The superior response speed of table tennis players is associated with proactive inhibitory control

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Objective. To explore the mechanism behind the faster volitional reaction time (RT) of open skill sports athletes from the perspective of proactive inhibitory control, with the hypothesis that the superior response speed of athletes from open skill sports is related to their enhanced capacity for releasing inhibition.

Methods. Participants were divided into two groups, an experimental group of 27 table tennis players and a control group of 27 non-athletes. By manipulating cue–target onset asynchrony (CTOA) in a simple cue-target detection task, the timing of target presentation occurred in different phases of the disinhibition process. The time needed for disinhibition were compared between groups.

Results. For the experimental group, RT varied with CTOA at delays less than 200ms; for CTOAs greater than 200ms, RTs were not significantly different. For the control group, RT varied with CTOA for delays as long as 300ms.

Conclusions. Table tennis players took less time (200ms) than non-athletes (300ms) to complete the disinhibition process, which might partly explain their rapid response speed measured in unpredictable contexts.

Significance. The study provided evidence for disinhibition speed as a new index to assess the capacity of proactive inhibitory control, and provided a new perspective to explore the superior RT of athletes from open skill sports. We also offered support for the fundamental cognitive benefits of table tennis training.

The Superior Response Speed of Table Tennis Players is Associated with Proactive Inhibitory Control

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Abstract

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Methods. Participants were divided into two groups, an experimental group of 27 table tennis players and a control group of 27 non-athletes. By manipulating cue–target onset asynchrony (CTOA) in a simple cue-target detection task, the timing of target presentation occurred in different phases of the disinhibition process. The time needed for disinhibition were compared between groups.

27 **Results.** For the experimental group, RT varied with CTOA at delays less than 200ms; for CTOAs

28 greater than 200ms, RTs were not significantly different. For the control group, RT varied with CTOA for

29 delays as long as 300ms.

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31 disinhibition process, which might partly explain their rapid response speed measured in unpredictable

32 contexts.

33 **Significance.** The study provided evidence for disinhibition speed as a new index to assess the capacity of

34 proactive inhibitory control, and provided a new perspective to explore the superior RT of athletes from

35 open skill sports. We also offered support for the fundamental cognitive benefits of table tennis training.

36

Introduction

38   The capacity to respond swiftly to environmental events is a defining feature of athletes from open

39 skill sports such as table tennis, football, and boxing (Castellar et al., 2019). Previous studies in simulated

40 sport environments showed that athletes from open skill sports had faster reaction times (RTs) than

41 athletes from closed skill sports and non-athletes. However, it is not known whether the same advantage

42 would be observed in non-sport RT tasks (Voss et al., 2010).

43   To prevent inappropriate responses to unexpected events, the human brain inhibits responses when

44 faced with unpredictable environments. Thus, the initiation of a response requires the release of proactive

45 inhibitory control (Criaud et al., 2016; Criaud et al., 2012; Perri, 2020). Disinhibition pathways can be

46 either endogenous or exogenous. The endogenous pathway is used when the environment is likely to

47 require a predetermined reaction. In this case the proactive inhibitory control is released in advance,

48   creating a preparatory state which can quickly process sensorimotor information to trigger automatic

49   responses when events occur. The exogenous pathway is used when there is uncertainty about the

50   upcoming event. In this case, proactive inhibitory control is necessary to prevent inappropriate responses,

51   and can only be lifted after confirming that the event is indeed a target event. Reactions of the exogenous

52   pathway are generally volitional, and slower than the automatic responses of the endogenous pathway

53   (Favre et al., 2013) (Fig. 1).

54   The environment of open skill sports is unpredictable (Pi et al., 2019; You et al., 2018), which means

55   the athletes have to observe their surroundings and wait for the precise timing before action (Lucia et al.,

56   2021; Nakamoto & Mori, 2008). Hence, athletes maintain a state of locked proactive inhibitory control

57   until it is appropriate to remove inhibition (i.e., the exogenous pathway) and their reactions to external

58   events are mostly volitional rather than automatic. Thus, we believe that the superiority of response speed

59   in athletes is mainly lied in volitional response. This may partly explain the athletes' inconsistent results

60   in tests of general RT, which may be that some studies tested volitional RTs while others tested automatic

61   RTs. For example, Kida et al. (2005) measured the RTs of baseball players by a general Go/No-go task

62   and a simple RT task. The results showed that baseball players outperformed controls only in the Go/No-

63   go task. Bianco et al. (2017b) found that fencers and boxers reacted faster than non-athletes in a general

64   Go/No-go task. Abernethy et al. (1999) and Nielsen et al. (1985) reported that athletes from open skill

65   sports had no obvious RT advantage in general simple RT tasks. The Go/no-go task, a classical task to

66   study proactive inhibitory control, tested volitional RTs due to its unpredictability (Aron, 2011); while the

67   simple RT task tested automatic RTs. Therefore, the key point to the obvious RT superiority of athletes is

68   probably not whether they are in a specific-sport situation, but whether the response is volitional.

