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Proactive and Reactive Motor Inhibition in Top Athletes Versus Nonathletes

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Abstract

We examined proactive (early restraint in preparation for stopping) and reactive (late correction to stop ongoing action) motor response inhibition in two groups of participants: professional athletes ($n = 28$) and nonathletes ($n = 25$). We recruited the elite athletes from Belgian national taekwondo and fencing teams. We estimated proactive and reactive inhibition with a modified version of the stop-signal task (SST) in which participants inhibited categorizing left/right arrows. The probability of the stop signal was manipulated across blocks of trials by providing probability cues from the background computer screen color (green = 0%, yellow = 17%, orange = 25%, red = 33%). Participants performed two sessions of the SST, where proactive inhibition was operationalized with increased go-signal reaction time as a function of increased stop-signal probability and reactive inhibition was indicated by stop-signal reaction time latency. Athletes exhibited higher reactive inhibition performance than nonathletes. In addition, athletes exhibited higher proactive inhibition than

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nonathletes in Session 1 (but not Session 2) of the SST. As top-level athletes exhibited heightened reactive inhibition and were faster to reach and maintain consistent proactive motor response inhibition, these results confirm an evaluative process that can discriminate elite athleticism through a fine-grained analysis of inhibitory control.

Keywords
motor response inhibition, elite athleticism, fencing, taekwondo

Introduction

Motor response inhibition refers to the ability to stop a planned or ongoing action when it interferes with updated goal-driven behaviors (Aron, 2011; Aron, Robbins & Poldrack, 2004; Baddeley, 1996; Logan, 1985, 1994; Verbruggen & Logan, 2009a, 2009b). This process is especially important when the individual is embedded in a constantly changing environment that requires rapid adaptation to stop a motor response that has become inappropriate or unwanted (Aron, 2011; Verbruggen & Logan, 2009a, 2009b); examples of such an environment are during the enactment of elite athletic performances in high-level sports competition (Moran, 2009; Swann, Moran, & Piggott, 2015).

Several studies have shown that elite athletes exhibit a heightened capacity for motor response inhibition, as compared with nonathletes (Di Russo, Taddei, Apnile, & Spinelli, 2006; Kida, Oda, & Matsumura, 2005; Nakamoto & Mori, 2008a; Yamashiro et al., 2015; D. Zhang, Ding, Wang, Qi, & Luo, 2015), and this skill difference has been shown to vary according to the level of sport expertise (Chan, Wong, Liu, Yu, & Yan, 2011; Huijgen et al., 2015; Verburgh, Scherder, Van Lange, & Oosterlaan, 2014, 2016; Vestberg, Reinebo, Maurex, Ingvar, & Petrovic, 2017) with top-level athletes displaying greater motor inhibition than lower level athletes. There have also been skill variances with different types of sports, with a higher motor response inhibition capacity observed in *open loop* as compared with *closed loop* sports (Jacobson & Matthaeus, 2014; Wang et al., 2013). Open-loop sports (fencing, tennis, and basketball) contrast with closed-loop sports (swimming, track, and field running) in that they are practiced in faster changing and more unpredictable environments, requiring athletes to frequently face and more quickly resolve conflicts between a go/no-go response in order to adapt optimally to game circumstances (Jacobson & Matthaeus, 2014; Nuri, Shadmehr, Ghotbi, & Attarbashi Moghadam, 2013; Wang et al., 2013).

Less well understood from past literature is whether or not top-level athletes exhibit enhanced ability in both *proactive* and *reactive* inhibition. These two components refer to distinct temporal dynamic modes of motor response inhibition (Aron, 2011; Braver, 2012; Braver, Paxton, Locke, & Barch, 2009).

Proactive inhibition refers to a form of early selection in which goal-relevant information is actively monitored to optimally bias attention, perception, and action systems to facilitate response inhibition as needed; proactive inhibition is used to strategically restrain actions in preparation for stopping (slowing down while driving in a school zone; Aron, 2011; Braver, 2012; Braver, Gray, & Burgess, 2007; Braver et al., 2009). By contrast, reactive inhibition is a late correction process, triggered by external signals (braking when a pedestrian suddenly crosses the street) and results in actual stopping of the ongoing action (Aron, 2011; Braver, 2012; Braver et al., 2007, 2009). Proactive inhibition has often been described as less effortful and more efficient than reactive inhibition (Aron, 2011; Duckworth, Gendler, & Gross, 2016; Fujita, 2011; Galla & Duckworth, 2015). Under proactive control, the stopping mode is preactivated by preparing to stop, which makes stopping easier when it is needed (Aron, 2011; Chikazoe et al., 2009; Jahfari, Stinear, Claffey, Verbruggen, & Aron, 2010). Thus, proactive inhibition might be key to the ability to refrain from behavioral tendencies in anticipating the need to stop, such as when an athlete has to adapt to cues signaling different levels of motor cautiousness (in martial arts: the athletes should be able to adapt their level of proactive control according to the stances adopted by the opponent when attacking, defending, advancing, or retreating).

