1 **Robot's social gaze affects conflict resolution but not conflict**

2 **adaptations.**

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14 **Abstract**

15 Robots are a new category of social agents that, thanks to their embodiment, can be used to train and

16 support cognitive skills such as cognitive control. Several studies showed that cognitive control mechanisms

17 are sensitive to affective states induced by humor, mood, and symbolic feedback such as monetary rewards.

18 In the present study, we investigated whether the social gaze of a humanoid robot can affect cognitive

19 control mechanisms. To this end, in two experiments, we evaluated both the conflict resolution and trial-by-

20 trial adaptations during an auditory Simon task, as a function of the type of feedback participants received

21 in the previous trial from the iCub robot, namely, mutual or avoiding gaze behaviour. Across three

22 experiments, we compared the effect of mutual, avoiding (Exp1 and Exp2), and neutral (Exp3) gaze

23 feedback between screen-based (Exp1) and physically embodied setups (Exp2 and Exp3). Results showed

24 that iCub's social gaze feedback modulated conflict resolution, but not conflict adaptations. Specifically, the

25 Simon effect was increased following mutual gaze feedback from iCub. Moreover, the modulatory effect

26 was observed for the embodied setup in which the robot could engage or avoid eye contact in real-time

27 (Exp2) but not for the screen-based setting (Exp1). Our findings showed for the first time that social

28 feedback in Human-Robot Interaction, such as social gaze, can be used to modulate cognitive control. The

29 results highlight the advantage of using robots to evaluate and train complex cognitive skills in both healthy

30 and clinical populations.

31 **Keywords:**

Introduction

Complex cognitive skills in humans are the result of interaction with the environment, including social interactions. Indeed as stated by Humpreys, *"[…] cognitive functions have evolved to their high level because they have been driven by the complexities of social living"* (Humphreys, 1976, p. 307). Nowadays, social interactions are not only limited to other humans but also include artificial agents, such as robots. The pivotal role that robots can play in promoting and supporting human cognitive skills is demonstrated by the increased interest in developing socially assistive robotics in the last years (Chevalier et al., 2019; Wykowska, 2020). Indeed, as social agents, robots represent a perfect combination of symbolic (e.g. language and communicative gestures) and artifactual instruments that, according to the socio-cultural approach (e.g., Vygotskij, 1932), are necessary to ensure and support the development of cognitive skills such as communication and behaviour regulation (Ciardo & Wykowska, 2020).

Among cognitive skills, one of the most crucial is cognitive control, which is the ability to adapt our behaviour to maintain and achieve task goals by reducing the cognitive conflict in task execution, when simultaneous and mutually incompatible goal representations competing for a single response are activated. Several studies showed that cognitive conflict can be modulated by either enhancement of processing of task-relevant information (e.g., Egner & Hirsh, 2005) or by inhibition of task-irrelevant features (e.g., Braver, 2012; Ridderinkhof, 2002). The former refers to the adjustments of task parameters and priority settings occurring at the level of task strategy (e.g. Braver, 2012; Logan, 1985), resulting in a better **conflict resolution** within a given trial. Namely, resources are allocated to prevent the negative impact of a cognitively demanding event on task performance (e.g., Marini, Chelazzi, & Maravita, 2013). This form of control differs from online **conflict adaptations** in performance triggered by the conflict experienced in the previous trial (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver, 2012).

The mechanisms allowing humans to deal with cognitive conflict have been studied in the literature using tasks that manipulate conflict, such as the Flanker task (Eriksen & Eriksen, 1974), the Stroop task (Stroop, 1992), the task-switching paradigms (e.g. Braem et al., 2012) or the Simon task (Simon & Rudell, 1967; for a review see Proctor & Vu, 2006). In a Simon task, participants are asked to respond to a feature of a target stimulus usually presented visually on the screen. The feature, colour, for example, determines which button a participant is supposed to press (e.g., left button for red targets and right button for green

61 targets). Most importantly, the target stimuli are presented laterally on the screen, and the responses are

62 also lateral. This means that each target will require a spatially corresponding or non-corresponding

63 response (in the example above, if the red target is presented on the left, the response will be spatially

64 corresponding, but if the red target is presented on the right, the response will not be corresponding).

65 Typically, corresponding target-response mappings elicit faster responses (and/or lower error rates) than

66 non-corresponding mapping (e.g. Simon & Rudell, 1967), although the spatial configuration is completely

67 irrelevant to the task. The correspondence effect in a Simon task is termed the Simon effect (SE), and it

68 has been explained as resulting from a conflict during response selection (e.g., Rubichi & Pellicano, 2004)

69 between two alternative response codes, one generated based on task instructions and the other

70 automatically activated through pre-existing associations linking a stimulus to its spatially corresponding

71 response (e.g., De Jong, Liang, & Lauber. 1994). The automatic association between stimulus and

72 response codes has laid the grounds for the Theory of Event Coding (Hommel et al., 2001) which postulates

73 a common code between perception and action. Most importantly, due to the automatic activation of a

74 stimulus-response code that incorporates spatial information, even though it is task-irrelevant, the response

75 selection process is facilitated in corresponding trials, in which the two activated response codes overlap,

76 leading to faster reaction times (RTs). Conversely, conflict occurs in non-corresponding trials in which the

77 irrelevant and the relevant stimulus dimensions activate different response codes, thus impeding RTs.

78 Interestingly, SE is reduced, null, or even reversed for trials that follow a non-corresponding trial, while it is

79 consistently observed for trials following a corresponding trial (e.g., Ciardo, Ricciardelli, & Iani, 2019;

80 Hommel, Proctor, & Vu, 2004). These trial-by-trial adaptations have been taken as evidence that the conflict

81 experienced in a given trial is accompanied by changes aimed at preventing the recurrence of the conflict

82 in the next trial (for a review, see Mansouri, Tanaka, & Buckley, 2009; but see also Hommel et al., 2004 for

83 an alternative account).

84   Although the independence of **conflict resolution** and **conflict adaptation** mechanisms is still

85 debated (see Egner, Ely, & Grinband, 2010; Scherbaum, Fischer, Dshemuchadse, & Goschke, 2011 for an

86 alternative account), they show different developmental strategies and are differently affected by individual

87 and contextual factors. Indeed, evidence shows that individual differences such as age, cognitive style, or

88 psychiatric disorders (e.g. eating or mood disorders) are reflected in conflict resolution, but not in conflict

89 adaptations (Larson, Clawson, Clayson, & South, 2012; Iani, Stella, & Rubichi, 2014; Iani, Ciardo,

90 Ricciardelli, & Nicoletti, 2016; Bartholdy, et al., 2017).

91   Another factor to which cognitive control seems to be sensitive is the affective state[1] induced by reward,

92 humor, and mood (see van Steenbergen, 2015 for a review). For instance, Kanske and Kotz investigated,

93 in a series of studies, whether and how conflict resolution is modulated by the emotional content of the

94 stimuli. Using different types of conflict tasks, the authors showed that both positive and negative words

95 can speed up conflict resolution (i.e. reduced Flanker and Simon effects for negative and positive targets,

96 respectively, Kanske & Kotz, 2010; 2011;2012). A similar result was reported by Yamaguchi & Nishimura

97 (2018), who manipulated monetary reward. Specifically, using a Flanker task, the authors showed that

98 conflict was reduced (i.e. smaller Flanker effect) for contingent-reward trials compared to trials in which the

99 reward was randomly assigned (Exp2, Yamaguchi & Nishimura, 2018). However, this was not the case for

100 conflict adaptations, as the authors showed that both contingent and non-contingent rewards had little effect

101 on trial-by-trial effects, highlighting the dissociation between conflict resolution and conflict adaptation.