69   This study aimed to explore the mechanism behind the faster volitional RTs of athletes from open

70   skill sports. Considering that volitional RT is affected by disinhibition process, we hypothesized that the

71   rapid speed of disinhibition may partly explain. Although other factors could be responsible, such as

72   motor readiness (Bianco, et al., 2017a; 2017b), but few reported the disinhibition speed.

73   To verify the aforementioned hypothesis, we used a simple cue-target detection task to compare the

74   disinhibition time between table tennis players and non-athletes (Boulinguez et al., 2008; Favre et al.,

75   2013). The stimuli of the task include cue and target. The cue serves as a prompt, appearing at different

76   time points before the target (or not at all) and requiring no response. The potential cue is both an

77   unpredictive stimulus that impedes rapid automatic response and a predictive prompt to enable

78   disinhibition, thus activating the exogenous pathway. The exogenous disinhibition pathway in this task

79   begins either when the cue appears or when the target appears (in conditions when no cue is present). RTs

80   vary with the cue–target onset asynchrony (CTOA): if CTOA is shorter than 300ms, the RTs are

81   relatively long; if CTOA is longer than 300ms, the RTs are almost as short as those measured in

82   automatic responses (Boulinguez et al., 2009). In other words, when CTOA is longer than the time needed

83   to release proactive inhibitory control, the disinhibition process is complete before the target is presented,

84   and RTs are not affected. When CTOA is shorter than the time needed to release proactive inhibitory

85   control, RTs are slowed down by the inhibition. In general, The CTOA where the RT begins to approach

86   the automatic response RT could represent the approximate time for disinhibition (Fig. 2).

87   Table tennis, along with badminton and squash are reactive sports (Kalpesh et al., 2012), which

88   means table tennis requires athletes react fast due to its high speed and constantly changing direction

89   (Castellar et al., 2019). Previous studies have reported the RT superiority of table tennis players (Deepa et

90 al., 2016). You et al. (2018) found that table tennis players showed faster RTs than non-athletes in a

91 general Go/no-go task. Therefore, we recruited table tennis players as the experimental group. We

92 hypothesized that table tennis players outperformed the controls only in volitional RTs, and took less time

93 when they release proactive inhibitory control.

94

95 **Materials & Methods**

96 Participants

97 The sample size was calculated by G*power 3.1. The effect size was 0.25 and the α was 0.05. To

98 make the power of a statistical test to 0.95 (He et al., 2021), the study needed 26 participants totally.

99 Actually, 29 table tennis players and 31 non-athletes were recruited. All participants were recruited from

100 Shanghai University of Sport. All were right-handed and had normal or corrected-to-normal vision. All

101 table tennis players were at national level 2 or above, with 10 to 15 years of training experience (average

102 12 years). The control group participated in sports occasionally but had no long-term experience. The

103 study was approved by the Ethics Committee of Shanghai University of Sport (Ethics No.

104 102772019RT012). All participants signed the written informed consent. The data of six participants were

105 excluded on the basis of insufficient task performance (<95% accuracy). The final groups comprised 27

106 table tennis players (aged 18–21 years, average 19.93; 18 female) and 27 controls (aged 18-25, average

107 22.41; 15 female).

108

109 Experimental Procedure

110   The experimental task was a simple cue-target detection task. All stimuli were displayed on a 14-

111 inch computer screen (resolution: 1366×768) positioned 50 cm from the subject's eyes. E-Prime 3.0

112 software was used to run the task program and complete data collection.

