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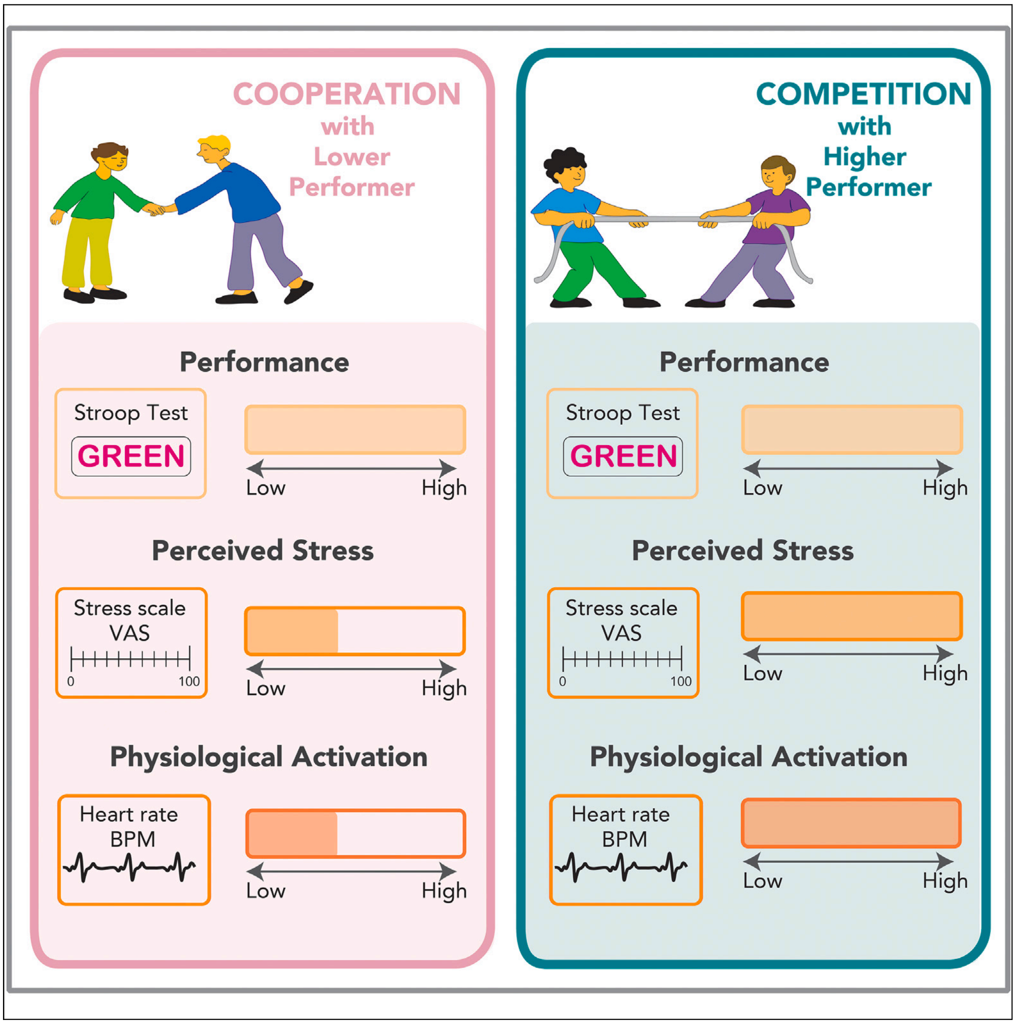

Lucia De Francesco, Alessandro Mazza, Matilde Sorrenti, ..., Francesco Strada, Andrea G. Bottino, Olga Dal Monte

olga.dalmonte@unito.it

Highlights

We examined how cooperation and competition influence individuals' performance

Competing with a more skilled opponent increases performance, stress, and BPM

Cooperating with a lower performer does not increase stress and BPM

These two patterns are stable when exposure to two contexts is prolonged over time

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Cooperation and competition have same benefits but different costs

Lucia De Francesco,[1] Alessandro Mazza,[1] Matilde Sorrenti,[1] Virginia Murino,[1] Edoardo Battegazzorre,[2] Francesco Strada,[2] Andrea G. Bottino,[2] and Olga Dal Monte[1,3,4,*]

SUMMARY

Cooperation and competition shape everyday human interactions and impact individuals' chances of success in different domains. Using a virtual Stroop test, classically employed to assess general cognitive interference, we examined the impact of social context (cooperation and competition) and other's ability (higher and lower performers) on performance, perceived stress, and autonomic activity. In Experiment 1, we found that both cooperation with a lower performer and competition with a higher performer led to similar enhancement in performance. However, only competition with a more skilled opponent induced an increase in perceived stress and physiological activity. Experiment 2 further demonstrated that these effects persisted even with prolonged exposure to these contexts. In summary, cooperation can be just as effective as competition in improving individuals' performance. However, cooperation does not carry the same level of stress and physiological burden as the competitive context, representing a healthier and more optimal way to boost individual performance.

INTRODUCTION

Humans as well as many other animals often cooperate or compete with others to achieve a common goal or outperform a conspecific, respectively.[1,2] From an evolutionary point of view, cooperation enhances survival chances against predators, facilitates mating, and helps to attain resources collectively; thus, it increases the group's overall survival fitness.[3,4] However, when resources are scarce or when social hierarchy must be established, individual rivalry emerges and competition becomes the optimal means to promote individual success.[5] Thus, unlike cooperation, competition inherently focuses on the victory of an individual over others.

Triplett,[6] in his seminal study, showed that competing with others while riding a bicycle leads to better performance than riding alone. Since then, many studies have confirmed that engaging in competitive context enhances individuals' performance.[7–9] This has given rise to a long-standing idea that people's extrinsic motivation can be heightened through competition.[10–12] However, what are the associated costs of this performance improvement? Competing contexts have been linked to an increase in autonomic activity, as measured by cardiovascular responses.[12–14] While these studies have shown that higher arousal is typically associated with improved performance, increased physiological activity has also been associated with detrimental effects on both physical and mental health.[15,16] As a consequence, the role of social stressors in controlling the autoregulation of the sympathetic nervous system is crucial for human well-being.[17–19]

Similarly to what has been reported in competition, some studies have observed an increase in performance during cooperative interactions compared to when individuals completed the same task alone.[20,21] However, unlike competition, this aspect has not been thoroughly explored and crucial information regarding the influence of cooperation on individual performance is still lacking. Moreover, given that increases in physiological activation within a social context can be associated to an enhancement in performance,[22–25] one would expect to observe this pattern within cooperation contexts as well. However, studies investigating the link between performance and physiological responses in cooperation have yielded inconsistent results. For example, Hariharan and colleagues[26] reported that during cooperation, a higher heart rate is associated with lower performance. Additionally, contrasting conclusions have also emerged from studies comparing individual performance during cooperation and competition. While some studies have highlighted how cooperation and competition might enhance distinct task dimensions,[27] others have reported results in favor of either competition[28] or cooperation[29] in terms of attention and performance enhancement. Along with these inconsistent and often contradictory results, to our knowledge, there have been no studies exploring the behavioral and physiological consequences of prolonged exposure to both cooperative and competitive contexts. Most studies examining both these social contexts have focused on short-term effects, often investigated through one-shot sessions in laboratory settings.[26,30] As a result, it remains unclear how these two social contexts might influence performance and psychophysiological stress during repetitive exposures.