102 Online conflict adaptations have also been shown to be modulated by affective states. Padmala and

103 colleagues (2011) presented both neutral and high-arousing negative images (i.e., mutilated bodies) in-

104 between Stroop task trials. The results showed that following negative pictures the usual trial-by-trial

105 adaptations did not occur. Similarly, van Steenberg and colleagues (2010) investigated the effect of

106 positive and negative mood-induction before performing a conflict-evoking Flanker task. Results showed

107 that trial-by-trial adaptations were affected by the pleasure of the induced mood, with a larger reduction in

108 cognitive conflict (i.e. less interference) for subjects assigned to the negative mood condition (i.e., anxious

109 and sad) compared to those assigned to the positive mood group (i.e., calm and happy). Similar results

110 have been also reported from studies that manipulated reward, showing an enhanced cognitive control

111 (i.e. less interference) following negative feedback (i.e. losses or small gains) than following gain

112 feedback (e.g., Braem et al., 2012; Stürmer et al., 2011; Schuch, Zweerings, & Koch, 2017; but see also

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[1] Please note that when talking about affective states we refer to positive or negative states that could be driven both by motivational factors and/ or emotions.

113   Yamaguchi et al.2020 for a series of studies failing in replicating the effect of affective states on trial-by-

114   trial effects).

115   It has been proposed that affective states (mood, reward, or emotions) seem to enhance cognitive

116   control in an affect-congruent manner (cf. Cabanac, 1992; van Steenberg, 2014). That is, negative affective

117   states might influence cognitive conflict for the demanding cases, i.e. incongruent (conflict) trials, as those

118   also trigger a negative and aversive state (Botvinick, 2007). A recent systematic review by Dignath and

119   colleagues (2020) underlies how the effect of affective states on conflict adaptations is influenced by the

120   way the affective state is induced during the task. While tonic affective states, like mood, showed consistent

121   results in support to the affect-congruent hypothesis, studies that manipulated affective states in a transient

122   way, such as monetary reward on random trials, showed mixed and contradictory results, mostly due to the

123   heterogeneity of the tasks and manipulations across studies (Dignath et al., 2020).

124   The studies reviewed so far manipulated mainly emotions and monetary rewards, focusing more on

125   the distinction between affective states and motivational factors. However, in everyday life during social

126   interactions, we are exposed to several non-verbal social communication signals, such as facial expression,

127   body language, and social gaze, that can induce affective states or, as feedback, modulate our motivation.

128   For instance, when we are taking an exam, a smiling examiner looking towards us can induce a more

129   relaxed state and, thereby, help in focusing on our task.

130   The social gaze is defined as the use of gaze direction with communicative intent (e.g., Emery, 2000).

131   Two social gaze behaviours that induce affective states are: avoiding and mutual gaze. Converging

132   evidence suggests that real-time mutual gaze increases arousal and evokes a positive affective state (but

133   see also Jarick & Kingstone, 2015, for evidence on mutual gaze being perceived as socially uncomfortable

134   and aversive). For instance, mutual gaze has been associated with increased skin conductance, heart rate,

135   suppression of alpha activity, and increased engagement compared to avoiding gaze (e.g., Hietanen et al.,

136   2008; Pönkänen, Peltola, & Hietanen, 2011; Kompatsiari et al., 2021a). Interestingly, such a modulation

137   appears to be null or reversed when the social gaze is presented within screen-based setups (Hietanen et

138   al., 2008; Pönkänen, Peltola, & Hietanen, 2011).

139   In a recent series of studies, Kompatsiari and colleagues showed that similar effects are elicited also

140   in interaction with a robot (e.g., Komptsiari et al., 2018; 2019; 2021a). Specifically, when the humanoid

141 robot iCub (Metta et al., 2010) established real-time mutual gaze it was judged as more engaging and

142 human-like compared to when it avoided eye contact. Similarly, Schellen et al. reported that mutual or

143 avoiding gaze presented after participants' choice in a decision-making task induced a change of strategy

144 in the subsequent trial. The decision-making task was related to giving honest or deceptive feedback to

145 iCub. The authors found that fewer deception choices occurred after trials in which iCub established mutual

146 gaze as a feedback (Schellen, Bossi, & Wykowska, 2021). In a recent EEG study, Kompatsiari and

147 colleagues examined oscillatory brain response to mutual and averted gaze established by the iCub robot

148 during an attentional cuing task (Kompatsiari, Bossi, & Wykowska, 2021). Results showed that mutual and

149 avoiding gaze differently affected the desynchronization of alpha-band activity, suggesting that following

150 mutual gaze, participants were inhibiting task-irrelevant information to a lesser extent, relative to averted

151 gaze. Such a result is in line with the hypothesis that cognitive control is reduced in social situations, as the

152 need of monitoring another agent reduces the attentional resources allocated to the task (e.g.Huguet et al.,

153 2014). In line with this latter hypothesis, there is evidence showing that conflict effects, such as the Stroop

154 effect, are reduced in the presence of another human or a humanoid agent (Huguet et al.,1999; Spatola et

155 al ., 2018; see Belletier et al 2019 for a review).

156   To summarize, the social gaze is a powerful (often implicit) feedback that in social interactions can

157 induce affective states. The effectiveness of mutual or averted gaze seems to be stronger for real-time

158 (embodied) interactions compared to screen-based setups (Hietanen et al., 2008; Pönkänen, Peltola, &

159 Hietanen, 2011), and it has been widely replicated in Human-Robot Interaction (HRI) (Kompatsiari et al.,

160 2018; 2019: 2021a). The fact that robotic agents can exert similar effects on cognitive mechanisms to those

161 induced by other humans is recent but consistent evidence across several tasks. For instance, it has been

162 shown that human and non-anthropomorphic robotic agents similarly affect sense of agency (e.g. Ciardo

163 et al., 2020), motor preparation, and attention allocation both at the behavioural and neural levels (Hinz et

164 al., 2021; Komptsiari et al 2018)

165   The increasing interest in developing socially assistive robotics for training purposes (Ciardo &

166 Wykowska, 2020; Wykowska, 2020) calls for the need to study whether the social signals of a robot can be

167 used as feedback to modulate cognitive control mechanisms. Therefore, the present study, aimed to i)

168 investigate whether using the social gaze of a robot as feedback modulates cognitive control; ii) understand

169   if the social gaze feedback of a robot modulates cognitive control by conflict resolution mechanism (i.e.,

170   adjusting task parameters and priority settings before the occurrence of cognitively demanding events), or

171   by affecting also trial-by-trial adaptations; iii) test the impact of physical embodiment. In three experiments,

172   we evaluated both the SE overall and trial-by-trial adaptations as a function of the type of social gaze

173   feedback that iCub exhibited at the end of the previous trial, namely mutual, avoiding, or neutral gaze.