Increased efficiency in anticipatory and preparatory action processes has been repeatedly highlighted as an advanced skill in elite athletes (Alder, Ford, Causer, & Williams, 2016; Balser et al., 2014; Del Percio et al., 2008; Di Russo, Pitzalis, Aprile, & Spinelli, 2005; Hung, Spalding, Maria, & Hatfield, 2004; Ida, Fukuhara, Ishii, & Inoue, 2013; Piras, Lobietti, & Squatrito, 2015; Rosalie & Müller, 2014; J. Zhang et al., 2013). Moreover, Bianco, Di Russo, Perri, and Berchicci (2017) highlighted enhanced suppression of prestimulus motor activity during a go/no-go paradigm in professional boxers and fencers, pointing to an improved general proactive control mechanism that prevents premature responding (Verbruggen & Logan, 2017). However, these studies did not focus specifically on proactive motor response inhibition, that is, a slowdown in responding as the probability of encountering a stop event increases (Aron, 2011; Verbruggen & Logan, 2009a; Zandbelt, Van Buuren, Kahn, & Vink, 2011). This process can be estimated using the stop-signal paradigm. Specifically, in the stop-signal task (SST), the go cue always precedes the stop signal, whereas in the go/no-go task the stop signal is presented unexpectedly in place of the go signals. Thus, the stop-signal paradigm permits both measurement of the inhibition of an already started action (i.e., action cancellation of a fast go response) and the alteration or inhibition of a planned response (i.e., action restraint of any fast go response; Bari & Robbins, 2013; Eagle, Bari, & Robbins, 2008; Schachar et al., 2007; Verbruggen & Logan, 2017). Another important difference between these paradigms is that the go/no-go task only offers general measures of proactive and reactive inhibition, whereas the SST allows researchers to measure both the latency and efficacy of reactive inhibition: (a) the stop-signal reaction time (SSRT) latency and (b) the level of proactive adjustment or slowdown in responding as the probability of encountering a stop event increases (Aron, 2011; Bari & Robbins, 2013; Verbruggen & Logan, 2009a, 2017; Zandbelt et al., 2011).

Importantly, proactive response inhibition during the SST has already been shown to discriminate between different populations (Kleerekooper et al., 2016; Van Rooij et al., 2014; Zandbelt et al., 2011). Zandbelt et al. (2011) showed that, in comparison with control participants, patients with schizophrenia exhibited reduced proactive inhibition but not different reactive inhibition. More specifically, as compared with controls, patients with schizophrenia failed to slow down or respond to increased probabilities for the need to stop (i.e., reduced proactive inhibition). In another study, Van Rooij et al. (2014) showed that war veterans with post-traumatic stress disorder (PTSD) showed reduced reactive inhibition (i.e., slower SSRT), as compared with nonmilitary controls. The veterans with PTSD also exhibited impaired behavioral proactive inhibition. More recently, Kleerekooper et al. (2016) showed that aging was associated with both lower proactive and reactive inhibition abilities. Together, these findings emphasize that investigating both reactive and proactive inhibition offers a nuanced, discriminative, and fine-grained analysis of inhibitory control in top-level athletes.

Thus, this study tested proactive and reactive motor response inhibition in athletes. We recruited top-level athletes from taekwondo and fencing, which require heightened reactive motor response inhibition and others aspects of motor control (Chan et al., 2011; Diamond & Lee, 2011; Lakes et al., 2013; Sanchez-Lopez, Fernandez, Silva-Pereyra, Martinez Mesa, & Di Russo, 2014; Sanchez-Lopez, Silva-Pereyra, & Fernandez, 2016; Van Dijk et al., 2013; D. Zhang et al., 2015). More specifically, these two disciplines constantly challenge athletes' abilities to rapidly stop planned responses (in response to movements initiated by opponents), both in terms of strategic proactive and more automatic reactive patterns of motor response inhibition. We used a SST that required participants to inhibit categorizing left and right arrows. The probability that a stop signal would occur was manipulated across blocks of trials in which the background screen color cued participants of the probability of the need to stop (green = 0%, yellow = 17%, orange = 25%, red = 33% of stop signal). We operationalized proactive inhibition with participants' increased go-signal reaction time (RT) as a function of the stop-signal probability level (Verbruggen & Logan, 2009b; Zandbelt & Vink, 2010; Zandbelt et al., 2011). In other words, proactive inhibition was reflected by participants' slower responses as the probability that they might have to stop increased. Reactive inhibition was operationalized by SSRT or the latency of the inhibition process (Verbruggen & Logan, 2009b). Higher SSRTs reflect worse reactive inhibitory control (slower inhibitory processes). Because elite athletes have been repeatedly shown to exhibit increased efficiency in motor inhibition processes, we hypothesized that, as compared with non-athlete controls, top-level athletes would exhibit higher capacities for proactive (a higher increase of go-signal RT as a function of the level of stop-signal probability) and reactive (a shorter SSRT) motor response inhibition.

Method

Participants

We recruited top-level athletes for this study from Belgian national fencing and taekwondo teams. This sample of elite athletes was selected with the help of the Royal Belgian Federation of Fencing Clubs and the Belgian Taekwondo Federation. This collaboration allowed us to recruit 14 fencers and 13 taekwondoka competitors, yielding a total sample of 27 professional athletes (Mean age = 19.21, *SD* = 3.58; Range: 15–29 years; men = 23, women = 4; see also Table 1 for information on fencing/taekwondo experience and rankings). We recruited nonathletes ($n = 25$) from among individuals in the community who did not exercise or practice any sport on a regular basis (i.e., less than once per week). Nonathletes were nearly matched on age and gender with the sample of top-level athletes (Mean age = 20.07, *SD* = 3.89; Range = 15–30 years; men = 22, women = 3). All participants had normal or corrected-to-normal visual acuity and were right handed. Participants were not remunerated for their participation. The research protocol was approved by the CHU-Brugmann University Hospital Institutional Review Board.

Power Analysis

Necessary sample size was computed a priori (using G*Power 3.1.9.2; Faul, Erdfelder, Lang, & Buchner, 2007) for repeated measures analysis of variance (ANOVA; effect size $f = 0.20$; α error probability = 0.05; Power ($1 - \beta$ error probability) = 0.95; two measurements; two groups; maximum correlation among repeated measures = 0.74; nonsphericity correction, $\varepsilon = 1$). This analysis indicated that at least 23 participants were required in each group (46 subjects in total) to detect a within–between interaction effect with a small effect size. This sample size is similar to those used in previous studies that have examined motor response inhibition in top-level fencers (Chan et al., 2011; D. Zhang et al., 2015).