[1]Department of Psychology, University of Turin, Torino, Italy
[2]Department of Control and Computer Engineering, Politecnico di Torino, Italy
[3]Department of Psychology, Yale University, New Haven, CT, USA
[4]Lead contact
*Correspondence: olga.dalmonte@unito.it
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Regardless of the interactive context and the type of exposure, a crucial factor contributing to a goal achievement is understanding the skills and shortcomings of the individual with whom we are about to compete or collaborate.[31] Indeed, both in competition and in cooperation, there is constant self-other monitoring[29,32,33] that allows individuals to adjust their effort based on the partner's skills and performance. For example, some studies have shown that competing with a skilled performer enhances people's outcomes by increasing motivation.[34–36] These findings have been interpreted in terms of the *assimilation effect*: when an observer compares his/her skills with those of a higher performer,[37] he/she witnesses a positive example and, in turn, performs better.[38] Concerning cooperation, the social compensation hypothesis states that when individuals anticipate that their colleagues may perform poorly on a task, they are inclined to exert more effort when collaborating compared to working alone.[39] However, in contrast to competition, no study has investigated how another's ability influences performance during cooperation, comparing different levels of the other's performance. Nevertheless, evidence suggests that in team-oriented settings such as cooperation, partners' alignment becomes crucial for team success[40,41]; thus, individuals might adjust their effort based on the partner's skills. As such, for common-goal achievement in team-centered contexts, it can be reasonable to expect individuals to increase their effort when the partner is less skilled, to compensate for their lack of ability.

In this study, we aimed to explore whether an individual's performance (accuracy), perceived stress (self-reports), and autonomic activity (heart rate) changed as a function of social context (cooperation and competition) and other's ability (higher or lower performer). To achieve this goal, we designed and implemented a virtual reality (VR) version of the Stroop test.[42] In the Stroop test, participants are presented with words representing colors (e.g., "Purple") that are written in either congruent or incongruent ink (e.g., in purple or green, respectively). They are then asked to report as quickly as possible the ink in which the word is written. In the incongruent condition, the subject faces a condition of cognitive conflict, which usually results in a lower accuracy. As such, the Stroop test measures selective attention and provides an index of cognitive interference. We invited participants to complete the Stroop task alone (solo condition), in cooperation, and in competition with either a higher or lower performing virtual agent (Figure 1A). We chose to adopt VR because not only it has been validated as a tool to reproduce social settings and investigate the influence of social variables,[36,43,44] but it also allowed us to rigorously control the skillfulness of the virtual co-actor by means of an algorithm specifically tailored on each participant's individual performance (Figure 1B). Additionally, as we were interested in investigating the long-term effects of competitive and cooperative interactions on performance, perceived stress, and autonomic activity, we conducted an additional experiment. In Experiment 2, participants were exposed to competitive and cooperative contexts over an extended period of time.

We hypothesized to find a *social facilitation effect*[24,45–47] by which participants would perform better in both cooperation and competition (i.e., social context) compared to when individuals completed the same task alone (solo condition). Also, we predicted a modulation of performance based on the combination of social context and other's ability. Specifically, we hypothesized to observe a boost in performance when subjects competed against a higher performer compared to a lower one (in line with the *assimilation effect*), combined with an increase in perceived stress and autonomic activity. Also, a boost in performance was expected when participants cooperated with a poorer performer teammate compared to a more skilled one, indicating a stronger individual effort to compensate for the co-actor's weaknesses to accomplish mutual goals. Finally, for the long-term effect (Experiment 2), we expected to observe similar results as those reported in the first experiment. Specifically, we hypothesized to find a prolonged increase in both perceived stress and autonomic activity during the competition with a higher performer compared to the cooperation with a less skilled teammate but equal performance between the two conditions. This effect is expected not only for the initial interaction but also over an extended period, suggesting a lasting impact of both the perceived stress and autonomic activity overtime.

RESULTS AND DISCUSSION

Experiment 1

Co-actors' ability as a modulator of performance in different social contexts

In the present experiment, we investigated how cooperation and competition influence individuals' performance in completing a Stroop test, depending on the virtual co-actor's ability. In the cooperation context, a participant played together with a virtual teammate: they needed to provide the correct answer for each Stroop item to earn a point collectively, aiming to outscore a fictional opposing team. In the competition context, a participant played against a virtual opponent, striving to score more points than him/her. In both contexts, the virtual co-actor was either a better or a lower performer compared to the participant.

Before investigating whether and how participants' performance in a social context was influenced by the skills of another individual, we first focused on validating the efficacy of our virtual version of the Stroop task (Figure S2A) in inducing cognitive interference in our participants.[42] Next, we confirmed the presence of a *social facilitation effect*,[24] defined as the occurrence of a performance improvement when a well-learned task is conducted in the presence of other individuals compared to when it is done alone.[24,25,48] Indeed, both competition and cooperation enhanced individual performance with respect to the solo condition (Figure S2B-C). Lastly, we confirmed a positive link between performance and competitive personality traits (Figure S2D-E).

To examine the impact that a co-actor's ability might have on someone's performance improvements when compared to a solo condition, we manipulated the skillfulness of the virtual co-actor; hence, participants (n = 50; STAR Methods for details) could either cooperate or compete with a better or a worse performer. The 2 × 2 ANOVA on accuracy with social context (competition and cooperation) and other's ability (higher and lower performer) as within-subjects factors (see STAR Methods for details) revealed no significant main effects but a significant interaction social context × other's ability ($F_{(1, 49)} = 18.974$, $p < 0.001$, $\eta^2_p = 0.279$), indicating that another person's ability has a

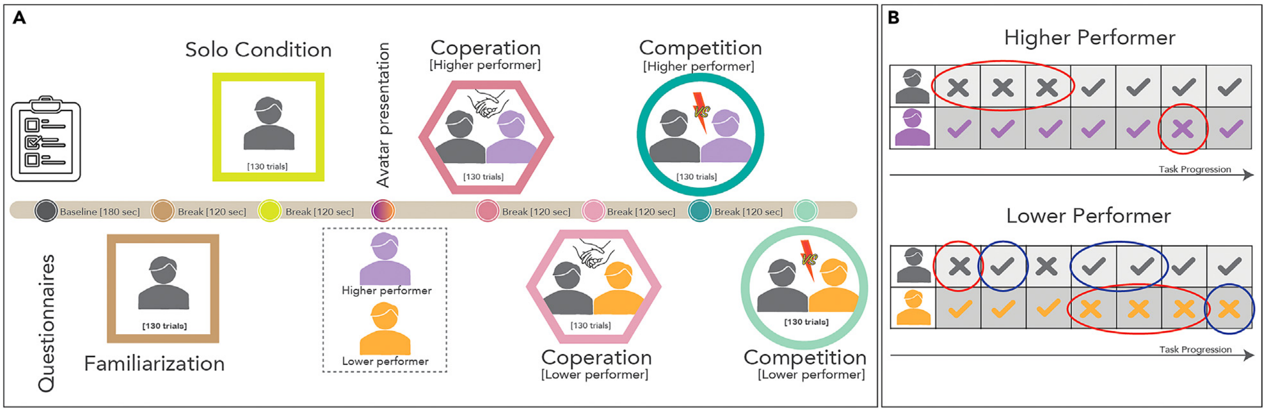

Figure 1. Experimental conditions, task progression, and algorithm for the virtual agent's performance

(A) Experimental conditions task progression. At the beginning of each experimental session, subjects were invited to fill in two questionnaires (see Methods section). After that, we asked participants to rest in the virtual environment for 180 s (baseline [180 s]) to record their baseline physiological activity. Then, before starting the experimental conditions, subjects underwent a *familiarization* phase (130 trials) to give them the opportunity to fully learn the task. After this initial phase, the experimental session started with a *solo* condition. Following the *solo* condition, participants were introduced to two virtual players (virtual agents' presentation). One agent was described as a higher performer (better accuracy and faster reaction time (RT) than the experimental subject in the *solo* condition) and the other as a lower performer (worse accuracy and slower RT than the experimental subject in the *solo* condition). Then each subject performed 4 social blocks in a counterbalanced order: *cooperation with a higher performer*, *cooperation with a lower performer*, *competition with a higher performer*, and *competition with a lower performer*. A pause of 120 s separated each block.