174   We implemented an auditory Simon task (Simon & Rudell, 1967) to avoid having too much visual

175   information to process while performing the task and to make sure that visual attention was focused on

176   iCub's face. In Exp1 and Exp2, we compared the effect of the social gaze feedback between screen-based

177   setups and setups involving physically present embodied iCub, respectively. In Exp 3, we ran a follow-up

178   control in which the robot was not providing any feedback to the participants. This was done to estimate

179   the baseline magnitude of the SE elicited by our embodied setup.

180   Based on the reviewed literature (Hietanen et al., 2008; Kompatsiari et al., 2018; 2019), we

181   hypothesized that iCub's mutual and avoiding gaze should influence cognitive control mechanisms by

182   inducing affective states. According to the hypothesis that affective states modulate cognitive control in an

183   affect-congruent way (van Steenberg, 2014), and the existing evidence showing that mutual gaze induces

184   positive affective states (Hietanen et al., 2008; Pönkänen, Peltola, & Hietanen, 2011; Kompatsiari et al.,

185   2021a), the SE was expected to be reduced following avoiding gaze feedback or increased after mutual

186   gaze feedback. Specifically, if the social gaze interacts with conflict resolution, then its modulatory effect

187   should be evident at the task strategy level, resulting in a smaller SE within a given trial. On the other hand,

188   if the social gaze modulates online conflict adaptations, then different trial-by-trial effects should emerge

189   across the two gaze conditions. Concerning the comparisons between screen-based and embodied setups,

190   we hypothesized that the social gaze (mutual or avoiding) should be more effective when manipulated in

191   physical presence and in real-time compared to when it is depicted on a screen. Thus, the modulating effect

192   of social gaze should be stronger for embodied setup (Exp2) compared to the screen-based setup (Exp1).

193   **Experiment 1**

194   *Participants.*

195   The sample size was estimated via a priori power analysis using G*Power. The analysis yielded a sufficient

196   number of 15 participants for the within-subject design [dz = 0.40, α = 0.05, and 1-β = 0.80].Twenty-one

197   participants (5 males; mean age: 24.4 ± 3.5 years) took part in the study. All participants had normal or

198   corrected-to-normal vision and were not informed about the purpose of the experiment. All participants gave

199   their informed written consent. All experiments were conducted under the ethical standards laid down in

200   the 1964 Declaration of Helsinki and were approved by the Local Ethical Committee (Comitato Etico

201   Regione Liguria). The data of one participant have been excluded due to a technical failure of the program.

202   Therefore, data of twenty participants were further analyzed.

203   **Materials and Methods**

204   *Apparatus and Stimuli.*

205   The experiment was carried out in a dimly lit and noiseless room. The participant was seated facing a 22"

206   LCD monitor driven by a 2.90 GHz processor computer at a viewing distance of 60 cm. Stimuli were 'high'

207   (800 Hz) or 'low' (400 Hz) tones presented through Sennheiser HD 569 headphones (10-28000 Hz).

208   Responses were executed by pressing the 'q' or the 'p' keys on the QWERTY keyboard with the left or the

209   right index finger, respectively. Two videos showed the iCub robot establishing real-time mutual or avoiding

210   gaze (from a participant's perspective). The keyboard was located centrally with respect to the body midline.

211   Stimulus presentation, response timing, and data collection were controlled by Psychopy software

212   (v.2020.1.3)

213   *Procedure.*

214   Participants were instructed to respond as quickly and as accurately as possible to the tone pitch presented

215   to one of their ears through either left or right headphones. Participants were asked to ignore the tone's

216   spatial location. Half of the participants responded to the high tone by pressing the "q" key and to the low

217   tone by pressing the "p" key, the other half experienced the opposite stimulus-response mapping. Each trial

218   began with the presentation of a white fixation cross in the center of a black screen for 900 ms, then the

219   fixation cross turned to yellow for 1100 ms. 200 ms after the fixation cross changed colour the tone was

220   played, see D'ascenzo et al. (2018) for a similar procedure. Given that evidence showed that left and right

221   auditory stimuli produce a decreasing Simon effect distribution (Xiong & Proctor, 2015) due to the

222   dissipation of the automatic activation of the spatial corresponding response, the maximum time allowed to

223   respond was 1000 ms. After a response was made, or the maximum time allowed expired, a video depicting

224   iCub establishing Mutual or Avoiding gaze was presented for 6000 ms (see Video 1). The inter-trial interval

225   was 1000 ms. Participants were also instructed to pay attention to the iCub following their response

226   because at the end of the experiment they would be asked to answer questions about its behaviour. At the

227   end of each block, feedback indicating the cumulative amount of correct responses, and the average

228   response time across the experiment was presented.

229   The task consisted of 4 blocks with 64 trials each. A short practice of 8 trials preceded the task. In each

230   block, the trial sequence was controlled so that each trial was preceded by either a corresponding (C) or

231   non-corresponding (NC) trial, with equal probabilities to be preceded by Avoiding or Mutual Gaze condition.

232   As a result, in both Avoiding and Mutual gaze conditions, four different trial sequences occurred (*C*–C, *C*–

233   NC, *NC*–C, *NC*– NC, with italics denoting trial *n-1*).

234   << INSERT VIDEO 1 HERE: https://www.youtube.com/watch?v=JWV7I4rutHA >>

235   **Data Analysis**

236   We excluded from analyses the first trial of each block, trials that were preceded by an incorrect response,

237   incorrect responses, and correct responses faster than 150 ms and slower than 1000 ms (7.0%of the

238   administered trials). Mean correct RTs were submitted to a repeated-measures analysis of variance

239   (ANOVA) with Trial *n–1* Correspondence (*C* vs. *NC*), Trial n Correspondence (C vs. NC), and Preceding

240   Gaze Feedback (Avoiding vs. Mutual) as within-subject factors. When necessary, comparisons were

241   performed using paired samples t-tests. Analysis was run using the Jasp software (v.0.9.2).

242   **Results and Discussion**

243   The analysis revealed a significant main effect of Trial n Correspondence, $F(1, 19) = 156.74$, $p < .001$, η_p^2

244    $=.89$, indicating faster responses for corresponding (M = 464 ms, SE = 2.1 ms) than for non-corresponding

245   trials (M = 515 ms, SE = 2.2 ms), indicating the classical SE. The correspondence effect was modulated by

246   correspondence sequence, as indicated by the significant interaction between Trial n Correspondence and

247   Trial *n–1* Correspondence, $F(1, 19) = 14.18$, $p < .001$, $\eta_p^2 = .43$. Planned comparisons showed a 59-ms SE

248   after a corresponding trial, $t(19) = 13.3$, $p < .001$, $d = 3.0$; and a SE of 28-ms after a non-corresponding trial,

249   t(19) = 8.9, p < .001, d = 2.0. Paired simple t-test showed that the two effects differed in magnitude, t(19) =

250   3.8, p < .001, d = .8. No other main effect or interaction were significant, all ps > .094.