Stop-Signal Task

Paradigm and design. Participants performed two sessions of a modified SST (see Figure 1), a paradigm adapted from previous SST designs (Brevers, He, Keller,

Table 1. Demographics and Indices of Sport Expertise in Top-Level Athletes.

Discipline	Subject	Gender	Age	Years of practice	Class/ Category	Ranking/Most important results	Belgian ranking 2016/2017
Fencing	1	Male	25	18	Foil	184th at the world ranking	1st Senior
	2	Male	16	9	Foil	110th at the world ranking (junior)	5th Junior
	3	Male	17	11	Foil	520th at the world ranking	4th Junior
	4	Male	18	13	Foil	275th at the world ranking	2nd Junior
	5	Male	17	12	Foil	329th at the world ranking	3rd Junior
	6	Male	17	7	Foil	472th at the world ranking	1st Junior
	7	Male	21	11	Foil	273th at the world ranking	2nd Senior
	8	Male	19	10	Foil	279th at the world ranking	1st Junior
	9	Male	21	11	Sabre	145th at the world ranking	2nd Senior
	10	Female	20	12	Sabre	218th at the world ranking	1st Senior
	11	Male	21	11	Sabre	389th at the world ranking	5th Senior
	12	Male	15	7	Sabre	471th at the European ranking (junior)	16th Junior
	13	Male	15	4	Sabre	129th at the European ranking (junior)	12th Junior
	14	Male	15	4	Sabre	464th at the European ranking (junior)	–
Taekwondo	15	Male	17	10	−59 kg	International championships: 9 wins	4th Junior
	16	Female	15	9	−46 kg	International championships: 6 wins, 5th at the European championship	4th Junior

(continued)

Table 1. Continued

Discipline	Subject	Gender	Age	Years of practice	Class/ Category	Ranking/Most important results	Belgian ranking 2016/2017
	17	Male	21	10	−54 kg	International championships: 13 wins, 3rd at the world ranking, Europe Champion, Olympic athletes	1st Senior
	18	Male	19	9	−68 kg	Ranked, 56th at the world ranking, International championships: 26 wins, Europe Champion, Olympic athletes	2 e Senior
	19	Male	16	7	−59 kg	International championships: 6 wins	5 e Junior
	20	Male	15	7	−55 kg	International championships: 7 wins	2 e Junior
	21	Male	29	20	−55 kg	3 times Belgian Champion	–
	22	Male	23	11	−87 kg	3 times Belgian Champion	3 e Senior
	23	Male	23	11	−87 kg	International championships: 1 win	15th Senior
	24	Female	24	15	−59 kg	International championships: 1 win	1st Senior
	25	Male	20	15	−80 kg	International championships: 0 win	–
	26	Female	16	3	−52 kg	International championships: 9 win	2nd Junior
	27	Male	22	14	−64 kg	1 time Belgian Champion	17th Senior
	28	Male	21	17	−58 kg	1 time Belgian Champion	1st Senior

Noël, & Bechara, 2017; Brevers, Bechara, et al., 2017; Verbruggen & Logan, 2009a; Zandbelt & Vink, 2010; Zandbelt et al., 2011; Zandbelt, Bloemendaal, Neggers, Kahn, & Vink, 2013). Stimulus presentation and timing of all stimuli and response events were scripted using Matlab 7.14 (Mathworks Inc., Natick, MA, USA) and Psychtoolbox 3.0.12 (www.psychtoolbox.org) on a 15-inch MacBook Pro.

In this task, participants had to discriminate, as quickly as possible, between right and left arrows. Participants categorized right and left arrows by pressing the *right arrow* or the *left arrow* key on an AZERTY keyboard with the index and middle fingers of their right hand, respectively. Subjects were asked to stop their keyboard responses when they heard a tone (stop signal). During the experiment, stop-signal delay (SSD; the interval between trial onset and the presentation of the stop signal) was continuously adjusted, separately for right and left arrows, according to a tracking procedure to obtain a probability of stopping of .50 (Logan 1994); if a stop response was successful, then stopping was made more difficult on the next stop trial by increasing SSD by 25 ms. The process was reversed when a stop response failed.

The probability that a stop signal would occur was manipulated across trials and was indicated by the color of the computer screen background: 0% (green), 17% (yellow), 25% (orange), and 33% (red). In order to optimize the impact of each context of stop-signal probability (i.e., green, yellow, orange, red) on proactive inhibition, we divided trials into blocks of 9, 18, or 27 trials in a same context (participants were informed that each context change occurred when a gray screen appeared). Specifically, in a pilot version of the task, we observed that RT difference between the different contexts of stop-signal probability was lower when the background color varied from trial to trial. The proportion of misses on go-signal trials was also increased. One explanation is that changing the background color on each trial of the SST required the participants to reinitiate context identification on every trial, which might have lowered proactive adjustment between each context of stop-signal probability in our SST.

In the current SST, each trial started with the presentation of the probability level cue for 1,100 ms (Figure 1(b)). Each picture then appeared for 1,250 ms (Figure 1(c)), regardless of the participants' picture categorization RT. Each probability level change was separated by a 3,350-ms gray screen (Figure 1(a)). Block length was randomized with the restriction that there was no repetition of a same probability context and that blocks of 9, 18, and 27 trials occurred with equal probability. In total, 350 go-signal trials and 82 stop-signal trials were presented in a single run in pseudorandom order (total = 432 trials).

