go/nogo task, observed that interceptive sports athletes showed overall faster mean RTs as compared to strategic sports and closed-skill sports athletes. Taken together, our results of mean RTs replicate earlier findings and suggest superior inhibitory control in athletes practicing interceptive sports. Such cognitive advantage was not found in strategic sports athletes, however, consistent with many previous studies (Alves et al., 2013; Pesce et al., 2007; Wylie et al., 2018), probably due to the fact that the mean-level measures are not sensitive enough to probe the relevance of the specific cognitive profile of strategic sports athletes (Wang, Lin, et al., 2020). For example, the analysis of a single value of mean RT might not be able to reveal the time-varying changes associated with individual cognitive differences.

In order to better elucidate and characterize the cognitive features of athletes, we used a non-parametric workload capacity measures underlying inhibitory control, the resilience capacity (Little et al., 2015), which exploits information from the overall empirical RT distribution and may thus achieve higher sensitivity than measures of central tendency alone (Townsend & Nozawa, 1995). The results of *R* (*t*) scores revealed a group difference in cognitive processing system. Strategic sports athletes generally exhibited super-capacity to unlimited-capacity processing from faster to slower responses, suggesting that the processing time of an individual channel sped up when making faster responses in response to increased workload. In contrast, interceptive sport athletes and non-athletes displayed unlimited-capacity processing when processing multiple signals, suggesting that individual-channel processing time was unaffected with increasing workload. Specifically, we further used the fPCA analysis to provide more direct evidence for making inference about the group difference in resilience capacity and found greater resilience capacity over faster responses in strategic sports athletes compared to interceptive sports athletes and non-athletes, whereas no such effect was seen over middle to later responses. These findings suggest that athletes practicing strategic sport type may process multiple sources of information in a more efficient manner, especially when making quicker responses.

It is worth pointing out that the difference in cognitive processing system could be associated with the individual difference in the processing order of multiple signals, despite that they are independent measures of information processing (Townsend & Nozawa, 1995). To elaborate, given that a coactive system is commonly assumed to show super-capacity, the strategic sports athletes appeared to process redundant information in a coactive fashion. That is, signals from multiple channels were processed simultaneously and in parallel, and separate activations from each channel were accumulated and integrated into a single accumulator, resulting in more efficient decision. By contrast, interceptive sports athletes and non-athletes exhibited unlimited-capacity processing, implying that they had less capacity for effective multiple-signal processing such that they are more likely to process multiple signals independently. That is, activation from the two channels may be processed simultaneously but compete for the decision independently.

Previous research using SFT and electroencephalographic (EEG) on soccer players may provide supportive evidence corroborating our behavioral observations, with findings showing that only soccer players but not non-athletes elicited enhanced and earlier P3 as well as greater oscillatory alpha phase coherence during the processing of redundant-target relative to the processing of single-target condition (Wang, Lin, et al., 2020). The authors suggest that the two targets in the redundant-target condition may concurrently contribute to the joint representation, resulting in the evident modulation of neural activities and greater workload capacity observed in the soccer players. In contrast, the redundant information was not processed coactively in the non-athletes, which could presumably be explained by the race model (Mishler & Neider, 2017), in which the two target features race against each other for a decision. Moreover, the authors also suggest another interpretation for the group difference in neural activities: soccer players were more likely to attend to the two target features simultaneously (i.e., both the target color and the target shape), thus resulting in more information being processed. In contrast, controls might tend to specifically focus on one of the target features (i.e., eighter the target color or the target shape), and thus the less attended target feature do not contribute to further processing. If this was the case in the present study, we conjecture that the perceptual-cognitive expertise of strategic sports may be more closely related to a greater ability to process and integrate multiple sources of information, which may also reflect their need or tendency to adopt the processing strategy for concurrently processing a series of complex information, in order to make an optimal decision during real-world game playing. Nevertheless, future investigations are required to confirm these assumptions, by investigating whether interceptive and strategic sports athletes show different patterns of neural modulation according to the variance in perceptual workload.