113   The experimental session included two blocks of tasks: a mixed block containing a random mixture

114 of no-cue and cue-target trials, and a baseline block containing only no-cue trials, which was used to

115 measure the automatic response speed. In no-cue trials, a fixation point consisting of a white cross

116 (1.03°×1.03°) remained in the center of the screen. Participants were instructed to focus on the fixation

117 point. After a delay of 1100–1600ms the target, a white "X" (2.46°×3.55°), presented at 3.89° randomly

118 to the left or right of the fixation point for a duration of 50ms. There was a 2000-ms delay following the

119 target presentation. In cue-target trials the cue, consisting of two white squares (4.18°×5.14°), appeared at

120 3.89° to both sides of the fixation point for a duration of 50ms. The cue would appear randomly 100, 200,

121 300, 400, or 500ms earlier than the target, denoted as CTOA-100, CTOA-200, CTOA-300, CTOA-400,

122 and CTOA-500. In both cue and no-cue trials, participants were instructed to press " ↓ " key on a

123 keyboard with their right index finger as soon as they saw the target (Fig. 3).

124   The experimental procedure began with a training baseline block consisting of 40 no-cue trials

125 followed by a training mixed block of 40 trials. Participants were instructed to comply with a maximum

126 error rate of 5% in each block. Two types of errors were possible: 1) anticipation, defined as responding

127 before the target appeared or having an RT shorter than 150ms; 2) omission, defined as no response or

128 having an RT longer than 1000ms. Whenever an error occurred, an error signal and the current error rate

129 were displayed on the screen. The formal experimental task consisted of a baseline block with 80 trials

130 and a mixed block with 360 trials. Participants were encouraged again to comply with a maximum error

131   rate of 5% in each block, and to respond as quickly as possible. The order of the two blocks was

132   counterbalanced across participants.

133

134   Statistical Analyses

135   A 2 (group: table tennis players, non-athletes) × 3 (condition: no-cue/mixed, no-cue/baseline, cue-

136   target) repeated ANOVA was performed for each type of error (anticipation and omission). Similarly, a 2

137   (group: table tennis players, non-athletes) × 7 (condition: no-cue/mixed, CTOA-100, CTOA-200, CTOA-

138   300, CTOA-400, CTOA-500, no-cue/baseline) repeated ANOVA was performed for mean RTs. RTs that

139   were more than three standard deviations from the mean were excluded from analysis. All tests were two-

140   sided and considered significant when $P<0.05$. Post hoc comparisons were performed by Bonferroni tests.

141

142   **Results**

143   Errors

144   *Anticipation*

145   A significant effect of condition was observed, $F_{(2, 104)}=173.679$, $P<0.001$, $\eta_p^2=0.770$. Post hoc

146   comparisons reported that the anticipation rate was smaller in no-cue/mixed trials ($M=0.000\%$,

147    $SD=0.000\%$) and no-cue/baseline trials ($M=0.069\%$,$SD=0.289\%$) than in cue-target trials ($M=3.909\%$,

148    $SD=2.150\%$). No significant effect was observed for group ($F_{(1, 52)}=0.038$,$P=0.847$), or for the

149   group×condition interaction ($F_{(1, 52)}=0.107$,$P=0.899$).

150   *Omission*

151   No significant effect was observed for group ($F_{(1, 52)}$=0.099,P=0.754), condition ($F_{(2, 104)}$=1.484,

152   P=0.231), or group×condition interaction ($F_{(1, 52)}$=0.159,P=0.853).

153

154   Reaction Times

155   No RT difference between response to the left and right stimulus was observed. There was a

156   significant effect of group on reaction time ($F_{(1, 52)}$=4.475,P=0.039,η_p^2=0.079). Post-hoc tests showed

157   that RTs of the experimental group (M=307.169ms, SD=50.124) were significantly shorter than those of

158   the control group (M=324.889ms, SD=53.371). There was also a significant effect of condition ($F_{(6, 312)}$

159   =346.923, P<0.001,η_p^2=0.870). RTs for CTOA-200 (M=321.496ms, SD=38.261) were significantly

160   shorter than those for CTOA-100 (M=367.334ms, SD=38.627), and RTs for CTOA-300 (M=291.544ms,

161   SD=36.045) were significantly shorter than those for CTOA-200. A significant group × condition

162   interaction was observed, $F_{(6, 312)}$=2.426, P=0.026,η_p^2=0.045. Post-hoc comparisons showed that the

163   RTs of the experimental group were significantly shorter than those of the control group in no-cue/mixed,

164   CTOA-100, and CTOA-200; in the other four conditions, no significant RT differences were observed

165   between the two groups. For the experimental group, RTs for CTOA-200 were significantly shorter than

166   those for CTOA-100, but there was no significant difference in RTs between CTOA-300 and CTOA-200.