(B) Virtual agent's performance algorithm. The left side depicts the algorithm implemented for the higher performer. The top row depicts a subject's behavior example in terms of fails (i.e., ✕) and correct (i.e., ✓) answers (in gray). The bottom row represents the higher agent's performance (in purple) following the subject's behavior. For the higher performer, we implemented a delayed "tit for three tats": for every three participant's fails, the agent failed one with a delay of three trials (red circles). The right side depicts the algorithm implemented for the lower performer. The top row depicts a subject's behavior example (in gray). The bottom row represents the lower agent's performance (in orange) following the subject's behavior. For the lower performer we combined two algorithms: (1) a delayed "three tits for one tat": for each participant's fail, the agent failed three times with a delay of three trials (red circles); (2) for every three correct participant's responses, the agent failed one with no delay (blue circles).

different impact on competition and cooperation. Post hoc pairwise comparisons showed a double dissociation, in which during cooperation participants were more accurate with a lower than a higher performer ($t_{(49)} = 2.715$, $p = 0.018$), while during competition they performed better with a higher than a lower performer ($t_{(49)} = 3.008$, $p = 0.016$). Interestingly, the accuracy during cooperation with a lower performer did not differ from the accuracy in competition with a higher performer ($t_{(49)} = 1.122$, $p = 0.356$) (Figure 2A), suggesting a comparable performance in the two social contexts. This double dissociation shows that the skillfulness of another person is a crucial factor to be considered during dyadic interactions, yielding opposite outcomes depending on whether people are competing or cooperating with a specific individual. We speculate that this result might be explained by two separate mechanisms relative to each social context.

First, cooperating means working together to reach a common achievement: the goal is not self-centered but team-centered, and cooperation works when each component of the team contributes to achieve a common goal.[49] Such a reciprocal interdependence prompts individuals to estimate how much collective effort is required to achieve a goal, based on reliance and concerns about the team.[50] Thus, acknowledging the co-actor's task-related weaknesses and strengths directly weighs the perceived chances of success[41] and influences one's prediction about the individual effort required to accomplish the task. It is therefore plausible that when our participants cooperated with a lower performer, they anticipated that they needed to compensate for the co-actor's weaknesses, hence performing at their individual best to reach an otherwise unachievable common goal. Classical game theory frameworks define cooperation as the altruistic act of sacrificing self-interests to benefit another individual.[51] However, more naturalistic perspectives suggest that cooperation might also serve as a means to pursue direct or indirect benefits.[52,53]Both these observations could also explain our results, and it is possible that participants decided to invest extra effort in order to reach a common goal, which would yield benefits not only for others or the team but also for themselves. Indeed, studies on both animals and humans have shown that during cooperation, the actor's objective is not solely to provide benefits exclusively to the others but rather to achieve a common goal. Reaching a common goal, indeed, is at the basis of cooperation and it not only ensures a great performance but also increases the likelihood of future engagement in this social construct again.[54,55] Similarly, when they cooperated with a higher performer, they possibly foresaw that the team's chances of success were higher *a priori* and could afford to save cognitive energies without compromising their chances of success, resulting in relatively poorer individual performance. Within this framework, it becomes relevant to consider the potential external motivations that arise during this type of intergroup rivalry. Such motivations, usually present in a competitive context, may have influenced participants in evaluating the effort needed to outperform the opposing team.[56] To the best of our knowledge, this is the first study investigating the influence of a co-actor's ability on an individual's performance during a cooperation context, and our results might help to shed light on this unexplored topic and provide suggestions for future investigations.

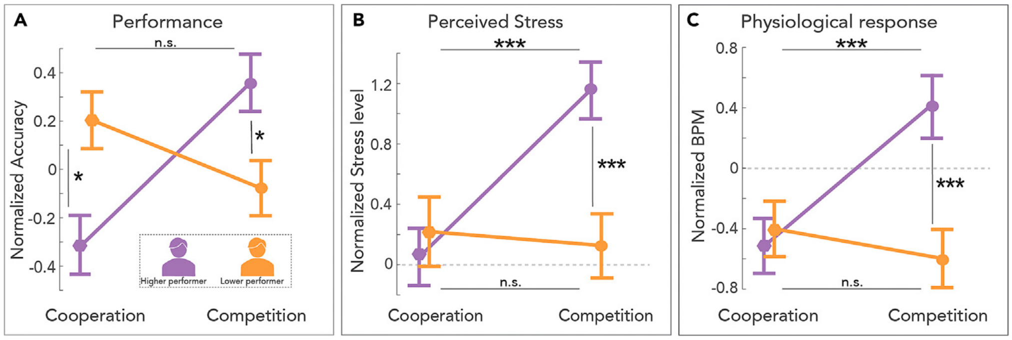

Figure 2. Short-term effects of social context and other's ability on performance, perceived stress, and physiological response

(A) *Z* scored mean accuracy values during cooperation (hexagon) and competition (circle) with a higher performer (purple line) and a lower performer (orange line).

(B) *Z* scored mean perceived stress level values during cooperation (hexagon) and competition (circle) with a higher performer (purple line) and a lower performer (orange line). Horizontal dotted gray line indicates stress level during solo condition.

(C) *Z* scored mean BPM values during cooperation (hexagon) and competition (circle) with a higher performer (purple line) and a lower performer (orange line). Horizontal dotted gray line indicates BPM level during solo condition. Values shown are *Z* scored $\pm$ SEM. Significant results are indicated by asterisk * = $p < 0.05$; *** = $p < 0.001$. n.s. = not significant.

Second, during competition, the individuals' goal is self-centered; by definition, performing better than others is necessary to win in competitive contexts. Under specific conditions, facing an individual known to be a good performer can increase motivation, a pivotal proximal mechanism in task engagement during competition[56–58] that prompts individuals to perform better.[10,59,60] For this to happen, such upward comparison should be directed toward a target that is perceived as attainable.[35,36,61–64] In this case, upward comparison triggers the emergence of positive feelings and results in an enhanced commitment to the task.[38] This mechanism, known as an *assimilation effect*,[37] might explain our results: indeed, our participants performed a well-learned task (as shown by the learning curves during the familiarization phase; Figure S2F), and the higher performer's skillfulness was tailored such that it remained a few points ahead of the experimental subject's scoring (STAR Methods for details). Accordingly, it is possible that when the other is known to be a poor performer, the goal is perceived as much more achievable, and there is no need to spend a high amount of energy to win: this might translate into a lower motivational state, less engagement, and therefore result in relatively poorer performance.

In summary, the two social contexts that maximize performance were cooperation with a lower performer and competition with a higher performer, allowing us to infer that individuals can achieve the same level of performance in both cooperation and competition, contingent upon others' abilities.

Competing with a better performer increases perceived stress

Along with the experimental subjects' performance, we also tracked the stress level that participants reported at the end of each condition. We ran a 2 × 2 ANOVA on perceived stress (see STAR Methods for details) with social context (competition and cooperation) and other's ability (higher and lower performer) as within-subjects. Results showed a significant main effect of social context ($F_{(1,\ 47)} = 19.549$, $p < 0.001$, $\eta^2_p = 0.294$), with competition showing higher stress than cooperation ($t_{(47)} = 4.421$, $p < 0.001$). It also showed a significant main effect of other's ability ($F_{(1,\ 47)} = 12.822$, $p = 0.001$, $\eta^2_p = 0.214$), indicating that participants felt more stressed when interacting with a higher performer compared to a lower performer ($t_{(47)} = 3.581$, $p < 0.001$). Crucially, we also found a significant interaction social context × other's ability ($F_{(1,\ 47)} = 29.096$, $p < 0.001$, $\eta^2_p = 0.382$). Post hoc comparisons revealed that both main effects were driven by competition with a higher performer, as this condition resulted in greater perceived stress than all the other conditions (all *p*s < 0.001), which, in turn, did not differ among them (all *p*s > 0.05; Figure 2B). Furthermore, to test whether these measures also reflected a neat increase/decrease with respect to the solo condition, we ran four separate one-sample t tests against zero (i.e., solo condition), for each condition separately. Results revealed that only competition with a higher performer significantly increased perceived stress with respect to the solo condition ($t_{(47)} = 6.218$, $p < 0.001$), as opposed to the other social contexts (all *p*s > 0.05; Figure 2B).