Selection of initial SSD value. The SSD initial value used was 550 ms based on repeated observations made during pilot testing of the task (i.e., before running the behavioral task validation included in the article). Specifically, on the one hand, we observed that the probability of response on stop signal, *p*(responding), was not optimal (<.40) when using a shorter period, such as 250 ms

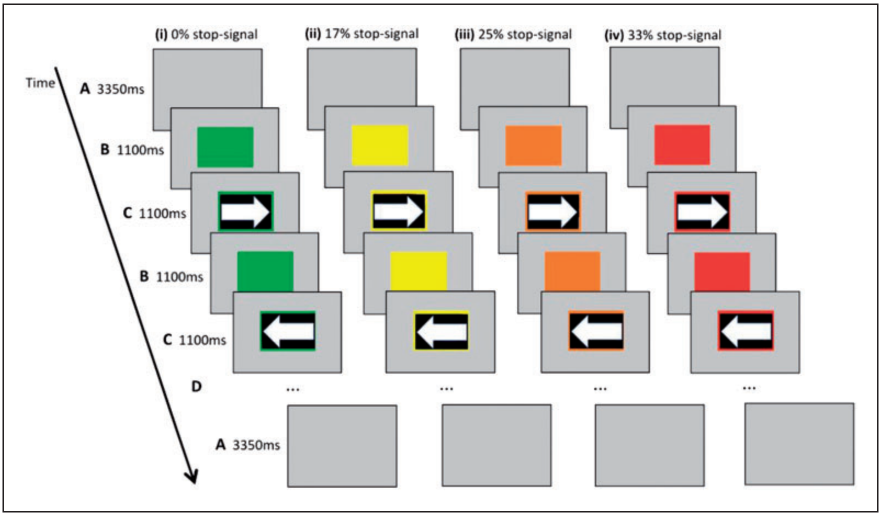

Figure 1. An example of a succession between a neutral and a poker picture in the (i) green (0% stop signal), (ii) yellow (17% stop signal), (iii) orange (25% stop signal), and (iv) red (33% stop signal) contexts of the stop-signal task. (a) Each context change was separated by a 3,500-ms gray screen. (b) Each trial started with the presentation of the context cue for 1,100 ms. (c) Each picture then appeared during 1,250 ms, regardless of participants' categorization reaction time. (d) Trials were divided into runs of 9, 18, or 27 trials in a same context.

(i.e., the first half of the SST was too easy). This might be explained by the complexity of the task induced by the processing of the context cue (green, yellow, orange, or red) in addition to arrows categorization and reactive response inhibition processes (see also Yamaguchi, Logan, & Bissett, 2012). Noteworthy, in one of our experiments using similar SST but with more complex stimuli categorization (cannabis or gambling vs. neutral pictures), an initial SSD value of 800 ms was optimal for obtaining a mean *p*[respond|signal]) (pooled across the yellow, orange, and red contexts) that approximates .50 (Brevers, Bechara, et al., 2017; Brevers, He, et al., 2017). In summary, when using 550 ms as initial SSD value, we obtained a mean *p*[respond|signal]) (pooled across the yellow, orange, and red contexts, approximation of .50, and with an acceptable level of miss on go trials (< 10 % across all trials).

Procedure

All participants were tested individually within a quiet room. For the athletes, we made sure that the testing session did not occur during or after one of their daily fencing/taekwondo training sessions. Participants were first provided written informed consent. They were then given the following SST instructions (based on previous works by Zandbelt et al., 2010, 2011):

- Categorize left and right arrows as quickly as possible, unless you hear a *beep* sound while the picture appears on the screen.
- Performance accuracy on the go-signal task and SST are equally important. It may not always be possible to suppress a response when a stop-signal occurs.
- Stop-signals will never appear on trials with a green cue, and stop-signals could occur on trials with non-green cues. Stop-signals will be least likely in the context of a yellow cue and most likely in the context of a red cue, with orange cues signaling intermediate stop-signal probability.

Participants performed the SST while sitting in a chair, with the 15-inch laptop placed on the table in front of them. Throughout the SST, participants were asked to keep the index and middle fingers of their right hand on the *right arrow* or the *left arrow* key of the AZERTY keyboard. Participants first received a computerized practice session in order to familiarize them with the SST. Specifically, we needed to be sure that participants understood that it was equally important to be fast on go-signal trials and to inhibit their motor response on stop-signal trials. An experimenter remained alongside the participants during the training in order to ensure task comprehension. The training consisted of nine trials for each of the four stop-signal probability levels (total of 36 trials: 9 go-signal trials under the green context; 8 go-signal trials and 1 stop-signal trial under the yellow context; 7 go-signal trials and 2 stop-signal trials under the orange context; and 6 go-signal trials and 3 stop-signal trials under the red context). Then, participants performed the SST a first time (Session 1). After a 60-s break, participants performed the SST a second time (Session 2). Importantly, the initial SSD value for Session 2 was adapted from the last SSD value from Session 1. This procedure was implemented to ensure continuity in task performance between Sessions 1 and 2.