167   For the control group, RTs for CTOA-300 were significantly shorter than those for CTOA-200 (Fig. 4).

168

169   **Discussion**

170   In the present study, the dynamics of RTs in the control group were consistent with those reported

171   previously. That is, the longer the delay between disinhibition and target presentation, the shorter the

172   response time, approaching the RTs measured in automatic responses (Jaffard et al., 2007; Jaffard et al.,

173   2008). Boulinguez et al. (2009) found that RT was no longer affected by proactive inhibitory control

174   when CTOA reached 300ms, thus it was speculated that the time required for untrained people to

175   complete the disinhibition process was about 300ms. Here we found that the RTs of the experimental

176   group were already approaching those measured in automatic responses when CTOA was as low as

177   200ms, while the RTs of the control group did not approach those of automatic responses until the CTOA

178   reached 300ms. Thus, we conclude that it required about 200ms for the experimental group, but 300ms

179   for the control group, to completely release proactive inhibitory control. In addition, when the time

180   interval between disinhibition and target presentation was shorter than 300ms (no-cue/mixed, CTOA-100,

181   and CTOA-200), a significant difference in RT was observed between groups. Conversely, when the time

182   interval exceeded 300ms (CTOA-300, CTOA-400, CTOA-500, and no-cue/baseline), there was no

183   significant difference in RT between groups. Perhaps because only in these conditions (no-cue/mixed,

184   CTOA-100, and CTOA-200) were RTs affected by proactive inhibitory control. If the experimental group

185   required less time to lift proactive inhibitory control, their RTs would be less affected by the disinhibition

186   process. Therefore, in conditions under the influence of proactive inhibitory control (i.e., volitional

187   response), the experimental group showed an obvious advantage in response speed, whereas no

188   significant advantage was observed in conditions divorced from the effect of proactive inhibitory control

189   (i.e., automatic response).

190   All in all, we proved that the RT advantage of table tennis players mainly lied in the volitional

191   response; we found that the disinhibition time of table tennis players was shorter than that of the controls,

192   supporting that table tennis players disinhibit faster than non-athletes (Fig. 5B). It is worth noting that

193 researchers reported athletes' stronger proactive inhibitory control (i.e., the ERP component of prefrontal

194 negativity, pN) (Bianco, et al., 2017a; 2017b), which helped us rule out the possibility that the lower

195 degree of inhibition leaded to the shorter time of disinhibition (Fig. 5A). The stronger proactive inhibitory

196 control guarantees athletes' accuracy (Bianco, et al., 2017a; 2017b; Messel et al., 2019; Xu et al., 2015),

197 which is as important as response speed for athletes from open skill sports.

198   Inhibitory control is one important aspect of cognitive control, and can be either proactive or reactive

199 (Braver, 2012). Proactive inhibitory control refers to the ability to control one's attention, behavior,

200 thought, and/or emotion; to overcome strong internal predisposition or external temptation; to refrain

201 from reacting automatically to unpredictable events; and to instead do what's more appropriate or needed

202 (Braver, 2012; Diamond, 2013). It is thought to be a top-down process defined as the ability to formulate

203 a response strategy based on the environment (e.g., slowing down while driving in a school zone)

204 (Ballanger, 2009; Di Caprio et al., 2020; Duque et al., 2017). Reactive inhibitory control refers to the

205 ability to withdraw from already-planned actions when necessary, and is thought to be a bottom-up, late

206 correction process triggered by external signals (e.g., braking when a pedestrian suddenly crosses the

207 street) (Aron, 2011; Aron et al., 2004, 2014; Braver, 2012; Hampshire & Sharp, 2015). Previous studies

208 found that athletes, especially those in open skill sports, exhibited a heightened capacity for inhibitory

209 control (Huijgen et al., 2015; Jacobson & Matthaeus, 2014; Meng et al., 2019; Yamashiro et al., 2015);

210 however, most of the studies looked at reactive rather than proactive inhibitory control (Heppe &

211 Zentgraf, 2019; Liao et al., 2017; Wang et al., 2013). Using a modified version of the stop-signal task,

212 Brevers et al. (2018) estimated proactive inhibitory control by increased go-signal RT as a function of

213 increased stop-signal probability (i.e., a higher change in go-signal RTs per stop-signal probability unit

214   indicated a better capacity for proactive inhibitory control) and reported that elite athletes exhibited

215   superior proactive inhibitory control. In light of these results, we posit that proactive inhibitory control

216   facilitates inhibition efficiency (i.e., accuracy), and measures of inhibition efficiency can provide an

217   important index to a person's ability for proactive inhibitory control. However, according to our results,

218   we also believe disinhibition speed should be another index, which determines whether a person can react

219   rapidly even in unpredictable circumstances.