251   The results of Experiment 1 showed that the SE was modulated by the correspondence of the

252   preceding trial. Specifically, in line with previous studies, the typical trial-by-trial adaptations occurred (e.g.,

253   Ciardo et al., 2019; Iani et al., 2014) with a larger SE evident following a corresponding (59 ms) than a non-

254   corresponding trial (28 ms). These results support the idea that the detection of conflict in trial *n–1* triggers

255   adaptations that are aimed at eliminating the impact of spatial S–R correspondence on response selection

256   in the following trial (Braver, 2012; Ridderinkhof, 2002). No effect of preceding gaze feedback emerged.

257   Such results may suggest that the mutual and avoiding gaze feedback of a humanoid robot may not act as

258   an affective signal and do not affect performance in the subsequent trial. However, in Experiment 1 mutual

259   and avoiding gaze feedbacks were manipulated through a robot face presented on the screen. Such a

260   setup may lack ecological validity. Indeed, several studies showed that embodiment plays a crucial role

261   when investigating social cognition mechanisms (e.g. Vasco et al., 2019; Wiese, Metta, Wykowska, 2017),

262   especially in the context of mutual gaze, with higher arousal and faster responses associated with real-time

263   mutual gaze compared to direct gaze presented on a screen (Hietanen et al., 2008; Pönkänen et al., 2011).

264   Taking this into account, we designed Experiment 2, in which we implemented the screen-based paradigm

265   to a 3-D physical-presence setup in which the mutual and avoiding gaze feedbacks from iCub were

266   displayed in real-time.

267   **Experiment 2**

268   **Materials and Methods**

269   *Participants.*

270   Twenty-five new participants (7 males; 3 lefthanded; Mean age: 25.6 ± 4.2 years) took part in the study. All

271   participants had normal or corrected-to-normal vision and were not informed about the purpose of the

272   experiment. All gave their informed consent before participating and the study was conducted under the

273   same ethical procedures and protocol as in Experiment 1. The data of five participants were excluded due

274   to: technical failure of the robot (2), technical failure of the program (2), or because the participant was

275   unable to perform the task (1). Therefore, data of twenty participants were further analyzed.

276 *Apparatus and Stimuli.*

277 The experiment was carried out in a dimly lit and noiseless room. The participant was seated facing the

278 iCub robot at a viewing distance of 70-80 cm (see Figure 1). We used a version of the iCub robot consisting

279 of a full robotic head and a 3D printed torso mounted on a stool. The iCub's eyes have 3 degrees of freedom

280 (common tilt, vergence, and version) and three additional degrees of freedom in the neck (roll, pitch, yaw).

281 To control the eyes and the neck of iCub, we used the YARP (Yet Another Robot Platform, Metta, Fitzpatrick,

282 & Natale, 2006) Python wrappers.

283 In our procedure, to make iCub gaze at a specific location, a 6-DOF gaze controller has been used

284 (Roncone, Pattacini, Metta, & Natale, 2016). This controller uses inverse kinematics to find eyes and neck

285 positions to make the robot look at certain 3D Cartesian coordinates. In our experiment, the target location

286 was predefined for the Avoiding gaze feedback (x: 0°,y: -26°, z: 3°), whereas, in the Mutual gaze feedback

287 coordinates of target location were calculated online in each trial, to make the robot establish eye contact

288 in real-time (see Video 2). Participant's eyes were detected using a face detection algorithm applied to the

289 images coming from the camera sensors placed in the eye bulbs of the iCub robot (Cao, Hidalgo Martinez,

290 Simon, Wei, Sheikh, 2017). The vergence of the eyes was set to 3 degrees and maintained constant. The

291 trajectory time for the movement of eyes and neck was set to 500 ms, to maintain the impression of a

292 smooth and naturalistic movement.

293 Stimuli were the same as those used in Experiment 1. Responses were executed as in Experiment 1. The

294 keyboard was placed on the participant's lap centrally with respect to the body midline. Stimulus

295 presentation, response timing, and data collection were controlled as in Experiment 1.

296   << INSERT VIDEO 2 HERE: https://www.youtube.com/watch?v=eOktX7GCuJA >>

297 *Procedure.*

298 As in Experiment 1, participants were instructed to discriminate the tone pitch in one of the headphones,

299 ignoring its spatial location. Participants were also instructed to pay attention to the iCub because at the

300 end of the experiment they would be asked to answer questions about its behaviour. Each trial started with

301 the robot depicting a neutral expression and closed eyes with the neck located at the rest position. Following

302 1500 ms the expression of the robot turned from neutral to surprise for 1700 ms. 200 ms after the facial

303 expression changed the stimulus tone was played. The maximum time allowed to respond was set at 1000

304 ms from stimulus onset. After a response was given, or the allowed response time elapsed, the robot

305 opened the eyes and moved the neck and the eyes toward the Avoiding or Mutual gaze target location, see

306 Video 2. At the end of each block, feedback indicating the cumulative amount of correct responses and the

307 average response time across the task was given to participants. Contrary to Experiment 1, instructions

308 and   feedback   were   given   verbally   by   iCub   using   the   text   to   speech   library:

309 https://github.com/robotology/speech/tree/master/svox-speech. The task consisted of 5 blocks of 48 trials

310 each. A short practice of 8 practice trials preceded the task. As in Experiment 1, in each block, the trial

311 sequence was controlled so that each trial was preceded by either a corresponding (C) or non-

312 corresponding (NC) trial, with equal probabilities to be preceded by Avoiding or Mutual Gaze condition. As

313 a result in both Avoiding and Mutual gaze conditions, four different trial sequences occurred (*C*–C, *C*–NC,

314 *NC*–C, *NC*– NC, with italics denoting trial *n-1*).
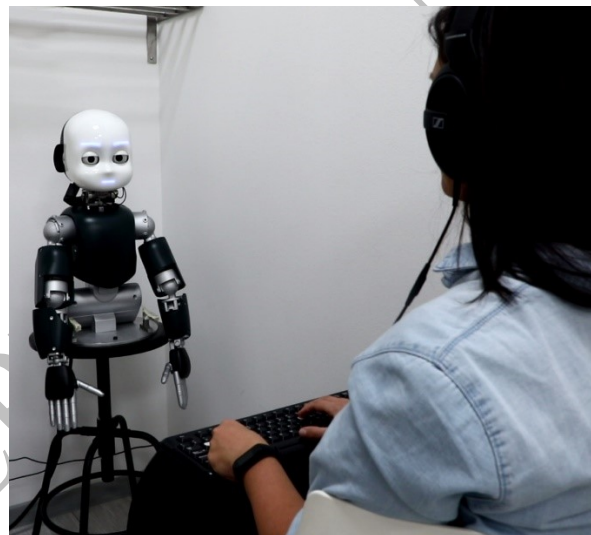
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316 Figure 1 Experimental setup in Experiment 2.