Data Analyses

Data were analyzed using custom software in Matlab 7.14 (Mathworks Inc., Natick, MA, USA) and SPSS 24 (SPSS, Inc., Chicago, IL, USA). In keeping with previous studies (Van Rooij et al., 2014; Zandbelt et al., 2010, 2011) a single-value behavioral index was used to estimate proactive inhibition. Specifically, we used the stop-signal probability slope (Zandbelt et al., 2011), defined as the change in go-signal trial response times (in milliseconds) per stop-signal probability unit increase. The stop-signal probability slope was estimated separately for Sessions 1 and 2 of the SST. Reactive inhibition was indexed by the SSRT, a measure of the latency of the inhibition process. The SSRT was obtained through the integration method (Verbruggen & Logan, 2009b) and pooled across stop-signal probability levels > 0% (yellow, orange, red; based on Zandbelt et al., 2010, 2011). The integration method involves subtracting the mean SSD from *n*th RT (with *n* equal to the number of RTs in the RT distribution) multiplied by the overall *p*[respond|signal]). The SSRT was estimated separately for Sessions 1 and 2 of the SST. We defined outliers as go trials with response times more than 1.5 times away from the interquartile range of the 25th and 75th percentiles of the response time distribution of each stop-signal probability level.

Because of atypical SST participant performance, data from six participants (four athletes and two controls) were excluded as outliers, yielding data from 24 athletes and 23 nonathletes for further analyses. Two outliers gave extreme scores on SSRT for Session 1 (i.e., 35 ms, 357 ms), and outliers gave an extreme score on SSRT for Session 2 (i.e., 57 ms). Three outliers had extremely high RT for stimuli categorization in the green context (i.e., 851 ms, 871 ms, 945 ms). Importantly, within-group and between-groups effects were unchanged whether or not these six subjects were included in data analyses. Statistical analysis of proactive inhibition (influence of stop-signal probability on go-signal response time) consisted of a repeated-measures ANOVA on stop-signal probability slope, with session (1 vs. 2) and group (athletes vs. nonathletes) as factors. Statistical analysis of reactive inhibition (stopping latency) involved repeated-measures ANOVA on SSRTs, with session (1 vs. 2) and group (athletes vs. nonathletes) as factors.

Results

Proactive Inhibition

Preliminary analyses. First, in the total participant sample ($N = 47$), we aimed to test whether go-signal trials RT (in milliseconds) were modulated by the level of stop-signal probability, separately for both Sessions 1 and 2. Because of non-normal RT distributions in the orange and red contexts, Wilcoxon Signed Ranks Tests were performed with the following within-subject comparisons: green versus yellow, yellow versus orange, and orange versus red. For Session 1, these analyses revealed that go-signal response RT was higher in the yellow context (mean rank = 24.00) than in the green context (mean rank = 0.00; $Z = -5.97$, $p < .001$), in the orange context (mean rank = 24.53) than in the yellow context (mean rank = 22.87; $Z = -2.34$, $p = .019$), and in the red context (mean rank = 26.77) than in the orange context (mean rank = 10.50; $Z = -5.08$, $p < .001$). Similarly, in Session 2, go-signal response RT was higher in the yellow context (mean rank = 24.00) than in the green context (mean rank = 0.00; $Z = -5.97$, $p < .001$), in the orange context (mean rank = 26.55) than in the yellow context (mean rank = 18.00; $Z = -3.30$, $p = .001$), and in the red context (mean rank = 26.66) than in the orange context (mean rank = 12.78;

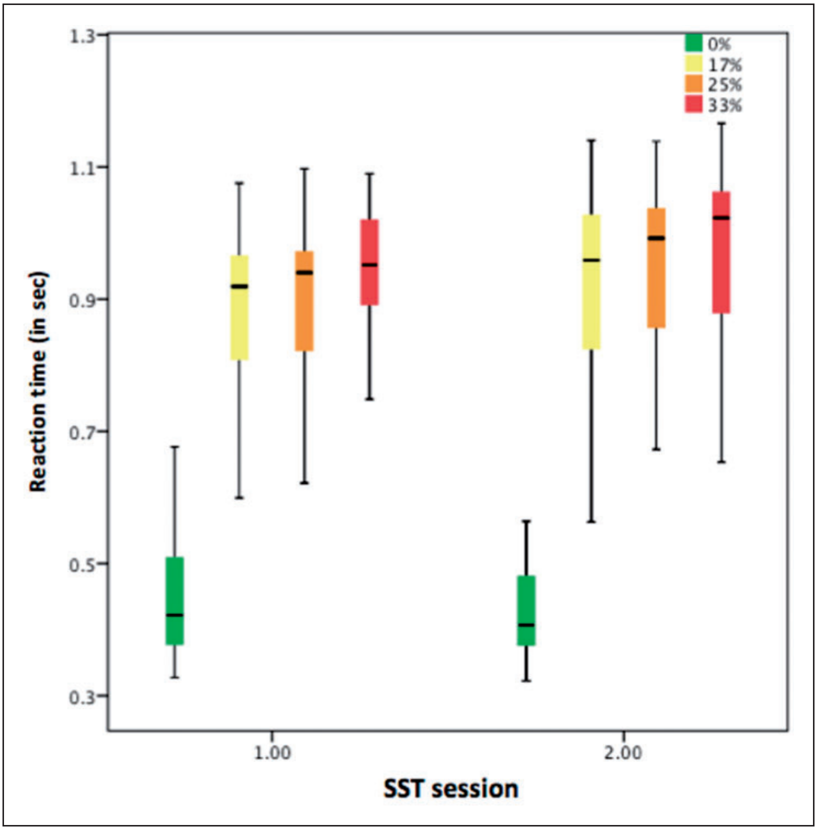

Figure 2. Median, interquartile ranges, and range on go-signal trials stimulus categorization reaction time in the green (0% of stop signal), yellow (17% of stop signal), orange (25% of stop signal), and red (33% of stop signal) contexts, separately for Session 1 and Session 2 of the SST. SST = stop-signal task.

$Z = -4.75$, $p < .001$). These results are depicted in Figure 2 (see also Table 2 for descriptive statistics on RT associated with each context).