220   The brain network underlying proactive inhibitory control includes right inferior prefrontal gyrus,

221   pre-supplementary motor area, subthalamic nucleus, and striatum (Coxon et al., 2006; Meyer & Bucci,

222   2016). We speculated that table tennis players could release proactive inhibitory control rapidly, perhaps

223   because they could switch swiftly between the inhibitory state and the automatic response state (Favre et

224   al., 2013; Messel et al., 2019), a process which may be controlled by connections between this inhibition

225   network and the primary motor cortex (Duque et al., 2017). Experience-based neuroplasticity studies have

226   shown that repeated and frequent participation in a particular sport alters the relevant neural

227   representations (Calvo-Merino et al., 2006; Koeneke et al., 2004; Naito et al., 2014; Weisberg et al.,

228   2007). Changes in neuroplasticity caused by sports training could explain why elite athletes outperform

229   novices and non-athletes (Jellinger, 2007; Kelly et al., 2005; Pascual-Leone et al., 2005; Raz et al., 2013).

230   The rapid disinhibition speed of table tennis players may be one of the manifestations of the changes in

231   neuroplasticity caused by long-term sports training.

232   We must admit the limitations of this study. First, the effect of different levels of physical activity

233   and aerobic fitness on brain and cognition could not be excluded (Erickson et al., 2015) for we could not

234   control the sports training time of table tennis players. Second, only table tennis players were recruited.

235 We are cautious about whether these results could be applied to athletes from other open skill sports due

236 to different technical, tactical and strategic demands of different open skill sports, which might influence

237 the motor-skill experience in different ways as an effect of neuroplasticity (Voss et al., 2010). Thus,

238 athletes from other open skill sports and closed skill sports are needed to verify our results. Third, further

239 replications of our tasks coupled with neurophysiological measurements are needed for the exploration of

240 the disinhibition process, which is what we are going to do in future studies.

241

242 Conclusions

243   In conclusion, our study took table tennis players as the experimental group and, through simple cue-

244 target detection tasks, showed that the rapid speed of releasing proactive inhibitory control might partly

245 explain their superior performance in volitional RTs.

246

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Figure 1

Theoretical illustration of response locked and unlocked by proactive inhibitory control (Favre et al., 2013).

To prevent inappropriate automatic response, the response trigger was locked by proactive inhibition. Proactive inhibitory control can be unlocked by either endogenous or exogenous pathways. In the endogenous pathway , removal of proactive inhibition occurs under internal control, before stimulus presents, allowing a rapid automatic response to stimulus. In the exogenous pathway, disinhibition occurs only after the stimulus has been identified, triggering a relatively slower, volitional response.
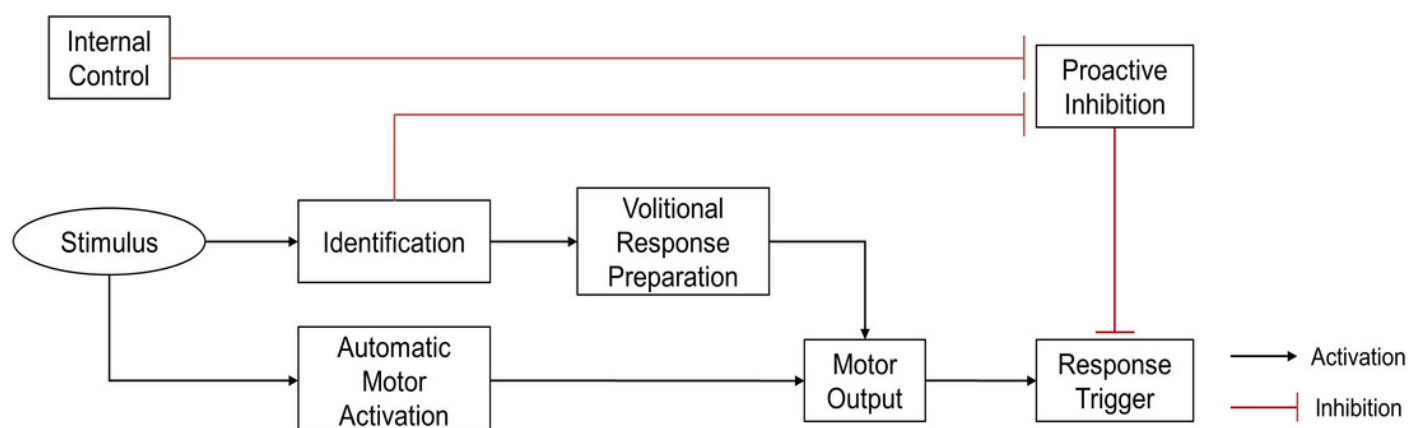
Figure 2