Overall, these results indicate that competing with a higher performer is not only associated with an enhancement in performance, as highlighted by the results on the accuracy, but also with a greater level of perceived stress compared to all the other conditions. Therefore, despite cooperating with a lower performer yielded a similar improvement in performance as competing with a higher performer, in this latter condition, participants also felt significantly more stressed. These findings shed light on the costs of performance improvement due to either cooperation or competition. It is indeed known that beyond performance improvements, competition also brings anxiety and stress in a wide range of activities[65,66] and can result in harmful psychological outcomes.[67,68] Notably, the competing context was also the only one where participants reported a net increase in perceived stress with respect to the solo condition. Therefore, if we consider psychophysiological rebounds, is there a preferable way of ameliorating individuals' performance? While competing with a more skilled opponent corresponded to performance amelioration, our participants also reported that this was the most stressful condition. On the contrary, cooperating with a poorer performer teammate yielded a comparable performance improvement, but with a significantly minor psychophysiological cost. Thus, even though competition revealed its advantages in terms of performance, it also revealed its negative side effects in terms of perceived stress.[65–67]

Competing with a better performer increases physiological responses

To investigate whether and how participants' autonomic activity was also influenced by social context and other's ability, we ran a 2 × 2 ANOVA on beats per minute (BPM) (see STAR Methods for details) with social context (competition and cooperation) and other's ability (higher and lower performer) as within-subjects factors. We found a significant main effect of social context ($F_{(1, 49)} = 5.978$, $p = 0.018$, $\eta^2_p = 0.109$), with competition showing larger BPM than cooperation ($t_{(49)} = 2.445$, $p = 0.018$) and a significant main effect of other's ability ($F_{(1, 49)} = 13.415$, $p = 0.001$, $\eta^2_p = 0.215$), indicating that participants had greater BPM when interacting with a higher performer compared to a lower performer ($t_{(49)} = 3.663$, $p = 0.001$). We also found a significant interaction social context × other's ability ($F_{(1, 49)} = 34.678$, $p < 0.001$, $\eta^2_p = 0.414$). Post hoc comparisons revealed that both main effects were driven by competing with a higher performer, as this condition resulted in larger physiological activation than all the other social contexts (all *p*s < 0.001), which, in turn, did not differ among them (all *p*s > 0.05; Figure 2C). Crucially, these results were not driven by an increase in motor response speed during competition with a higher performer (See STAR Methods – Experimental procedure – Data Analysis). Furthermore, to test whether these measures also reflected a net increase/decrease with respect to the solo condition, we ran four separate one-sample t tests against zero (i.e., solo condition), one for each condition separately. Similarly to the results obtained on perceived stress, we found that competing with a higher performer was the only condition that significantly increased heart rate with respect to the solo condition ($t_{(49)} = 2.086$, $p = 0.042$), whereas in all the other conditions, heart rate was lower than the solo condition (all *p*s < 0.05).

Thus, heart rate followed the same pattern of perceived stress: participants showed an increase in both explicit (stress perceived) and implicit (physiological activation) stress levels when competing against a higher performer compared to all the other social contexts as well as to the solo condition. The similarity between perceived stress and heart rate suggests that the increase in physiological activation could reflect a negative state rather than a positive challenging state. Heart rate is a reliable measure of induced stress both in virtual environments[69] and in competitive Stroop test.[70] Thus, while competition might motivate individuals to achieve greater performance, it also brings detrimental psychophysiological burdens typical of acute social stressors,[17–19] which can have deep impacts on mental and physical health.[67,71] On the contrary, a cooperative setting yielded the same performance as competition but did not imply any drawback at the stress level. These results might in part be also explained by recent meta-analytic studies reporting consistent associations between upward comparison and activations in pain-related brain areas as well as between downward comparison and activations in reward-related circuits.[72,73] While these findings support the idea that upward and downward comparisons are associated with negative and positive emotional states, respectively,[74,75] nonetheless, our results suggest that such associations might be selective depending on the social context. Only within a competition context, the upward comparison leads to increased stress and autonomic reactivity with respect to the downward comparison. Conversely, during cooperation, stress levels and heart rate are not modulated by the skills of another individual, although the best performance is achieved when cooperating with a poorer performer teammate.

Experiment 2

Long-term effect of cooperation and competition on performance

Given our interest in investigating the long-term effects of competitive and cooperative interactions on performance, perceived stress, and autonomic activity, we conducted a second experiment where participants were exposed to competitive and cooperative contexts over an extended period of time. Guided by the results obtained in the first experiment, here we focused on the two experimental conditions promoting a similar positive effect on performance but a different impact on stress level and autonomic activity (namely, cooperation with the lower performer and competition with the higher performer). Experiment 2 was conducted in the same virtual setting as Experiment 1 (Figure S1). The structure of the Stroop test as well as the algorithm monitoring the virtual co-actor's performance trial by trial and tailoring it to the accuracy of the experimental subject remained identical to that in Experiment 1. However, compared to the first experiment, participants were invited to perform three consecutive blocks for each social context of interest (Figure 3A). Before the beginning of the experimental session, participants (*n* = 58; see STAR Methods for details and power calculations) underwent a block of familiarization phase to prevent any learning effect in the experimental conditions (see STAR Methods – Data Analysis). The experimental session included seven blocks: one block of solo condition, 3 consecutive blocks of cooperation with the lower performer (1st block, 2nd block, and 3rd block), and 3 consecutive blocks of competition with the higher performer (1st block, 2nd block, and 3rd block). To investigate the behavioral consequences of prolonged exposure to cooperative and competitive contexts, we ran a 2 × 3 repeated measure ANOVA on accuracy (see STAR Methods for details) with social context (competition and cooperation) and repetition (1st block, 2nd block, and 3rd block) as within-subjects factors. The analysis revealed no significant main effect of social context ($F_{(1, 57)} = 0.289$, $p = 0.593$, $\eta^2_p = 0.012$), confirming the same performance during competition with higher performer and cooperation with lower performer (1st block: $t_{(57)} = 0.398$, $p = 1.038$; 2nd block: $t_{(57)} = 0.570$, $p = 1.712$; 3rd block: $t_{(57)} = 0.313$, $p = 0.755$). Then, the analyses also showed a significant main effect repetition ($F_{(1, 57)} = 9.938$, $p < 0.001$, $\eta^2_p = 0.290$) indicating that, regardless of social context, repeating the task for three blocks with no pauses influenced the performance. Post hoc analyses indicated a significant difference between the 1st block compared to the 2nd block ($t_{(57)} = 3.349$, $p = 0.001$) and between the 1st block compared to the 3rd block ($t_{(57)} = 4.273$, $p < 0.001$), showing that during the first

Figure 3. Experimental conditions, task progression, and long-term effects on performance, perceived stress, and physiological response

(A) Experimental conditions task progression. At the beginning of each experimental session, we asked participants to rest in the virtual environment for 180 s (baseline [180 s]) to record their baseline physiological activity. Then, before starting the experimental sessions, subjects underwent a *familiarization* block (130 trials) to give them the opportunity to fully learn the task. After this, the experimental session started with a *solo* block condition. Following the *solo* condition, participants were introduced to two virtual players (virtual agents' presentation). One virtual agent was described as a higher performer (better accuracy and faster RT than the experimental subject in the *solo* condition) and the other as a lower performer (worse accuracy and slower RT than the experimental subject in the *solo* condition). Then, each subject performed 3 consecutive blocks (130 trials each) of cooperation with a lower performer condition and 3 consecutive blocks of competition with a higher performer. The order of these two social contexts was counterbalanced across participants.