Second, we wanted to examine the mean percentage of misses in both sessions. Mixed-model ANOVAs were used with level of stop-signal probability (green, yellow, orange, and red) and sessions (1 vs. 2) as within-subjects factors; groups (athletes vs. nonathletes) as between-subjects factors; and proportion of missed responses as dependent measure. These analyses revealed a main effect of stop-signal probability, $F(3,45) = 55.89$, $p < .001$, $\eta^2 = .55$, indicating that the proportion of misses increased with the level of stop-signal probability. There was no main effect of group, sessions, or any significant interaction

Table 2. Overview of Performance for the SST: Go-Signal RT (in Milliseconds), Probability of a Missed Go Response, p(miss), and Probability of Responding on Stop-Signal Trials, p(respond$|$signal), as a Function of Level of Stop-Signal Probability (0%–33%), SST Session (1, 2), and Group.

			Go RT		p(miss)		p(respond $|$signal)	
Group	Level of p(stop signal)	Session	Median	25th, 75th	Mean	*SD*	Mean	*SD*
Nonathletes	0	1	485	413,523	.003	.01	–	–
	0	2	461	407,490	.01	.01	–	–
	17	1	893	796,954	.08	.07	.46	.16
	17	2	947	797,1023	.09	.10	.54	.11
	25	1	908	815,975	.06	.07	.40	.12
	25	2	939	853,1037	.09	.13	.54	.11
	33	1	926	863,1008	.14	.08	.36	.08
	33	2	974	867,1059	.16	.12	.43	.08
Athletes	0	1	386	367,436	.004	.01	–	–
	0	2	387	356,409	.001	.004	–	–
	17	1	928	816,984	.06	.05	.52	.12
	17	2	990	825,1036	.08	.07	.56	.14
	25	1	950	867,972	.07	.06	.35	.15
	25	2	996	857,1049	.08	.09	.52	.08
	33	1	1,004	928,1031	.10	.10	.34	.10
	33	2	1,033	932,1090	.12	.13	.38	.12

25th, 75th = 25th and 75th percentile; RT = reaction time; *SD* = standard deviation; SST = stop-signal task.

(all $p > .14$). Overall, we observed that the proportion of misses was acceptable (Session 1: green = .00, yellow = .04, orange = .05, red = .09. Session 2: green = .00, yellow = .05, orange = .04, red = .09; see also Table 2).

Third, a repeated-measure ANOVA was undertaken with session (1 vs. 2) as the within-subjects factor and group (athletes vs. nonathletes) as the between-subjects factor, with categorization RT in the green context as the dependent measure. This analyses revealed a main effect of group, $F(1,45) = 11.82$, $p = .001$, $\eta^2 = .21$, indicating athletes ($M = 403$ ms; $SD = 65$) were faster than nonathletes ($M = 466$ ms; $SD = 71$) at categorizing left and right arrows. This indicates that athletes exhibited faster baseline level of response categorization than nonathletes. Based on this finding, categorization RT in the green context (for both Sessions 1 and 2) was added as a covariate in the subsequent repeated-measure ANOVA on stop-signal probability slope.

Stop-signal probability slope. Repeated-measure ANOVA (with categorization RT in the green context as a covariate) revealed a main effect of sessions, $F(1,45) = 18.15$, $p < .001$, $\eta^2 = .30$, indicating that proactive motor response inhibition was higher in Session 2 ($M = 12.07$ ms, $SD = 3.18$) than in Session 1 ($M = 11.20$ ms, $SD = 4.08$) of the SST. There was no main effect of group, $F(1,45) = 0.58$, $p = .45$, $\eta^2 = .01$, indicating that proactive inhibition was no different in athletes ($M = 11.97$, $SE = 0.43$) versus nonathletes ($M = 11.29$, $SE = 0.44$), when controlling for categorization RT in the green context. Importantly, a significant session and group interaction was observed, $F(1,45) = 6.08$, $p = .018$, $\eta^2 = .12$, indicating that the athletes exhibited higher proactive motor response inhibition than nonathletes in SST Session 1, but not in Session 2 (see Figure 3(a)).

Reactive Inhibition

Preliminary analyses. First, on the total participant sample ($N = 47$), we observed that the mean p[respond|signal]) was .41 ($SD = .07$) for Session 1 and .51 ($SD = .07$) for Session 2, indicating that the tracking procedure was optimal in the second session of the SST. Second, we examined the probability of responding on stop-signal trials according to the level of stop-signal probability. Mixed-model ANOVAs were used with level of stop-signal probability > 0% (yellow, orange, red) and sessions (1 vs. 2) as within-subjects factors; groups (athletes vs. nonathletes) as between-subjects factors; and probability of responding on stop-signal trials as dependent measure (see Table 2 for descriptive statistics). These analyses revealed a main effect of level of stop-signal probability, $F(2,45) = 27.76$, $p < .0001$, $\eta^2 = .38$, indicating that probability of responding on stop-signal trials decrease in function of stop-signal probability. There was a main effect of sessions, $F(2,45) = 67.17$, $p < .0001$, $\eta^2 = .59$, indicating that probability of responding on stop-signal trials was higher in Session 1 than in Session 2. There was no main effect of groups or any groups and sessions or groups and levels of stop-signal probability interaction (all $p > .10$). Third, repeated-measures ANOVA on RT, with session (1 vs. 2) and RT types (mean failed stop-signal vs. mean go-signal RT) as factors, revealed that the mean failed stop-signal RT (Session 1: $M = 809.10$, $SD = 123.37$; Session 2: $M = 866.80$, $SD = 158.83$) was lower than the mean go-signal RT (Session 1: $M = 921.30$, $SD = 97.91$; Session 2: $M = 954.80$, $SD = 133.78$; $F(1,45) = 423.59$, $p < .001$, $\eta^2 = .89$), which is a criteria for independence between the finish times of the *go* and the *stop* responses.