Timeline of exogenous and endogenous disinhibition in simple cue-target detection tasks (Favre et al., 2013).

Red lines indicate proactive inhibitory control. In the simple cue-target detection task with 0% possibility of cue occurrence, the remove of proactive inhibitory control happens endogenously, the disinhibition process ends before presentation of the target, and RT is not affected (i.e., automatic RT) (g). In the simple cue-target detection task with 50% possibility of cue occurrence, the exogenous pathway could occur two different ways: if disinhibition begins at the same time as target presentation (i.e., no-cue trials), RT will be affected by the entire disinhibition process (a); if disinhibition beings at the same time as cue presentation (i.e., cue trials), effects on RT will depend on the magnitude of cue-target onset asynchrony (CTOA) (b-f). When the CTOA begins to approach the time needed for disinhibition (d), the RT of this condition is close to the automatic RT, and the CTOA represents the approximate time for disinhibition.
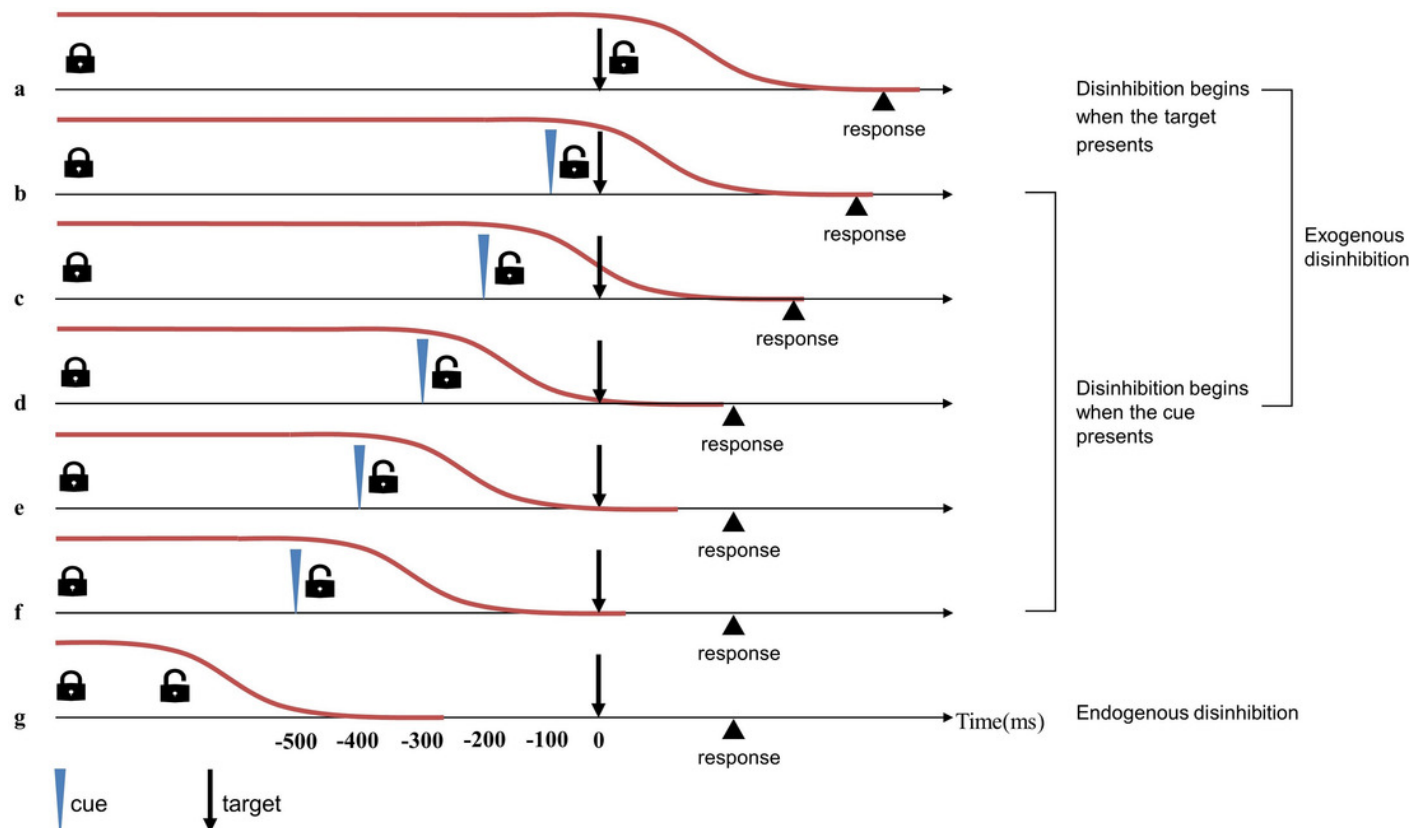
Figure 3