(B) *Z* scored mean accuracy values during the first block, the second block, and the third block of cooperation with the lower performer (pink) and competition with the higher performer (green). Values shown are *Z* scored ± SEM.

(C) *Z* scored mean perceived stress level in cooperation with the lower performer (pink) and competition with the higher performer (green) during the first block, the second block, and the third block. Values shown are *Z* scored ± SEM.

(D) *Z* scored mean BPM values in cooperation with the lower performer (pink) and competition with the higher performer (green) during the first block, the block, and the third block. Values shown are *Z* scored ± SEM. Significant results are indicated by asterisk ** = $p < 0.01$; *** = $p < 0.001$. n.s. = not significant.

block, participants performed worse compared to the other two blocks (Figure 3B). However, this result is not driven by any learning effect during the experimental session, given that participants achieved a consistent performance level after the familiarization phase (see STAR Methods – Data Analysis).

The results of Experiment 2, showing similar accuracy between the two conditions during the first block, reinforce the strength of our findings in Experiment 1 and validate them with a new and large sample of subjects. Additionally, the overtime effect also confirmed the existing literature, demonstrating that consecutive repetitions of a task can enhance performance,[76,77] regardless of the social context. Most importantly, these findings are crucial for understanding the impact of prolonged exposure to these specific social contexts, suggesting that both cooperation and competition promote a similarly enhanced performance also during several repetitions of the same task. Some studies have explored the long-term effects of cooperation and competition in longitudinal studies; for instance, they have investigated how competitive or cooperative settings affect learning in classrooms.[78–80] However, these studies have been conducted in naturalistic but loosely controlled contexts and have based their investigation on observational methods. Therefore, this study represents to our knowledge the first investigation into the effect of prolonged exposure to these specific social contexts, suggesting that even by repeating the task several times, participants can always reach the same level of performance in cooperation with the lower performer and competition with the higher performer.

The increase in psychophysiological stress during competition is persistent over time

Along with the experimental subjects' performance, we also tracked the stress level that participants reported at the end of each block as well as their physiological activity (heart rate) to investigate the long-term effects of competitive and cooperative interactions at the psychophysiological level. We ran two separate 2 × 3 ANOVAs on perceived stress and BPM, with social context (competition and cooperation) and repetition (1st block, 2nd block, and 3rd block) as within-subjects factors. The ANOVA on perceived stress level showed a significant main effect of social context ($F_{(1, 57)} = 19.796$, $p < 0.001$, $\eta^2_p = 0.258$), with competition showing higher stress than cooperation ($t_{(47)} = 4.449$, $p < 0.001$) at each repetition (1st block: $t_{(57)} = 2.903$, $p = 0.005$; 2nd block: $t_{(57)} = 3.425$, $p = 0.001$; 3rd block: $t_{(57)} = 4.345$, $p < 0.001$) (Figure 3C). Consistently, the ANOVA on BPM showed a significant main effect of social context ($F_{(1, 47)} = 37.247$ $p < 0.001$, $\eta^2_p = 0.466$), with competition showing larger BPM than cooperation ($t_{(47)} = 6.103$, $p < 0.001$). Post hoc analyses revealed that this difference was present at each repetition (1st block: $t_{(47)} = 4.846$, $p < 0.001$; 2nd block: $t_{(47)} = 3.597$, $p = 0.001$; 3rd block: $t_{(47)} = 3.280$, $p = 0.002$) (Figure 3D).

Overall, these results demonstrated that competing with a higher performer is associated with a greater level of perceived stress and crucially this level does not decrease overtime. This implies that the effect found in Experiment 1 is also consistent overtime, as the increased number of consecutive trials did not modulate the effect of competition on stress, which always persisted as the most stressful condition, while the performance levels remained comparable. Also, like in the first experiment, heart rate followed the same pattern of perceived stress: participants showed an increase in both physiological activation and stress level when competing with a higher performer with respect to when cooperating with a lower performer consistently overtime. Thus, not only did the performance boost show persistency across time in both contexts, but also the associated costs of competition remained constant across diverse blocks. This means that competing with a higher performer consistently emerged as the most stressful and arousing condition during each block, indicating that participants were unable to mitigate stress and sustained heightened activation compared to cooperative scenarios with a lower performer. Importantly, these results suggest that the mental and physical health risk found in Experiment 1[67,71] related to a competitive environment does not diminish with increased exposure to it, indicating that habituation to this social context does not mitigate its negative consequences. In summary, while individuals may maintain a great performance when exposed to a competitive environment even for a long period of time, the sustained physiological activation associated with such conditions may have lasting implications for overall well-being. This emphasizes the need to consider the psychophysiological consequences that prolonged high levels of stress might have on the organism.

Conclusions

The goal of this study was to examine whether and how an individual's performance, perceived stress, and autonomic activity vary based on social context (cooperation and competition) and other's ability (higher or lower performer). Additionally, through repetitive exposures to these two social contexts, our aim was to investigate the behavioral and physiological consequences of prolonged exposition, compared to one-shot experimental conditions, in both cooperative and competitive contexts. To achieve this goal, we created a virtual version of the Stroop test and asked participants to complete the task either alone or in dyadic interaction with a virtual agent, within a cooperative and competitive setting. Notably, most of the studies using this test to explore the influence of social stimuli only employed either paper-pencil or computer-based tasks.[21,62,81] Our study has explored this topic with 3D virtual co-acting agents as elements of social context. Virtual ecological environments increase participants' engagement and sense of presence while providing complete control over the experimental variables. Indeed, we implemented an algorithm capable of tailoring the agent's performance according to the accuracy of each subject, allowing us to examine whether the participants' performance changed when interacting with a higher or lower performer. Finally, we quantified how much stress the different settings induced in each participant by analyzing both perceived stress (i.e., self-reports) and physiological stress (i.e., heart rate).

We showed that the skills of others have a strong influence on performance, with the best performance observed both when cooperating with a less skilled teammate and competing with a better opponent. However, while performance in these two contexts was comparable, explicit (stress level) and implicit (heart rate) measures revealed that competition was also associated with increased autonomic activity and perceived stress. Finally, our findings indicate that when exposure to both cooperative and competitive contexts is prolonged over time, both are confirmed as effective boosters of performance. However, it is noteworthy that the increased stress and autonomic response in competition persist over time. Thus, while competition enhances motivation and performance, it also carries a negative impact on psychophysiological levels. Overall, our study suggests that cooperation could be considered an optimal solution when considering performance achievements and individual psychophysiological well-being.

Limitations of the study

While the study provides valuable insights into the influence of cooperation and competition on different behavioral and physiological variables, there are several limitations to consider. In the last decade, different studies have shown that VR is highly relevant in the study of social behavior, and the virtual scenarios are considered ecologically valid yet controlled environments.[36,43,44] However, repeating the experiment in a real-life setting could enhance its generalizability. Moreover, with the aim of using a task largely employed in the literature, the study adopted a virtual version of the Stroop test, which at the same time, may not fully represent or capture the complexity of human interactions in various contexts. Another limitation of this task could be its lack of adaptability across different conditions. Future studies might consider using a task that adjusts to various social environments, such as incorporating increased reciprocity in cooperation, for instance. Finally, the literature does not provide a unanimous definition of cooperation: its complexity has led to identifying different social contexts or behaviors as cooperative scenarios. For instance, some studies have used this term to indicate an act of prosocial behavior,[82,83] while others have employed a division of labor between teammates to create cooperative interactions and reach a common goal.[20,21] Finally, some imply building a team and reaching a shared goal by working on the same task together, which suggests that the team's components help each other and rely on the others to reach a better team performance.[84] In our study, we used this latest definition of cooperation to create a social context in which the subjects could genuinely feel they were making a concrete contribution to reach the goal, and simultaneously, they could recognize the contributions of others and rely on them in challenging situations. Although this type of team cooperation aimed at outperforming the opposing team, it may involve competitive elements. Participants may have experienced an extrinsic motivation similar to competitive interactions, thus creating a social context that could be also defined as intergroup competition.[56] To explore the concept of cooperation more thoroughly, future studies should investigate alternative cooperative settings not influenced by competitive dynamics, potentially validating our findings, or revealing differences across different collaborative contexts. Also, we did not quantify participants' level of effort, which could have provided clearer insight into how the co-actor's ability affects performance. Future research should take this aspect into account to better understand whether the enhanced performance observed in cooperation with a less skilled partner and competition with a more skilled one is indeed due to increased effort from participants. Finally, it is not possible to completely rule out the possibility that our physiological results might reflect a positive emotional state. For example, it is possible that, at least for some participants, competition had an excitatory effect,[14] thus possibly resulting in increased heart rate. Future studies should implement additional measurements to investigate the valence related to any physiological modulations.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.110292.