317 **Data Analysis**

318 As for Experiment 1, the first trial of each block, trials that were preceded by an incorrect response, incorrect

319 responses, and correct responses faster than 150 ms and slower than 1000 ms were excluded from the

320 analysis (12.0%of the administered trials). Mean correct RTs were submitted to a repeated-measures

321 analysis of variance (ANOVA) with Trial n – 1 Correspondence (C vs. NC), Trial n Correspondence (C vs.

322 NC), and Preceding Gaze Feedback (Avoiding vs. Mutual) as within-subject factors. When necessary,

323 comparisons were performed using paired samples t-tests.

324 **Results and Discussion**

325 The analysis on RTs showed that responses were faster following Avoiding gaze (M = 456 ms, SE = 1.9

326 ms) than Mutual gaze trials (M = 472 ms, SE = 2.2 ms), as indicated by the main effect of Preceding Gaze,

327 $F(1, 19) = 69.67$, $p < .001$, $\eta_p^2 = .79$. The main effect of Trial n Correspondence was significant, $F(1, 19) =$

328 69.67, $p < .001$, $\eta_p^2 = .79$, with faster responses for corresponding (M = 442 ms, SE = 2.1 ms) than for non-

329 corresponding trials (M = 485 ms, SE = 1.9 ms), indicating a classical SE. This correspondence effect was

330 modulated by correspondence sequence, as indicated by the significant interaction between Trial n

331 Correspondence and Trial *n–1* Correspondence, $F(1, 19) = 22.23$, $p < .001$, $\eta_p^2 = .54$. Planned comparisons

332 showed the typical sequential effects reported in Experiment 1 and in previous studies (e.g., Ciardo et al.,

333 2019; Iani et al., 2014) with a 59-ms SE after corresponding trials, $t(19) = 8.8$, $p < .001$, $d = 2.0$; and a 43

334 ms SE after a non-corresponding trials, $t(19) = 4.9$, $p < .001$, $d = 1.1$. Paired-samples t-test showed that

335 the two effects differed in magnitude, $t(19) = 4.72$, $p < .001$, $d = 1.05$. Importantly, the two-way interaction

336 between Preceding Gaze Feedback and Trial n Correspondence was significant, $F(1, 19) = 6.35$, $p = .021$,

337 $\eta_p^2 = .25$. Planned comparison showed that a larger SE occurred following Mutual gaze feedback (51 ms)

338 than Avoiding gaze feedback (35 ms), $t(19) = 2.59$, $p = .021$, $d = .56$ (see Figure 2). No other main effects

339 or interactions were significant, all ps > .14.

340 Table 1. Mean correct reaction times and standard deviation (in milliseconds) as a function of Experiment
341 (Exp1 vs Exp2), Preceding Gaze Feedback (Avoiding vs Mutual), Trial n – 1 (corresponding, C vs non-
342 corresponding, NC), and Trial n (corresponding, C vs non-corresponding, NC).

	Preceding Gaze Feedback	Trial n-1	Trial n	Mean	SD
Exp.1	Avoiding	C	C	450	89
			NC	509	106
		NC	C	471	96
			NC	515	98
	Mutual	C	C	461	94
			NC	520	96
		NC	C	474	95
			NC	516	103

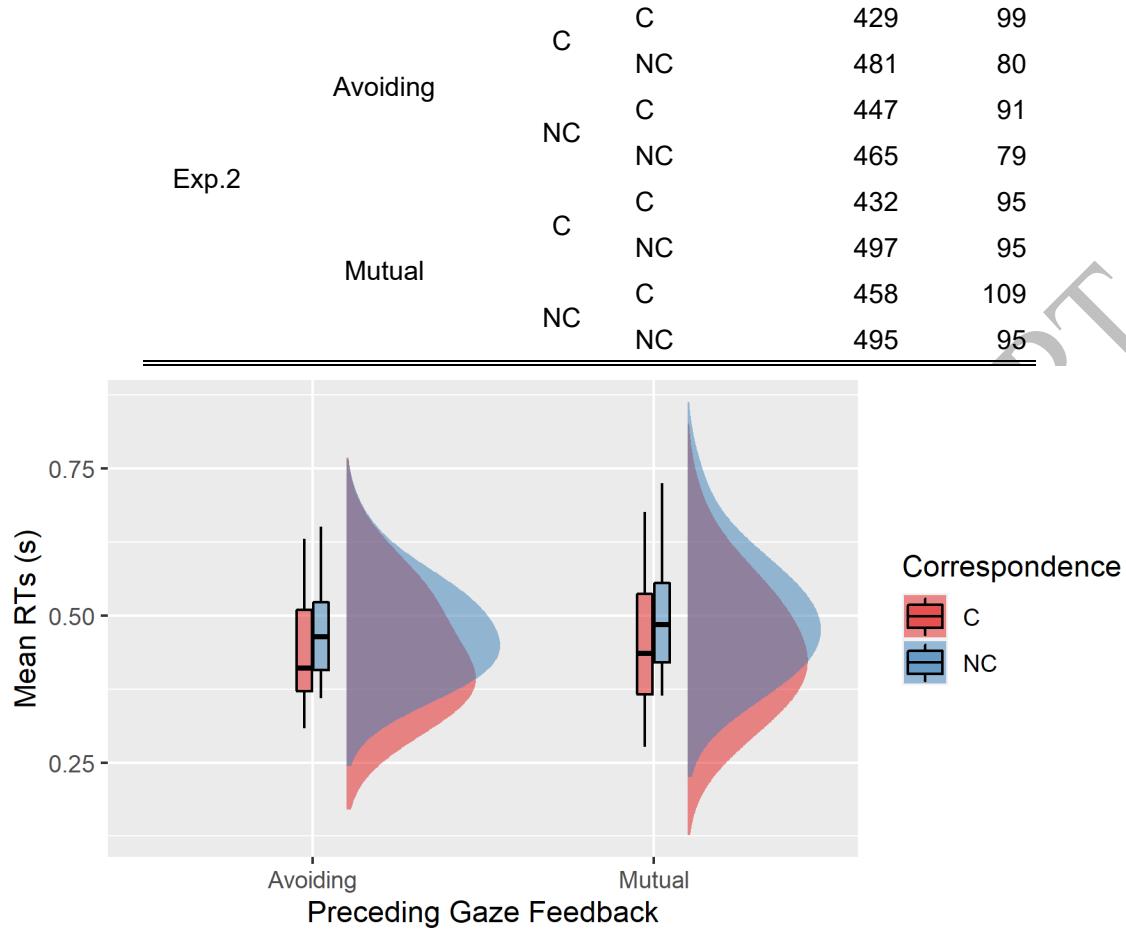| Exp.2	Avoiding	C	C	429	99
			NC	481	80
		NC	C	447	91
			NC	465	79
	Mutual	C	C	432	95
			NC	497	95
		NC	C	458	109
			NC	495	95

343

344 Figure 2 Mean reaction times in Experiment 2 for the corresponding (C) and non-corresponding (NC) Trial n, as a
345 function of Preceding Gaze Feedback (Avoiding vs Mutual).