Sample images from the cue-target detection task.

No-cue and cue-target trials were randomly mixed in the task. No-cue trials: 1100–1600ms after the fixation point (white cross) appeared, the target ("X") was presented randomly on the left or right side for 50ms, then followed by a delay of 2000ms. Cue-target trials: the cue (two white squares) appeared on both sides of the fixation point for 50ms, either 100, 200, 300, 400, or 500ms before the target appeared. In both types of trials, participants were asked to press "↓" key on the keyboard with right index finger as soon as they saw the target.

false
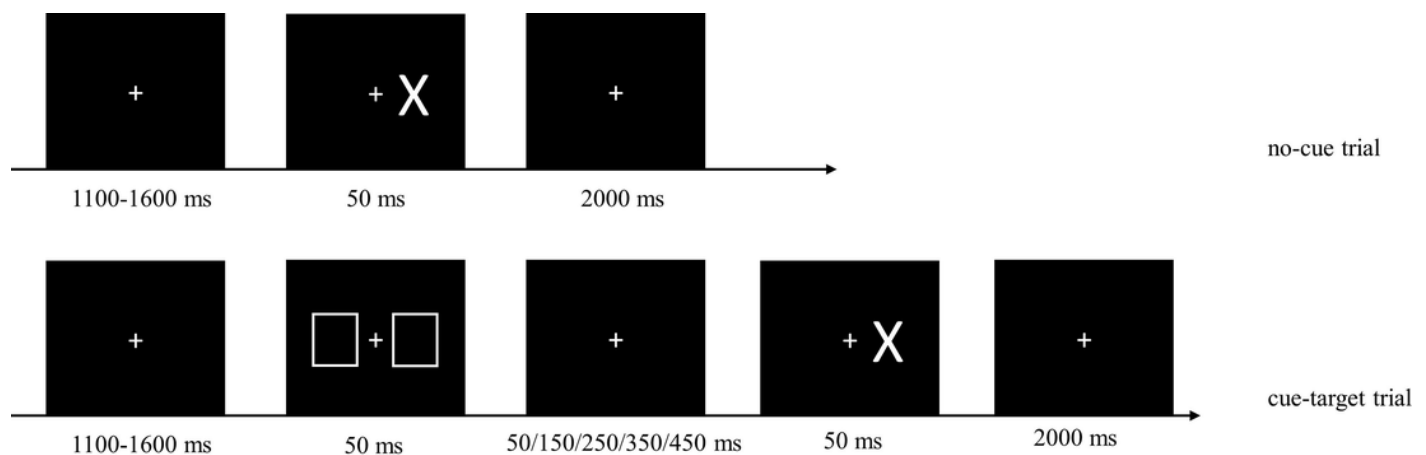
Figure 4

RTs in seven conditions.