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AUTHOR CONTRIBUTIONS

L.D.F., A.M., and O.D.M. designed the study; E.B., F.S., and A.G.B. implemented the virtual reality environment; L.D.F., M.S., and V.M. performed the experiments; L.D.F. and A.M. analyzed the data; and L.D.F., A.M., and O.D.M. wrote the paper. All authors reviewed the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Matlab (Version R2021a)	MathWorks	https://it.mathworks.com/?s_tid=gn_logo
SPSS (Version 29.0)	IBM	https://www.ibm.com/support/pages/downloading-ibm-spss-statistics-23
iMotions (Version 8.2)	iMotions	https://imotions.com/about-us/
Unity (Version 2021.1.20)	Unity Technologies	https://unity.com/
Other		
BIOPAC MP160	Biopac Systems, Inc	https://www.biopac.com/
Oculus Rift S	Meta Quest	https://www.meta.com/gb/en/quest/?utm_source=www.oculus.com&utm_medium=oculusredirect

RESOURCE AVAILABILITY

Lead contact

For additional details and inquiries regarding data sharing, please contact Olga Dal Monte (olga.dalmonte@unito.it), who will handle and fulfill your requests promptly.

Materials availability

This study did not generate any new unique materials other than the data collected and the virtual reality environment, which can be provided upon request to the lead contact.

Data and code availability

- The behavioral and psychophysiological data collected (datasets) are available in the following repository and publicly accessible: https://github.com/SocialInteractionLabUnito/Stroop_VR_CoopComp
- The original codes used to process and analyze data are available in the following repository and publicly accessible: https://github.com/SocialInteractionLabUnito/Stroop_VR_CoopComp
- For additional details and inquiries related to the data and the analysis reported in this paper refer to the lead contact

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

We recruited a total of 108 healthy participants for this study. A-priori power analyses run on GPower*3 (Faul et al., 2007) indicated that in order to achieve a 95% statistical power for observing a medium effect size of f = 0.25 with an α error level of 0.05, sample sizes of N = 36 and N = 28 were required for Experiment 1 (4 repeated-measure observations) and Experiment 2 (6 repeated-measure observations), respectively. Experiment 1 involved the participation of 50 experimental subjects (28 males; mean age = 24.57, SD = 4.14) and Experiment 2 of 58 (20 males; mean age = 24,41, SD = 5.85). All the participants reported normal or corrected to normal vision, did not have any history of neurological or psychiatric disease, and signed the written informed consent before taking part in this experiment, no other exclusion criteria were applied. All experimental procedures were approved by the Bioethical Committee of the University of Turin and conducted in accordance with the ethical standards of the 2013 Declaration of Helsinki (World Medical Association; 2013). Participants were recruited from a participants' database or through flyers posted on the University website. At the end of the experiments, all participants were informed about the aims and scopes of the experiment and did not receive any compensation for participation in this research study.

METHOD DETAILS

Study design and experimental procedures

Setting

An immersive virtual reality version of the Stroop test[85–87] was designed and implemented using the *Unity 3D* game engine and presented to all participants via a Head Mounted Display (HMD) (Oculus Rift S equipped with two Fast-switch LCD displays with a resolution of 1280x1440 each, refresh rate at 80 Hz, field of view of 115° and 6 degrees of freedom). The Stroop test was implemented in a virtual room (Figure S1A) and the virtual agents presented in the different scenarios were created in DAZ Studio. The experimental subject was represented by either a female or a male virtual agent seated on an armchair aligned with respect to her/his actual physical body coordinates to guarantee a sense of body ownership (Figure S1B). Participants could control their avatar's hands with the HMD controllers and received vibratory feedback when pressing a virtual button. Furthermore, to enhance the sense of immersion and presence in our experimental subjects, inverse kinematics was used to animate the movements of the virtual avatar's upper body in response to the participant's hand movements.

Virtual Stroop test

The stimuli were displayed on a black screen in front of the participant's avatar and the subject was instructed to respond as fast and accurately as possible to the stimulus presented by virtually pressing one of the six colored buttons on the control panel in front of him/her (Figure S1B). The Stroop stimulus was represented by a word depicting the meaning of a color (e.g., "PURPLE") colored in either a congruent (e.g., in purple) or incongruent (e.g., in blue) manner. Additionally, within each block, the participant performed both the classical and the reverse versions of the Stroop test, alternately. In the classical version, participants responded to the non-dominant feature of the stimuli (ink of the word)[42,81,88,89]; whereas, in the reverse version, participants responded to the dominant feature of the Stroop stimulus (meaning of the word).[90,91] Thus, in each trial underneath the stimulus (word depicting the meaning of a color) participants were also presented with two possible different labels: "meaning" if they had to press the color matching the meaning of the word and ignore the color of the word, or the label "ink" if they had to press the color matching the word ink and ignore the meaning of the word (Figure S1C). Each block consisted of 130 trials (60% congruent and 40% incongruent), each lasting a maximum of 1.5 seconds. The switch between classical and reverse versions of the Stroop test occurred every 12 trials. Also, to avoid spatial learning effects, the colored buttons changed their position over the control panel every 10 trials throughout the block.

Physiological recordings

For the physiological data recordings, an MP160 (Biopac Systems, Inc.) biosignal amplifier was used during the whole experimental session. For ECG recordings, pre-gelled shielded electrodes were applied with a Lead II montage using the standard limb electrode placement.[92] The gain parameter was set at 1000 ($\pm$ 10 mV), and the signal was sampled at 500 Hz with a 150 Hz low pass and a 0.05 Hz high pass filter.

Experiment 1

Before the experimental session started participants signed the written informed consent, provided their demographical data, and completed in a counterbalanced manner the following two questionnaires: the Competitive–Cooperative Personality Scale (CCPS[93]) to assess competitive and cooperative personality traits and the General Self-Efficacy scale (GSE[94]) to assess subject's self-efficacy. After, electrodes were placed on each participant to record electrocardiogram (ECG) activity.