It is worth noting that despite some positive associations between cognitive and athletic performance (Scharfen & Memmert, 2019;

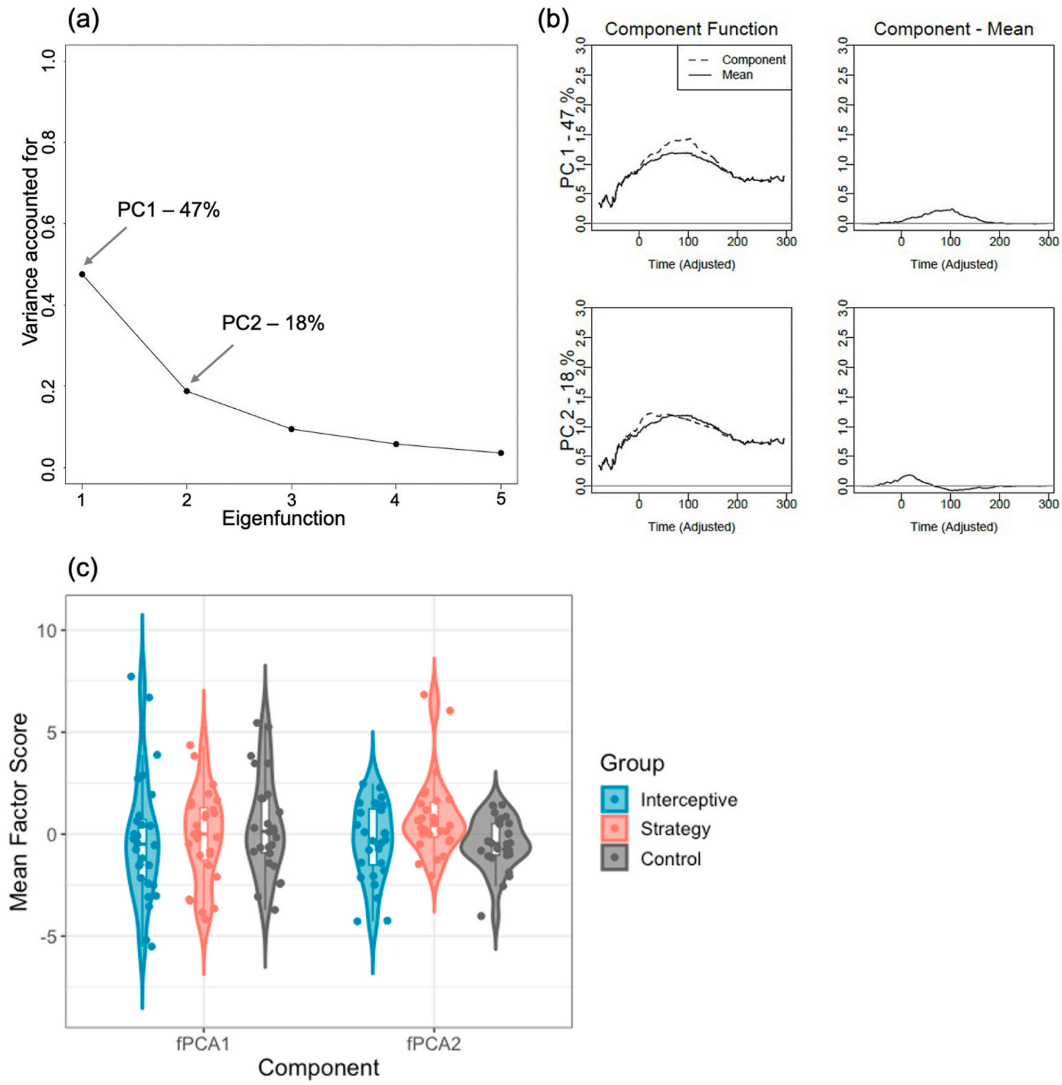


**Fig. 4.** (a) A screen plot showing the amount of variance accounted for by each Eigen function, ordered from highest to lowest. (b) The first two principal components of the capacity function. The left column shows the component functions, weighted by the average magnitude of the factor score, compared to the mean. The right column shows the component function weighed by the average magnitude of the factor score. (c) Violin plots for the distribution of *f*PCA components from each group together with the mean (box central dot), median (box central line), first and third quartile (box edges), minimum and maximum (whiskers), and each participant (dots).