Stop-signal reaction time. Repeated-measure ANOVA of SSRTs revealed a main effect of group, $F(1,45) = 10.80$, $p = .002$, $\eta^2 = .19$, indicating that the elite

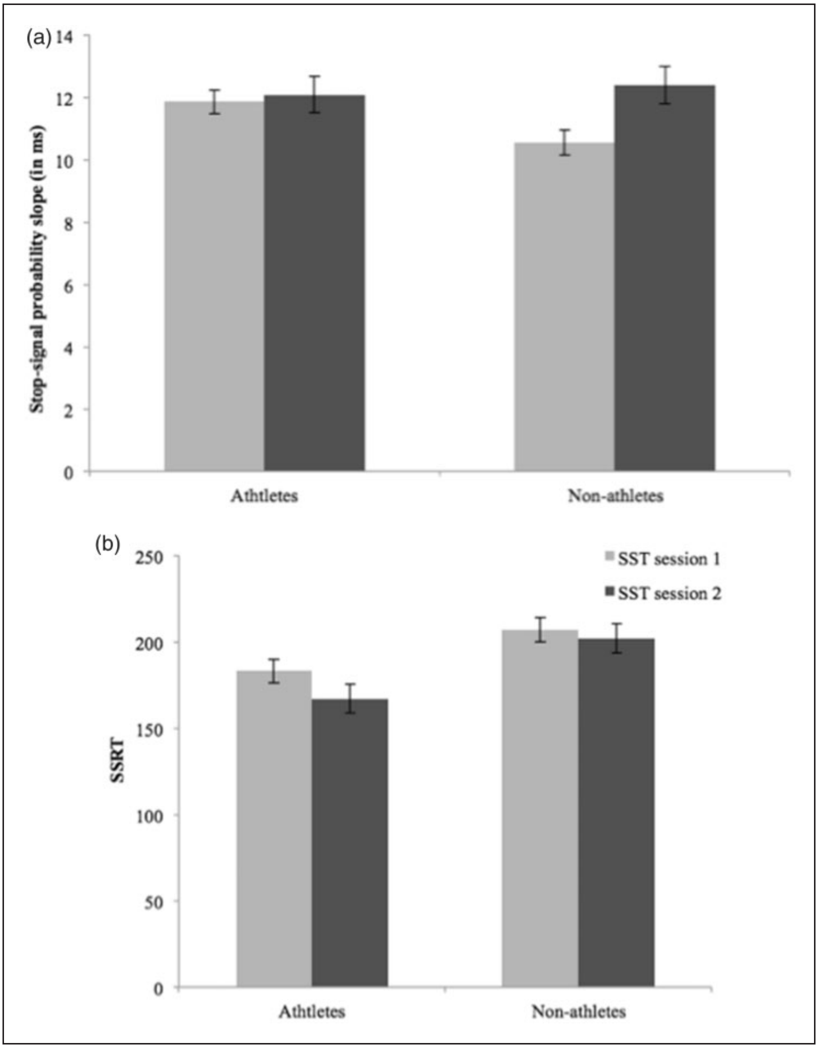

Figure 3. (a) Stop-signal probability slope (in milliseconds) for the Session 1 and Session 2 of the SST in the athlete and nonathlete groups. (b) SSRT for Session 1 and Session 2 of the SST in the athlete and nonathlete groups. All errors bars indicate 95% confidence intervals. SSRT = stop-signal reaction time; SST = stop-signal task.

athletes ($M = 174.46$, $SD = 41.43$) obtained better reactive motor response inhibition scores than nonathletes ($M = 205.67$, $SD = 33.74$; see also Figure 3(b)). There was no significant effect of sessions, $F(1,45) = 2.62$, $p = .11$, and no significant sessions and group interaction, $F(1,45) = 0.76$, $p = .39$.

Discussion

In this study, we aimed to examine differences in proactive and reactive motor response inhibition between samples of top-level athletes (fencing and taekwondo) and nonathletes, nearly matched for age and gender. We used a modified version of the SST that requested participants to inhibit categorizing left and right arrows, and with knowledge of the probability that a stop signal would occur manipulated with cues involving the color of the background computer screen. We observed that athletes obtained lower SSRT scores than nonathletes. That is, they exhibited higher performance on reactive motor response inhibition during the SST (Session 1 and Session 2). This result is consistent with previous studies showing that top-level athletes are better at reactively inhibiting their motor response (Chan et al., 2011; Di Russo et al., 2006; Diamond & Lee, 2011; Huijgen et al., 2015; Kida et al., 2005; Nakamoto & Mori, 2008a; Verburgh et al., 2014, 2016; Vestberg et al., 2017; Yamashiro et al., 2015; D. Zhang et al., 2015). By contrast, athletes and nonathletes did not differ in their overall performances of proactive motor response inhibition (as assessed with the stop-signal probability slope across SST Session 1 and Session 2). We observed, however, that athletes differed from nonathletes in their pattern of proactive motor response adjustment between Session 1 and Session 2 of the SST. More specifically, top-level athletes exhibited higher proactive motor response inhibition than nonathletes in Session 1, but not in Session 2. This suggests that elite athletes were faster in reaching and maintaining a consistent level of proactive motor response inhibition. This assumption is in line with the extensive literature on elite sports, which has shown that high-skilled athletes are better at strategically modulating their cognitive and motor resources according to specific task demands (for reviews, see MacIntyre, Igou, Campbell, Moran, & Matthews, 2014; Mann, Williams, Ward, & Janelle, 2010; Voss, Kramer, Basak, Prakash, & Roberts, 2010). Of note, present findings on proactive inhibition were obtained while controlling for participants' baseline response time (i.e., left- and right-arrow categorization speed in the green context). Indeed, we observed that athletes exhibited faster categorization speed than nonathletes in the green context (0% of stop signal). This finding is in line with the literature on perceptual, motor, and cognitive abilities in athletes reporting strong evidence for a heightened speed of stimulus discrimination in elite sports (Di Russo et al., 2006; Nakamoto & Mori, 2008b; Piras et al., 2014; Williams & Ericsson, 2005).