During the experimental session, participants sat on a chair for the entire duration of the study. Once seated, they were asked to wear the HMD, which allowed them to interact in the virtual environment. Before introducing them to the virtual Stroop test, we asked participants to rest in the virtual environment for 180 seconds to record their baseline physiological activity. Then, before starting the experimental conditions, subjects underwent a Familiarization condition (130 trials) to prevent any learning that could affect the experimental conditions. After this initial phase, the experimental session started and included: a block of Solo condition, two blocks of Cooperation conditions, and two blocks of Competition conditions (Figure 1A). During the Solo condition, the player performed the Stroop test alone in the virtual room, and a single score tracking bar in the inferior part of the screen traced the subject's performance (**Fgure S1C top**). Following the Solo condition, participants were introduced to two virtual players (Figure 1A and Figure S1D). One virtual agent was described as Higher performer (better accuracy and faster RT than the experimental subject in the Solo condition) and the other one as Lower performer (worse accuracy and slower RT than the experimental subject in the Solo condition). We implemented an algorithm to precisely adjust trial by trial the virtual co-actor's performance based on the accuracy of the experimental subject (Figure 1B). Specifically, for the Higher performer, we implemented a delayed "tit for three tats": every three participant's fails, the virtual agent failed one with a delay of three trials (Figure 1B-**left**). For the Lower performer, we combined two algorithms: (i) a delayed "three tits for one tat": for each participant's fail, the agent failed three times with a delay of three trials; (ii) for every three correct participant's responses, the agent failed one with no delay (Figure 1B-**right**). This implementation avoided the virtual agent's performance being perceived as stereotyped and tailored the skill level on the subject's performance. Moreover, to better clarify the difference between a Higher and Lower performer, in each social block, the virtual agent was seated next to the experimental subject (blue chair, Figure S1A) who could perceive audio and visual feedback of the ongoing co-actor's Stroop test performance. In competitive scenarios, the subject had to outperform the virtual agent, while during Cooperation, the subject was required to collaborate to secure victory against an opposing team. During the Cooperation condition, to elicit a sense of teamwork, a single tracking score bar was displayed at the bottom of the virtual screen, tracking the team's performance (Figure S1C **middle**). When at least one of the two team members gave a correct answer, the team scored one point; when neither of them gave a correct answer, the team scored zero points. This scoring method ensured that the final result depended on the combined contributions of both actors, creating an environment where each individual could perceive the direct impact of their performance on the team's overall success. During Competition, two different scoring bars were presented on the screen representing the experimental subject's score and the co-actor's score separately (Figure S1C **bottom**). There were three possible trial outcomes: correct answer, wrong answer (i.e., error), and time expired (max time = 1500 msec). Participants received feedback for each trial; a correct answer was indicated by a green smiley face and a success sound, an error trial by a red frowny face and buzzer sound, and a time expired was represented by a "time expired" label depicted on the virtual monitor and a timer alert sound.

Each subject performed a total of 6 blocks: Familiarization, Solo, Cooperation with a Higher and Lower performer, and Competition with a Higher or Lower performer (Figure 1A). A pause of 120 seconds separated each block. To quantify the amount of stress that each experimental condition elicited in the participants, at the end of each block, we asked them to report their perceived stress on a visual scale displayed on the black screen ranging from 0 to 100 (subjective rating; "how stressed have you felt during the task?"). Before the beginning of the experiment, participants were briefed on the significance of the extreme anchors of the stress scale: they were told to calibrate their responses accordingly, with 0 indicating 'absence of any kind of stress' and 100 indicating 'the highest and most intolerable stress possible'. All participants started by completing the Solo condition, which allowed to record each subject's baseline performance and tailor the virtual agents presentation of the Higher and Lower performer accordingly. For this reason, the Solo condition was always presented before the social contexts. Instead, the order of the four social blocks was counterbalanced across participants. The whole experiment lasted about 60 minutes including the placement of the electrodes for the physiological recordings and questionnaires.

Experiment 2

Experiment 2 was conducted in the same virtual setting as Experiment 1 (Figure S1). The structure of the Stroop test as well as the algorithm implemented to precisely adjust trial by trial the virtual co-actor's performance based on the accuracy of the experimental subject, remained identical to that in Experiment 1. However, in contrast to the first experiment, participants were invited to repeat each Social context three times. This approach was designed to explore whether variations in performance, subjective rating, and physiological activation observed in Experiment 1 persisted after the completion of numerous trials. Guided by the results obtained in the first experiment, here participants engaged in the two social contexts found to enhance performance equally but with different effects on perceived stress and autonomic activity: Cooperation with the Lower performer and Competition with the Higher performer.

As for the first experiment, before the experimental session started participants signed the written informed consent and provided their demographical data. After, electrodes were placed on each participant to record electrocardiogram (ECG) activity. Once seated and with the HMD on, the experimental session started. Again, before introducing them to the virtual Stroop test, we recorded 180 seconds of their baseline physiological activity. Then, subjects underwent a block of Familiarization condition (130 trials) to prevent any learning effect in the experimental conditions. The experimental session included seven blocks (130 trials each): one block of Solo condition, 3 consecutive blocks of Cooperation with the Lower performer (1^{st} block, 2^{nd} block, 3^{rd} block), and 3 consecutive blocks of Competition with the Higher performer (1^{st} block, 2^{nd} block, 3^{rd} block) (Figure 3A).

To quantify the amount of stress that each experimental condition elicited in the participants, at the end of each experimental block, we asked them to report their perceived stress on a visual scale displayed on the black screen ranging from 0 to 100 (subjective rating; "how stressed have you felt during the task?"). As for Experiment 1, all participants started by completing the Solo condition, which allowed to record each subject's baseline performance and tailor the Higher and Lower performer virtual agents' presentation accordingly. For this reason, the Solo condition was always presented before the social contexts. Instead, the order of the social blocks was counterbalanced across participants. The whole experiment lasted about 60 minutes including the placement of the electrodes for the physiological recordings and questionnaires.

QUANTIFICATION AND STATISTICAL ANALYSIS

Experiment 1

Performance

For each condition, participant's correct answers ratio was first normalized by subtracting the score in the Solo condition and then z-scored. Then, we ran a 2x2 ANOVAs on accuracy, with Social context (Competition and Cooperation) and Other's ability (Higher and Lower performer) as within-subjects factors (Figure 2A). For all dependent measures significant main effects were followed up by t-tests corrected by false discovery rate (FDR; Benjamini & Hochberg, 1995) correction: values of $p < 0.05$ were considered significant.

Perceived stress

The perceived stress level data provided by participants' subjective ratings (from 0 to 100) at the end of each experimental block were first z-scored then analyzed with a 2x2 ANOVA with Social context (Competition and Cooperation) and Other's ability (Higher and Lower performer) as within-subjects factors (Figure 2B). Self-reports of two subjects were missing due to technical problems, therefore analyses on perceived stress were run on 48 participants. For all dependent measures significant main effects were followed up by FDR-corrected t-tests: values of $p < 0.05$ were considered significant.

Physiological measures

ECG data were processed using custom scripts on Matlab (release 2021a, The MathWorks, Inc.). We extracted beats per minute (BPM) from each experimental block as well as from the 3-minute resting period occurring before the beginning of the experimental session (baseline). In order to control for inter-individual variability data from all the conditions were first normalized by subtracting the baseline and subsequently z-scored. Similarly to behavioral analyses, we were interested in investigating the effects of the Other's ability on participants' physiological responses within the two social contexts. Then we ran a 2x2 ANOVAs on BPM, with Social context (Competition and Cooperation) and Other's ability (Higher and Lower performer) as within-subjects factors (Figure 2C). For all dependent measures significant main effects were followed up by FDR-corrected t-tests: values of $p < 0.05$ were considered significant.

Additional and control analyses

We conducted several control analyses to investigate the robustness of our results and ensure that they were not affected by confounding variables.

First, we explored whether our customized Virtual Stroop test successfully induced the Stroop effect, defined by faster Reaction Times (RT) in congruent trials,[42] by investigating the difference in RT between incongruent and congruent trials. We ran three one-sample t-tests contrasting RT in incongruent trials with RT in congruent trials, separately for each Context (Solo, Cooperation, Competition). As expected, participants took more time to complete incongruent trials than congruent trials in all contexts (Solo: $Mean_{Incongruent} = 1.156$, $Mean_{Congruent} = 1.045$, $t = 13.352$, $p < 0.001$; Cooperation: $Mean_{Incongruent} = 1.084$, $Mean_{Congruent} = 0.968$, $t = 18.338$, $p < 0.001$; Competition: $Mean_{Incongruent} = 1.086$, $Mean_{Congruent} = 0.971$, $t = 18.615$, $p < 0.001$) (Figure S2A). These results are in line with previous studies[85,95] and validated the efficacy of our virtual version of the Stroop task in inducing the well-known and well-validated Stroop effect, thus allowing us to further analyze the effect induced by different social variables on subjects' performances.