346   Results of Experiment 2 showed that mutual and avoiding gaze feedback differently affected the SE

347 in the subsequent trial. Specifically, we found that the SE was smaller in magnitude following avoiding gaze

348 feedback, relative to mutual gaze (35 vs. 51, respectively). Social gaze feedback did not modulate

349 sequential effects, as there was no significant three-way interaction. These results indicate that social gaze

350 feedback modulated conflict within a single trial, but not adaptation across trials. Hence, it seems that the

351 ability to manage conflict within a single trial and the ability to adapt performance based on the conflict

352 experienced in the previous trial depend on different mechanisms. Only the first mechanism appears to be

353 sensitive to the social gaze feedback delivered by the robot. Given that our experimental design did not

354 include a neutral condition, we cannot conclude the direction of our manipulation on the magnitude of the

355 SE. To estimate the direction of the SE in the two critical conditions of our protocol (mutual vs. avoiding

356 gaze feedback), we ran a follow-up control experiment (Exp3) in which the robot was not providing any

357 feedback to the participants.

358 **Experiment 3**

359 **Materials and Methods**

360 *Participants.*

361 Twenty-five new participants (6 males; 1 lefthanded; Mean age: 29.2 ± 11.4 years) took part in the study.

362 All participants had normal or corrected-to-normal vision and were not informed about the purpose of the

363 experiment. All gave their informed consent before participating and the study was conducted under the

364 same ethical procedures and protocol as in Experiment 1. The data of five participants were excluded due

365 to: Age of the participant above 45 years old (2 participants, see Van der Lubbe & Verleger, 2002), technical

366 failure of the program (1 participant), because the participant committed too many errors (1 participant;

367 error rate: 18%), or because outliers removal reduced to less than 50% the trials to be included in the

368 analysis (1 participant). Data of twenty participants were further analyzed.

369 *Apparatus, Stimuli, and Procedure.*

370 The apparatus, stimuli, and response execution were the same of Experiment 2. Stimulus presentation,

371 response timing, and data collection were controlled as in Experiment 2.

372 The procedure was the same as Experiment 2, with the only exception that after a response was given, or

373 the allowed response time elapsed, the robot did not open the eyes and did not move the neck and the

374 eyes. At the end of each block, feedback indicating the cumulative amount of correct responses and the

375 average response time across the task was given to participants. As in Experiment 2, instructions and

376 feedback were given verbally by iCub. The task consisted of 3 blocks of 40 trials each. A short practice of

377 8 practice trials preceded the task. Since we were not interested anymore in sequential adaptations, the

378 trial presentation order was fully randomized.

379 **Data Analysis**

380   As in Experiment 2, the first trial of each block, trials that were preceded by an incorrect response, incorrect

381   responses, and correct responses faster than 150 ms and slower than 1000 ms were excluded from the

382   analysis (9.2%of the administered trials). Mean correct RTs for corresponding and non-corresponding trials

383   were compared using paired samples t-tests.

384   **Results**

385   The analysis on RTs showed that responses were faster for corresponding (M = 420 ms, SE = 1.7 ms) than

386   for non-corresponding trials (M = 454 ms, SE = 1.7 ms), $t(19) = 4.83$, $p < .001$, $d = 1.08$.

387   Results of Experiment 3 showed that when participants were not provided with any feedback from

388   the robot, our setup induced a Simon effect of 34 ms.

389   **The role of embodiment: Comparison between Exp1 and Exp2.**

390   To assess the effect of embodiment, we conducted an additional analysis to compare the data of the two

391   experiments. The IQR method on the average RTs of correct trials for each participant was applied to

392   identify possible outliers. Indeed, 1 participant showed an average RT above the upper limit (Q3+1.5 IQR).

393   Thus we ran the analysis excluding this participant on a sample size of N=39. Mean RTs were entered into

394   an ANOVA with Trial n Correspondence (C vs. NC) and Preceding Gaze Feedback (Avoiding vs. Mutual)

395   as within-subject factors and Experiment (Exp1 vs.Exp2) as a between-subjects factor. In addition to the

396   main effect of Trial n Correspondence, $F(1, 37) = 209.67$, $p < .001$, $\eta_p^2 = .85$, the analysis revealed a main

397   effect of Preceding Gaze, $F(1, 37) = 5.87$, $p = .020$, $\eta_p^2 = .14$ and a significant two-way interaction Trial n

398   Correspondence * Preceding Gaze Feedback, $F(1, 37) = 4.90$, $p = .033$, $\eta_p^2 = .12$. Importantly, the three-

399   way interaction was significant, $F(1, 37) = 5.53$, $p = .039$, $\eta_p^2 = .11$. Independent T-test showed a marginally

400   significant difference in the magnitude of the SE, $t(37) = 2.0$, $p = .056$, $d =.63$ (see Figure 3). No significant

401   difference in the SE occurred across experiments following a Mutual gaze, $t<1$. No other main effects or
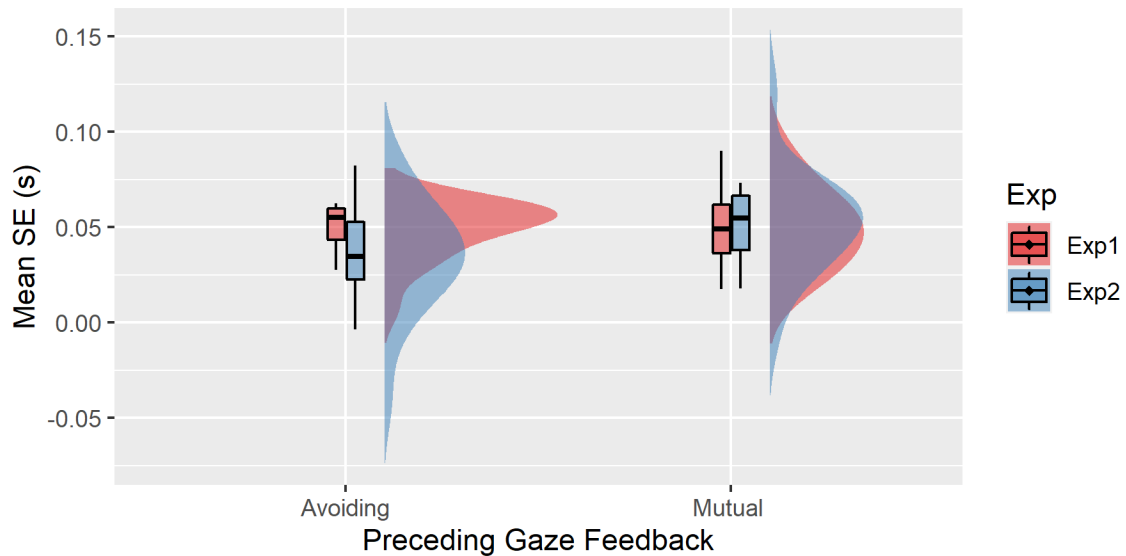
402   interactions were significant, all ps > .326.