Interestingly, we observed that nonathletes significantly increased their level of proactive control over time (i.e., SST Session 1 vs. Session 2). This result is consistent with previous studies on response inhibition in the general population that reported similar go-signal RT increases throughout the SST (Verbruggen & Logan, 2009a; Verbruggen, Chambers, & Logan, 2013). By contrast, no significant difference was observed between groups on indices of reactive inhibition (SSRT) between Session 1 and Session 2 of the SST. One explanation for this finding is that the SSRT was estimated with the integration method (Verbruggen & Logan, 2009b). This procedure controls for variations in go-response RT, as well as in the proportion of incorrect inhibition (Verbruggen & Logan, 2009b). In other words, the integration method allows measuring one's ability to reactively inhibit a motor response while controlling for proactive control adjustment. Nevertheless, it is important to acknowledge that the integration method has also been reported to underestimate SSRT when response latencies gradually increase through the SST, especially when using extended versions of the SST (Verbruggen et al., 2013). Hence, because of the relatively small participant sample size in this study, the nonsignificant SSRT difference between Session 1 and Session 2 of the SST ($p = .11$) must be taken with caution.

Overall, present findings show that, among top-level experts in fencing and taekwondo, there are advances in both proactive (braking motor output when it is less activated) and reactive (stopping motor output completely when strongly activated) response inhibition. It follows that the extensive practice of fencing and taekwondo might enhance both earlier and later level motor response inhibition. Importantly, present findings were obtained using an SST that did involve sport-specific movement (i.e., categorized right and left arrows by pressing keys from a computer and while sitting in a chair). This suggests that there is an overlap between sport expertise in fencing and taekwondo and general mechanisms of motor response inhibition. In this context, one main avenue for future studies is to examine whether the training of proactive and reactive motor response inhibition could further increase sport performance in top-level athletes. Evidence of such a transfer between motor control domains would have two important implications. First, it would provide direct support for the hypothesis that there is an overlap in executive mechanisms that regulate sport expertise and motor response inhibition. Second, it could open new avenues for the training of athletes, especially during rehabilitation from injury.

Additional studies are also needed for further assessing proactive and reactive motor response inhibition while adopting alternative experimental procedures. Specifically, in this study, proactive motor inhibition was manipulated by varying the probability of stop signal associated with the color of the background screen. Participants were explicitly informed of this procedure (green = *no stop signal*, yellow = *low*, orange = moderate, red = high). Comparable methods have been shown to discriminate clinical from healthy control participants on proactive motor response inhibition (Kleerekooper et al., 2016; Van Rooij et al., 2014; Zandbelt et al., 2011). Nevertheless, in the present sample of participants, this procedure may not have been sufficiently demanding to fully discriminate athletes from nonathletes on proactive inhibition. Indeed, in contrast to reactive inhibition findings, we found no group difference between athletes and nonathletes on overall proactive inhibition performance (i.e., across Sessions 1 and 2 of the SST). Therefore, future researchers might examine proactive response inhibition while modifying the type of information given to participants on the different levels of stop-signal probability. For instance, it would be interesting to replicate this study while not informing participants about the probability of the stop signal. This alteration would illuminate how athletes and nonathletes learn to adjust their level of proactive response inhibition throughout the SST. Another complementary change might use neuroimaging techniques (electroencephalography, functional magnetic resonance imaging) to identify the nature and the intensity of cognitive resources triggered by the SST in both athletes and nonathletes. For instance, D. Zhang et al. (2015) showed that fencers, compared with nonfencers, exhibited behavioral as well as electrophysiological advantages (i.e., less cognitive resources needed) when suppressing planned responses. Future studies should also examine whether proactive (and reactive) motor inhibition is diminished after extended physical or mental effort. This ‘‘backfiring’’ pattern could relate to a mechanism of ego depletion (–ter, Bratslavsky, Muraven, & Tice, 1998), which has been repeatedly highlighted in athletes when an extended effort in one domain causes subsequent impairment in a second domain (for reviews, see Englert, 2016; Schapschröer, Lemez, Baker, & Schorer, 2016).

One main limitation of this study is that the small participant sample size did not allow direct comparisons of elite athletes from the two different sports of fencing and taekwondo. Nevertheless, because these athletes were similar in their professional status and in their practice of a sport discipline requiring fast motor response adaptation, it is unlikely that these two types of athletes significantly differ in their motor response inhibition capacity. In this context, additional studies are needed to examine proactive and reactive inhibition by comparing sport disciplines that have already been shown to differ on reactive motor response inhibition (closed-loop vs. open-loop sports; Jacobson & Matthaeus, 2014; Wang et al., 2013). Another limitation of this study is that our participant sample included few women, precluding an examination of any gender impacts on proactive and reactive motor response inhibition. Despite the fact that men and women have shown no differences in overall accuracy or response inhibition during an SST (Li, Huang, Constable, & Sinha, 2006; Thakkar et al., 2014), an interaction effect between sport expertise and gender on inhibitory control remains to be tested.

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