Second, to confirm that also our social contexts produced the *social facilitation effect*,[24] we ran a one-way repeated measures ANOVA on accuracy (computed as the ratio between the number of correct trials and the total number of trials) with Context (Solo, Cooperation, and Competition) as within-subjects factor. Results indicated a significant Context effect [$F_{(2, 98)} = 30.168$, $p < 0.001$, $\eta^2_p = 0.485$], with post-hoc pairwise comparisons revealing that both Cooperation [$t_{(49)} = 5.654$, $p < 0.001$] and Competition [$t_{(49)} = 6.692$, $p < 0.001$] ameliorated participant's accuracy scores with respect to the Solo condition, but did not differ between them [$t_{(49)} = 1.060$, $p = 0.294$] (Figure S2B). Also, to understand in which way our experimental variables affected the number of errors made (pressing the wrong color button) and time expired trials (not answering within 1,5 seconds), we ran two different one-way ANOVAs on the percentage of errors and time expired with Context (Solo, Competition, and Cooperation) as the within subject factor. Interestingly, the number of errors did not vary among different Context [$F_{(1, 49)}= 0.616$, $p = 0.537$, $\eta^2_p = 0.012$], whereas we found a significant Context effect on the number of time expired trials [$F_{(1, 49)}= 38.653$, $p < 0.001$, $\eta^2_p = 441$]. Post-hoc analyses revealed that both Cooperation [$t_{(49)} = 6.412$,$p < 0.001$] and Competition [$t_{(49)} = 6.786$, $p < 0.001$] showed a significant lower number of time expired trials than Solo condition (Figure S2C) and that the two social conditions did not differ between them.

Third, to make sure that performance in Solo, Cooperation, and Competition conditions were not affected by any learning effect, for each condition, we analyzed learning effects within each scenario by extracting the average accuracy over ten-time bins (each bin representing the mean accuracy over 13 consecutive trials) and subsequently computing Pearson correlations between bin accuracy and bin number. During the Familiarization condition, participants increased their performance significantly ($r = 0.921$, $p < 0.001$). Interestingly, we did not observe any variation in accuracy over trials for Solo ($r = -0.339$, $p = 0.338$) Cooperation ($r = -0.345$, $p = 0.329$), and Competition ($r = -0.125$, $p = 0.731$), showing that participants had acquired a stable performance after the Familiarization condition (Figure S2F). This analysis allowed us to confirm that participants had acquired a stable performance after the Familiarization phase and that the results found in the following sections were not influenced by a learning process.

Finally, BPM results raised the question of whether higher values in Competition with a Higher performer could be due to an increased speed in responding to the stimuli. To verify if the increase in physiological activation was related to a motor response, we ran a 2x2 ANOVA on RT with Social context (Competition and Cooperation) and Other's ability (Higher and Lower performer) as within-subjects factors. Here we found a significant main effect of Other's ability [$F_{(1, 49)} = 28.218$, $p < 0.001$, $\eta^2_p = 0.365$], indicating that participants were faster when interacting with a Higher performer than with a Lower performer [$t_{(49)} = 5.312$, $p < 0.001$]. Also, the ANOVA revealed a significant interaction Social context x Other's ability [$F_{(1, 49)} = 4.528$, $p = 0.038$, $\eta^2_p = 0.085$]. Post-hoc comparisons following the significant interaction showed no difference between competing or cooperating with a Higher performer [$t_{(49)} = 1.036$, $p = 0.305$]. Indeed, participants maintained similar RT in Competition and in Cooperation with a Higher performer, while BPM increased only during Competition with a Higher performer. A similar pattern of results was observed when comparing RT in Competition and Cooperation with a Lower performer [$t_{(49)} = 1.351$, $p = 0.366$]. These results confirm that the increase in physiological activation during Competition with a Higher performer was not driven by participants' motor response but instead by the social context itself. Thus, although Cooperation with a Lower performer yielded a similar performance as Competition with a Higher performer, the latter condition was associated with higher reported stress levels and increased autonomic responses.

Competitive traits and self-efficacy drive performance during competition

To investigate the correlation between the performance during each condition and personality traits we ran ten different Spearman Correlations between the normalized accuracy during each of the five blocks (Solo, Cooperation with the Higher performer, Cooperation with the Lower performer, Competition with the Higher performer, Competition with the Lower performer) and two questionnaires: CCPS[93,96] and GSE[94] (Schwarzer & Jerusalem, 1995). We found a positive correlation between the competitive-CCPS questionnaire score and accuracy during Competition ($r = 0.400$ $p = 0.004$; Figure S2D), indicating that individuals with higher competitive traits performed better in Competition compared to subjects with lower competitive traits. Similarly, we found a positive correlation between the general self-efficacy scale (GSE) and accuracy during Competition ($r = 0.294$ $p = 0.038$; Figure S2E) indicating that higher accuracy scores are associated with more self-efficacy.

Thus, higher accuracy scores in Competition are linked to both higher competitiveness and higher self-efficacy. No other significant correlations were found. All the other correlations were not significant (all ps > 0,05).

These results reveal that personality traits might also have an important role in modulating an individual performance in a social context. Indeed, it is known that personality traits can broadly influence performance and motivation [97–99], and here we showed that this is particularly true for competitive personalities when they are engaged in a competition to win against another individual, while these traits do not influence within a cooperative setting.

Experiment 2

Performance

Given that the focus of this experiment was to investigate the long-term effects of competitive and cooperative interactions (Cooperation with the Lower performer and Competition with the Higher performer). Thus, we focused on accuracy as the dependent variable and normalized it like in the first experiment. Then, we ran a 2x3 ANOVAs on accuracy, with Social context (Competition and Cooperation) and Repetition (1^{st} block, 2^{nd} block, 3^{rd} block) as within-subjects factors (Figure 3B). For all dependent measures significant main effects were followed up by t-tests corrected by false discovery rate (FDR; [100]) correction: values of $p < 0.05$ were considered significant.

Perceived stress

The perceived stress level provided by participants' subjective ratings (from 0 to 100) at the end of each experimental block was also analyzed with a 2x3 ANOVA with Social context (Competition and Cooperation) and Repetition (1^{st} block, 2^{nd} block, 3^{rd} block) as within-subjects factors, after applying the normalization used in the Experiment 1 (Figure 3C). For all dependent measures significant main effects were followed up by FDR-corrected t-tests: values of $p < 0.05$ were considered significant.

Physiological measures

The pre-processing and normalization of the ECG data was identical to the one employed in the first experiment. Then, as for the other dependent variables, we ran a 2x3 ANOVAs on BPM, with Social context (Competition and Cooperation) and Repetition (1^{st} block, 2^{nd} block, 3^{rd} block) as within-subjects factors (Figure 3D). Due to technical problems, we could analyze the physiological data from 48 participants only, which were however enough according to power analysis (see STAR Methods – Participants Details). For all dependent measures significant main effects were followed up by FDR-corrected t-tests: values of $p < 0.05$ were considered significant.

Control analyses

We investigated whether the experimental conditions were affected by any learning effect within-block. We analyzed it by extracting for each block the average accuracy over ten-time bins (each bin representing the mean accuracy over 13 consecutive trials) and subsequently computing Pearson correlations between bin accuracy and bin number. We observed a significant correlation in accuracy over trials only during the Familiarization phase ($r = 0.830$, $p = 0.003$; Pearson correlation). After that, participants achieved a consistent performance level, indeed we did not observe any significant correlation for all the other conditions (all ps > 0.05).