Compared with the control group, the RTs of the experimental group in no-cue/mixed, CTOA-100, and CTOA-200 trials were significantly shorter (*P* values = 0.003, 0.023, and 0.033, respectively). The RTs of both groups in CTOA-200 was significantly shorter than that in CTOA-100 (*P*<0.001). No significant difference was observed between CTOA-300 and CTOA-200 for the experimental group (*P*=0.229), but in the control group the RTs for CTOA-300 were significantly shorter than those for CTOA-200 (*P*=0.003). Note:#: between-group variance, *: between-condition variance; ***: *P*<0.001, ** & ##: *P*<0.01, #: *P*<0.05.
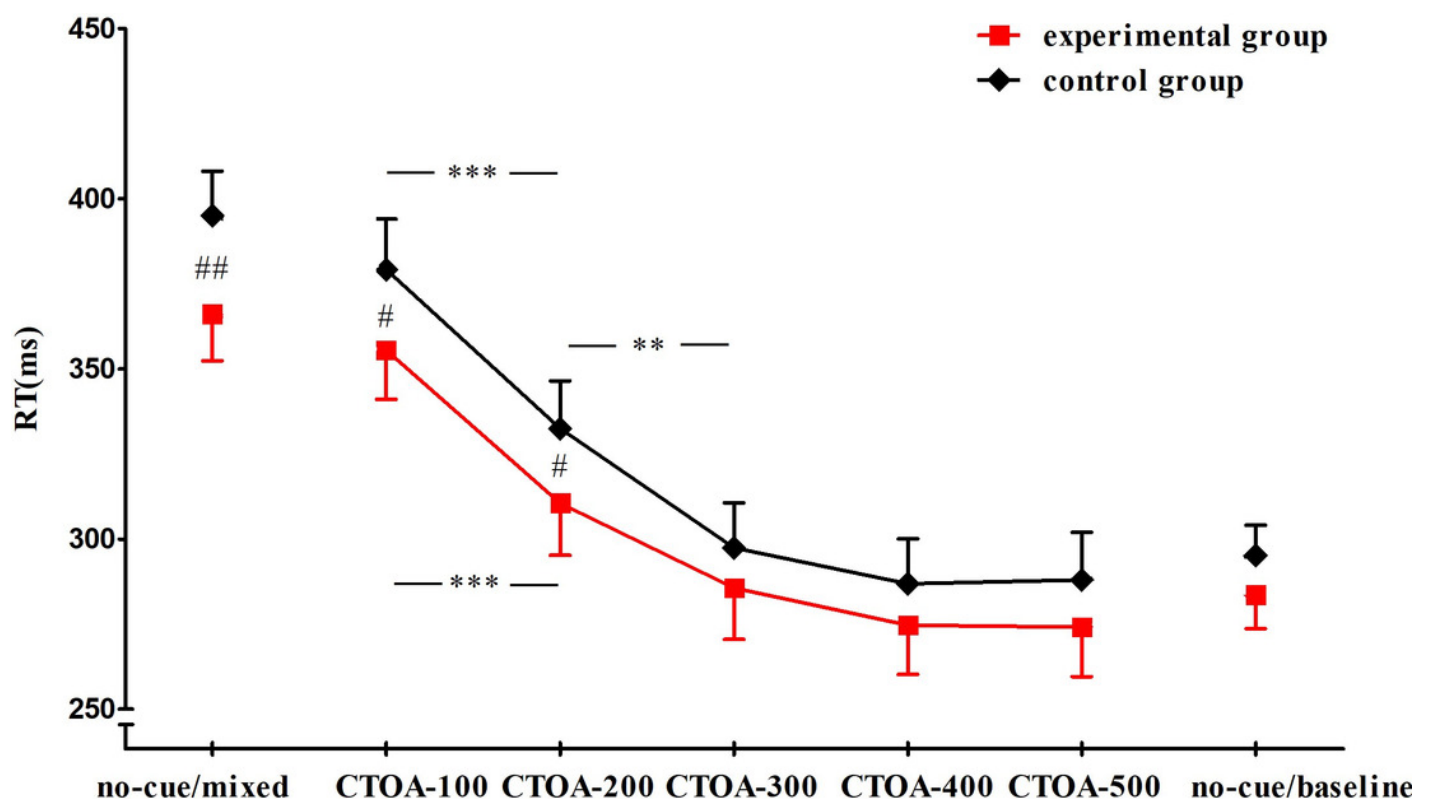
Figure 5

Schematic illustration of the hypothetical model of disinhibition curves.

A) There is no significant difference between groups in disinhibition speed, but the non-athletes have stronger proactive inhibitory control, so they need more time for disinhibition.
B) Table tennis players have stronger proactive inhibitory control, but they disinhibit faster than non-athletes, so they spend less time for disinhibition.