403
404 Figure 3. Mean Simon Effect (s) plotted as a function Preceding Gaze Feedback (Avoiding vs. Mutual) across
405 experiments.

406 **The effect of social gaze: Comparison between Exp2 and Exp3.**

407 We ran two exploratory analyses to compare the SE elicited following Mutual and Avoiding gaze

408 feedback with the SE when no feedback was provided. Specifically, we compared the SE of Exp 3 with the

409 SE of Exp2 for mutual gaze and avoiding gaze conditions separately. Mean RTs were entered into an

410 ANOVA with Trial n Correspondence (C vs. NC) as within-subject factors and Gaze Condition (Avoiding or

411 Mutual vs. Neutral) as a between-subjects factor.

412 *Avoiding vs Neutral*

413 Apart from the main effect of Trial n Correspondence, $F(1, 38) = 51.70$, $p < .001$, $\eta_p^2 = .585$, no other

414 main effects or interactions were significant, all ps > .470.

415 *Mutual vs Neutral*

416 The analysis showed a main effect of Trial n Correspondence, $F(1, 38) = 87.22$, $p < .001$, $\eta_p^2 = .70$. The

417 two-way interaction Trial n Correspondence* Gaze Condition showed a tendency to a significant effect, $F(1,$

418 $38) = 3.39$, $p = .073$, $\eta_p^2 = .08$. Independent-samples t-test showed that the 34-ms SE of the Neutral gaze

419 condition marginally differed from the 51-ms SE following mutual gaze feedback, $t(38) = 1.84$, $p = .073$, d
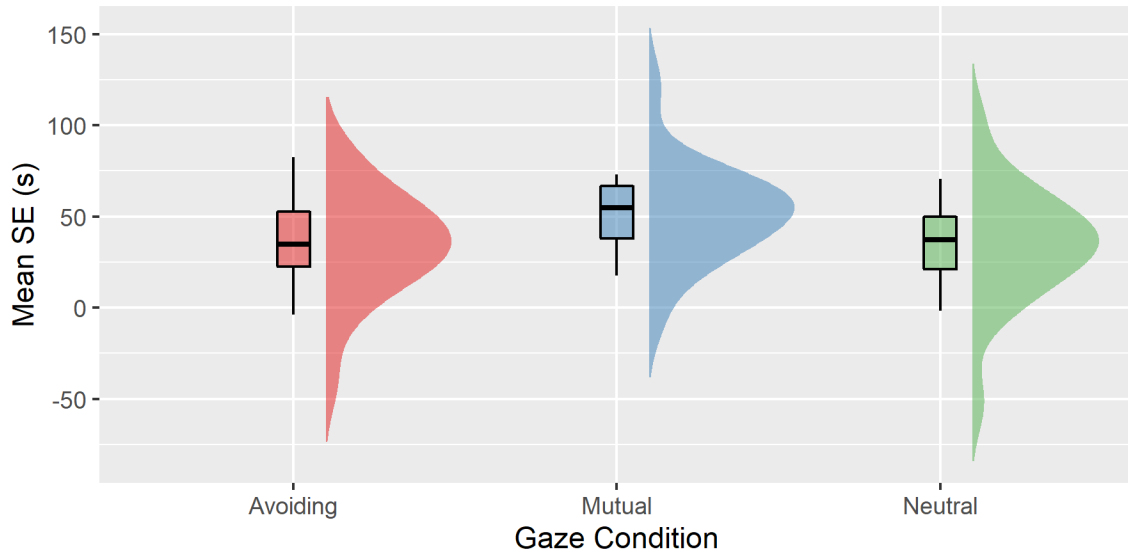
420 = 0.58.

Figure 4. Mean Simon Effect (s) plotted as a function Gaze Condition (Avoiding vs. Mutual vs. Neutral).

General Discussion

The main goal of the present study was threefold: i) investigating whether the social gaze feedback of a robot can modulate cognitive control; ii) understanding if the social gaze feedback of a robot affects cognitive control through within-trial conflict resolution (i.e., adjusting task parameters and priority settings before the occurrence of cognitively demanding events) or it acts through trial-by-trial adaptations; iii) testing the impact of the embodied physical presence of an agent displaying social gaze. To meet these aims, in three experiments we evaluated both the SE and trial-by-trial adaptations as a function of the type of feedback participants received in the previous trial from the iCub robot, namely, mutual or avoiding gaze. Across experiments, we compared the effect of the social gaze feedback between screen-based (Exp1) and embodied setups with the robot's physical presence (Exp2 and Exp3).

Results of Experiment 1 revealed that the 51 ms SE was modulated by the correspondence of the preceding trial. Specifically, in line with previous studies, the typical sequential effects occurred (e.g., Ciardo et al., 2019; Iani et al., 2014; 2016) with a larger SE evident following a corresponding (59 ms) than a non-corresponding trial (28 ms). Moreover, Experiment 1 showed that when the social gaze feedback was manipulated in a screen-based setup, it did not modulate either conflict resolution or conflict adaptations. In Experiment 2, apart from the expected correspondence and trial-by-trial adaptation effects, the results

439   showed faster responses following avoiding gaze than mutual gaze feedback. Most importantly for the aim

440   of the present study, results of Experiment 2 showed that when the social gaze feedback of the robot was

441   manipulated in a setup involving physical embodied presence, the SE was larger in magnitude following

442   mutual gaze feedback (51ms) than following avoiding gaze (35ms). No effect of social gaze emerged for

443   trial-by-trial adaptations as indicated by non-significant three-way interaction. Given that Experiment 2 did

444   not include a no-gaze condition, we ran the control Experiment 3 to estimate the baseline magnitude of the

445   SE elicited by our embodied setup.

446   Our results showed that when the robot did not display social gaze feedback, a SE of 34 ms was observed,

447   suggesting that our setup elicited overall a SE similar in magnitude to those reported in previous screen-

448   based studies using a similar procedure (e.g. D'ascenzo et al., 2018; Xiong & Proctor, 2015). Such result

449   is not in line with previous evidence showing that conflict effects, such as the Stroop effect, are reduced in

450   the presence of another agent (Huguet et al.,1999; Spatola et al ., 2018; see Belletier et al 2019 for a

451   review).

452   Overall, our results suggest that mutual gaze feedback affects conflict resolution in the subsequent

453   trial but only with the physical presence of the robot, i.e. when the gaze behaviour can be established in

454   real-time.