Vestberg, Gustafson, Maurex, Ingvar, & Petrovic, 2012), the results of a recent meta-analysis including ten prospective studies did not support this argument, showing insufficient evidence to determine whether cognitive performance is a valid index to predict future sport performance (Kalén et al., 2021). Indeed, one recent longitudinal study found that soccer players' EFs developmental trajectories follow those of general populations, despite their extensive experience in professional training and game play (Beavan et al., 2020). Our analysis of multiple levels of RT data offers novel evidence in the study of the cognitive advantage of athletes practicing open-skill sports. The finding that superior processing speed in interceptive sports athletes and greater workload capacity in strategic sports athletes underlying inhibitory control processes may reflect the differential cognitive demand and characteristics inherent in different sport types. Moreover, some previous studies argued that athletes from different types of sport may have their own dominant cognitive function (Jacobson & Matthaeus, 2014; Yongtawee, Park, Kim, & Woo, 2022); for example, interceptive sports athletes were shown to exhibit superior visuospatial functioning and processing speed, while athletes of strategic sports yielded better executive functions (Yongtawee et al., 2022). Therefore, the present findings may help explain the inconsistent associations between sport expertise and cognition across studies, and provide a new and valuable perspective for expanding our understanding of perceptual-cognitive expertise in athletes.

Some study-specific limitations that should be acknowledged. First, although our findings suggest that the individual difference associated with sports expertise in workload capacity could be related to some extent to the difference in processing architecture (e.g., the way that redundant information is processed), the two measures are independent indexes of information processing and thus cannot provide direct evidence to support this claim (Townsend & Nozawa, 1995). That is, greater workload capacity seen in strategic sports athletes do not necessarily mean that they adopt different processing strategies from interceptive sports athletes. Second, this study only used one type of redundant-target tasks such that our findings cannot infer whether athletes' workload capacity performance may vary depending on the nature of tasks. Given that athletes with different domains of expertise may favor different aspects of cognition (Jacobson & Matthaeus, 2014; Yongtawee et al., 2022), it would be interesting to explore whether the type of cognitive function may affect the relationship between workload capacity and sports expertise. Finally, one weak point of our study is the absence of prospective design so that we could only speculate about the reasons for our results and cannot exclude other confounding factors. Moreover, it would be possible that the cognitive superiority of athletes seen in this study is due to predispositions that lead these individuals to practice or choose the specific sport type. For example, the individual differences reported in this study might at least partially reflect some genetic, personality, or physical fitness differences. To alleviate this concern, given that exercise or sport interventions involving open-skills have been demonstrated to have the capacity to produce evident cognitive gains (Chou et al., 2023; Moreau, Morrison, & Conway, 2015), future studies might benefit from employing randomized controlled trials (RCTs) to determine how different types of cognitive measure could be differentially related to future sporting performance. Despite these limitations, our study has the merit of being the first to examine the utility of SFT-derived workload capacity measure to refine our understanding of cognitive feature of open-skill athletes, yet further research is needed before we can reliably establish that workload capacity is an effective tool in applied settings.

## 5. Conclusion

The novelty of this study was to examine the sports expertise effect on inhibitory control performance by using multiple levels of RT analysis. The mean RT finding corroborates previous evidence by showing superior processing speed in athletes practicing interceptive but rather strategic sports in the condition inducing perceptual conflict. When the overall RT dynamics were considered via the analysis of SFT, we showed for the first time that strategic sport athletes exhibited greater workload capacity over earlier responses compared to interceptive sport athletes and physically active non-athletes, which may reflect their flexibility and efficiency in processing information from multiple sources in an integrative approach. These findings suggest that the two types of open-skill sports may be associated with different processing specificity, possibly resulting from their own specific rules and requirements (e.g., the complexity and the speed of the game). Collectively, the joint consideration of the mean and distribution of RT data provides a better picture of the cognitive characteristics of athletes practicing open-skill sports, which may help reconcile previous discrepancies in the literature.

## Declaration of competing interest

We declare no competing finical interests.

## Data availability

In accordance with guidelines of the HREC, the data acquired in the present study cannot be shared with researchers without the written re-consent of the participants.

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