455   Our results extend earlier findings showing for the first time that social gaze feedback (even when

456   displayed by an artificial agent such as a humanoid robot) affects cognitive control. Specifically, its

457   modulatory effect on cognitive conflict appears to be in contrast to previous studies showing that the

458   negative affective state induced by losses or negative emotion enhances cognitive control resulting in a

459   smaller interference effect in conflict tasks (see van Steenbergen, 2015 for a review) and do not support

460   the affective-congruent hypothesis. Our results suggest that following mutual gaze feedback, **conflict**

461   **resolution** might be reduced in efficiency. Such a result is in line with evidence showing that mutual, but

462   not avoiding, gaze interferes with the inhibition of task-irrelevant information (Kompatsiari et al., 2021a).

463   Specifically, in a series of recent studies, Kompatsiari and colleagues showed that mutual gaze delays

464   attention disengagement from the non-predictive cue in a gaze cueing task. As a result, the distracting

465   effect of gaze cues was prolonged in time even when the stimulus onset asynchrony was equal to 1s

466   (Kompatsiari et al., 2021b). Using a decision-making task Belkaid et al., (2021) showed that mutual gaze

467 delayed reaction times by increasing the decision threshold. Also, iCub's mutual gaze was associated with

468 higher alpha synchronization in the EEG signal, indicating that during mutual gaze with the robot,

469 suppression mechanisms were activated. In a similar vein, in our study, mutual gaze may have affected

470 attention control on response selection. As a consequence, participants were delayed in solving the

471 response conflict elicited by the task-irrelevant spatial feature in non-corresponding trials. Interestingly, our

472 results showed that the effect of mutual gaze occurs not only when social gaze is provided as a cue

473 (Kompatsiari et al., 2021b) but also when the social gaze is manipulated as feedback, as its effect was

474 transferred to the processing of a stimulus presented in a subsequent trial. Our results can be considered

475 in the context of the proposal that social brain networks may be in antagonism with the frontoparietal

476 attentional network (e.g. Bossi et al., 2020; Anticevic et al., 2012; Fox et al., 2005). In line with this reasoning,

477 it could be that when presented with a socially relevant event, like the communicative mutual gaze, the

478 recruitment of social brain areas may act against the attentional focus. Future studies should systematically

479 address this hypothesis both at the neural and behavioural levels. One intriguing issue that remains to be

480 addressed is whether social signals interfere at the target processing level or the response selection stage.

481 This could be examined by presenting social gaze at the same time as the target stimulus.

482 Overall, our results indicate that social gaze feedbacks of a robot seem to be effective in modulating conflict

483 resolution but not for conflict adaptions. A similar dissociation has been shown in literature in those studies

484 that investigated individual differences in the cognitive control mechanism. For instance, Iani et al. (2014)

485 showed that while conflict resolution in a given trial is affected by age of the participants, the trial-by-trial

486 adaptations are not. Specifically, the authors reported a larger SE for first-grade children (6–7 years)

487 compared to second-graders (7–8 years) children, however, the reduction in the magnitude of the SE

488 following a conflict event (i.e. a non-corresponding trial) was comparable across groups (see also Larson,

489 et al., 2012; for similar results in elderly).

490 The lack of modulation in the trial-by-trial adaptations could be due to the fact that in our study, iCub's gaze

491 feedback was independent of participants' performance. Strümer and colleagues (2011) showed that, in a

492 Simon task, monetary gains and losses in between trials affected trial-by-trial adaptations only when they

493 were contingent on the actual performance (i.e., reward and penalties were assigned to the 25% fastest

494 and slowest responses) but not when they occurred randomly. Similar results have been reported also

495   using different conflict tasks, such as the Flanker task and the task-switch paradigm (Braem et al., 2012).

496   Future studies should investigate the effect of the social gaze feedbacks of a robot in affecting conflict

497   resolution and conflict adaptations in a response-contingent way. For instance, mutual and avoiding gaze

498   feedbacks could be provided to reward or punish the 25% fastest and slowest responses.

499   Finally, by comparing the effect of the social gaze feedback between screen-based and embodied

500   setups, our results show that only the latter was effective in affecting conflict resolution. Such a result

501   extends previous evidence showing that when investigating social gaze, screen-based protocols might lack

502   ecological validity (Kompatsiari et al., 2021b). For instance, Hietanen et al., (2008) showed that real-time

503   mutual gaze was associated with greater sympathetic arousal (skin conductance responses), than averted

504   gaze. Similarly, Pönkänen et al. (2011) reported different EEG asymmetries for faces that were presented

505   live through an electronic shutter and those that were presented as pictures on a computer screen. It has

506   been proposed that real-time social gaze is likely to play a greater role in influencing sensations of intimacy,

507   experienced self-relevance, and awareness about being seen by another person (or a robot) who is

508   physically present, as compared to seeing a picture of a face on a computer screen (Hietanen et al.,

509   2008, Pönkänen et al., 2011; Kompatsiari et al., 2018; 2019).

510   We believe that our results are crucial not only for fundamental research but also for applied

511   scenarios. The findings open up the possibility of using robots to train complex cognitive skills like self–

512   regulation. The main advantage of embedding robots within cognitive training protocols is the possibility of

513   maintaining good experimental control on the one hand and increased ecological validity on the other, an

514   aspect crucial for certain mechanisms of cognition, as our data show. Through their social presence, robots

515   can interact in real-time with the user in a shared environment. Through the implementation of motivational

516   and social behaviours, we believe that robots can improve learning. To date, robots have been mostly used

517   in rehabilitation protocols for motor and social skills, such as joint attention (see Chevalier et al., 2019 for a

518   review). However, taking into consideration that cognitive control, and response inhibition specifically, is

519   impaired not only in aging but also in several psychiatric disorders, such as but not limited to, eating and

520   mood disorders, Tourettes' syndrome, and obsessive-compulsive spectrum disorders, we propose that also

521   cognitive control training protocols can benefit from the implementation of robots. For instance, several

522   studies showed that children with attention-deficit/hyperactivity disorder (ADHD) report larger Simon and

523   Flanker effects when compared to children with typical development (for a review see Mullane, Corkum,

524   Klein, & McLaughlin, 2009). Also, it has been shown that conflict resolution and conflict adaptation

525   mechanisms are differently impaired in patients with eating disorders (Bartholdy et al., 2017). Using a stop-

526   signal task Bartholdy and colleagues showed that conflict resolution was enhanced in women with anorexia

527   compared to healthy controls, whereas no difference across groups was reported for reactive control

528   mechanisms. Similarly, Sellaro and Colzato (2017) reported a larger SE for overweight individuals

529   compared to normal-weight controls.

530   To conclude, the present study shows that robots' social gaze feedback modulates conflict resolution

531   in a Simon task but not conflict adaptations. The modulatory effect was observed for the embodied setup

532   in which the robot could engage or avoid eye contact in real-time, opening up the way to a new potential

533   application of robots in protocols aiming to investigate, and train, cognitive control and self-regulation in

534   both healthy and clinical populations.

535 **Acknowledgments**

542 **Additional information**

543 Data, videos, and stimuli are available at https://osf.io/nvcz6/

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